Designing Energy-Efficient Façades to Meet Energy Transition Targets

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Preamble

This thesis is part of the PV2050 joint research project: *Next-generation photovoltaics*, and falls within the context of its subproject 4: *Photovoltaics into the built environment: from semi-transparent PV glazing to high efficiency integrated solutions*. This research project is funded by the Swiss National Science Foundation for Scientific Research (SNSF) under the National Research Program (NRP) 70 – Energy Turnaround.

Subproject 4 is an interdisciplinary research project where collaboration among BIPV producers (H.Glass), BIPV developers (CSEM) and architects (LAST-EPFL) has been established. This collaboration targets bridging the identified gap between technology and design. For this, subproject 4 of the PV 2050 research project aims to develop design strategies to integrate BIPV's expressive issues into today's façade construction, focusing on new collective residential dwellings. High efficiency and emerging ultra-high-efficiency module technologies are analysed and optimised to improve the visual aspect and acceptance of photovoltaic systems installed in Switzerland. In this context, this thesis provides an assessed and implemented energy-efficient façade design to foster and motivate the introduction of energy-efficient technologies into architectural professional practices.

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Abstract

The contemporary energy context can be considered as a period of energy transition, where the latest protocols focus on limiting greenhouse gas (GHG) emissions and improving energy efficiency across the different energy consumption sectors. As the largest single energy consumer in Europe, the building sector faces the particular challenge of meeting the latest energy efficiency requirements in the prospect of a growing population, whose growing demand results in increased construction activity and energy consumption.

In line with the objectives of the energy transition, the European Union (EU) is committed to drastically reduce its GHG emissions by 2050. This objective is applied to the construction sector through new building energy efficiency requirements specified in the latest building directives. The latter highlight the potential of the building envelope to yield energy efficiency by passively reducing energy demand and through the incorporation of active energy generation systems, including solar systems. Among the latter, Building-integrated photovoltaic (BIPV) systems have a demonstrated potential to increase energy efficiency, especially when they are an integral part of the building's design and construction.

However, despite their energy-efficiency improvement potential, BIPV systems are not widely used among architectural practices. This results simultaneously from the particular attention required by BIPV in terms of design and construction, the still low number of examples of successful architectural integration, the generalised lack of awareness among professionals and the perception of the high cost of this technology. These barriers, among others, reveal a tangible gap between the potential of energy-efficient technologies and their application to current architectural practices, specifically with regards to façade design due to its public character as an urban landscape generator.

To contribute bridging this gap in the context of energy transition, this thesis proposes a research-by-design methodology structured in different interdisciplinary research phases. These phases aim to design and assess an energy-efficient façade solution with the potential of contributing to the building sector's energy transition. The research adopts an architectural approach to explore the collective residential façade design potential and improve its construction energy efficiency. The research process entails an analysis of the contemporary residential façade design currents and the advanced practices on energy-efficient construction. The research methodology is structured in three iterative phases: the design of an energy-efficient façade, its quantitative assessment and the evaluation of its transfer potential towards professional practices.

The concrete contribution of this research is to provide architecture professionals with energy-efficient architectural visions that can guide them to explore such energy-efficient strategies, integrate these issues in their own design processes and thus contribute to the energy transition at that scale. Similarly, the design methodology and the assessment processes can support construction stakeholders' decisions concerning the integration of energy-efficient design strategies into building development, improving contemporary façade construction practices.

Keywords: energy-efficient façade design | integrated design | building-integrated photovoltaics (BIPV) | low-embodied-impact design | sustainable architecture | multi-criteria assessment

Résumé

Le contexte énergétique contemporain peut être considéré comme une période de transition énergétique, pendant laquelle l'accent est mis sur la limitation des émissions de gaz à effet de serre (GES) et sur l'amélioration de la performance énergétique. En tant que principal consommateur d'énergie en Europe, le secteur du bâtiment doit relever le défi particulier de répondre aux dernières exigences en matière d'efficacité énergétique dans un contexte de croissance démographique pesant de manière accrue sur la demande en énergie liée aux activités de construction.

Conformément aux objectifs de la transition énergétique, l'Union européenne (UE) s'est engagée à réduire considérablement ses émissions de GES d'ici 2050. Cet objectif est transposé au secteur de la construction par le biais de l'actualisation des directives établissant de nouvelles exigences d'efficacité énergétique des bâtiments. Le rôle de l'enveloppe du bâtiment, pour améliorer l'efficacité énergétique, y est mis en évidence grâce au potentiel qu'elle renferme pour l'incorporation de dispositifs énergétiques passifs (réduction de la demande) et actifs (production), tels que les systèmes solaires. Parmi ces derniers, les installations photovoltaïques sont particulièrement performantes, en particulier lorsqu'elles sont intégrées au bâtiment (BIPV) dès les phases de conception et de construction.

Cependant, malgré leur potentiel d'amélioration de l'efficacité énergétique, les systèmes BIPV sont peu utilisés au sein de la pratique architecturale. Cela résulte simultanément de l'attention particulière requise par le BIPV en termes de conception et de construction, du encore faible nombre d'exemples d'intégration architecturale réussie, du manque généralisé de sensibilisation des professionnels et de la perception du coût élevé de cette technologie. Ces obstacles, entre autres, révèlent un écart tangible entre le potentiel des avancées technologiques dans le domaine de la performance énergétique et leur transfert aux pratiques architecturales actuelles. Leur intégration à la conception de la façade est particulièrement délicate en raison de son caractère public, générateur de paysage urbain.

Compte tenu de ce décalage entre technologie et architecture dans le contexte de la transition énergétique, cette thèse propose une méthodologie de recherche par projet, structurée en trois phases itératives et interdisciplinaires. Les deux premières phases visent à concevoir et à évaluer des solutions de façades économes en énergie, susceptibles de contribuer à la transition énergétique du secteur du bâtiment. Cette étape repose sur une analyse des tendances contemporaines en termes de conception de façades résidentielles et de pratiques avancées en matière de construction sobre en énergie. Les variantes de design obtenues à l'issue de ces deux premières phases servent ensuite à nourrir une approche architecturale pour explorer le potentiel de transfert à la pratique de la conception de façades performantes pour les bâtiments de logements.

La contribution concrète de cette recherche est de fournir des nouvelles visions architecturales performantes aux professionnels de l'architecture pouvant les guider dans l'exploration de telles stratégies, intégrer ces questions dans leurs propres processus de conception et contribuer ainsi à la transition énergétique à cette échelle. Les apports méthodologiques de conception et d'évaluation peuvent, également, servir d'aide à la décision aux acteurs de la construction pour l'intégration, à grande échelle, de stratégies de conception performantes, et ainsi améliorer la pratique contemporaine de construction de façades.

Mots clés : conception de façades performantes | design intégré | photovoltaïque intégré au bâtiment | conception bas carbone | architecture durable | évaluation multicritère

Resumen

El contexto energético actual puede presentarse como un periodo de transición energética donde los últimos protocolos se centran en limitar las emisiones de gases de efecto invernadero (GHG) y mejorar la eficacia energética de procesos de los distintos sectores de consumo. El sector de la construcción, en su condición de mayor consumidor de energía, tiene ante sí el difícil reto de afrontar, bajo condiciones de eficacia energética, las previsiones de incremento de población que se prevé para los próximos años, implicando un aumento de la actividad constructiva y del consumo energético.

En línea con los objetivos de la transición energética, la Unión Europea (UE) se ha comprometido a reducir drásticamente las emisiones de GHG para el año 2050. Este objetivo afecta profundamente al sector de la edificación, que se ve condicionado por la aparición de nuevas directivas de construcción, que regulan el rendimiento energético de edificios y procesos constructivos. Las nuevas directivas destacan el potencial de la envolvente del edificio para reducir la demanda energética del mismo, al ser capaces de incorporar tecnologías de generación de energía renovable como es el caso de los sistemas solares. Entre estos últimos, destacan los sistemas fotovoltaicos, con un potencial demostrado, especialmente cuando se integran en el edificio con una doble condición; la energética y funcional (BIPV).

A pesar del potencial de mejora de la eficiencia energética del edificio que poseen los sistemas BIPV, no gozan de un uso extendido en el ejercicio de la practica de la arquitectura. Esto se debe principalmente a la atención que requieren en términos de diseño y construcción, al todavía reducido numero de ejemplos prácticos de calidad, al desconocimiento de la tecnología que existe entre los profesionales y a la percepción del alto coste de su instalación. Estos factores, entre otros, generan un alejamiento entre los profesionales que practican la arquitectura y las tecnologías BIPV, especialmente en lo que afecta al diseño de la fachada debido a la dimensión publica que estas poseen como generadoras del paisaje urbano de las ciudades.

Para implementar las tecnologías citadas en la propia arquitectura de los edificios, esta tesis propone una metodología de investigación basada en el diseño. Esta metodología incluye procesos interdisciplinares, que posibilitan proyectar y evaluar las soluciones de fachada que permitan el cumplimiento de los objetivos de la transición energética dentro del sector de la construcción. La investigación se centra específicamente en el potencial del diseño de fachadas en edificios residenciales destinados a vivienda colectiva, para mejorar su eficiencia energética, desde un enfoque arquitectónico. Por este motivo el desarrollo del trabajo, se basa en el análisis de las tipologías actuales de fachadas residenciales y de las practicas avanzadas de la construcción eficiente. La metodología de investigación estructura la investigación en tres fases interactivas: el diseño de un sistema de fachada de alto rendimiento energético, la evaluación de sus repercusiones de tipo cuantitativo y la valoración de su potencial de aplicación en la practica profesional arquitectónica.

La contribución concreta a la práctica profesional que aporta este trabajo de investigación, consiste en el desarrollo de referencias de apoyo para el diseño de arquitecturas energéticamente eficientes, que pueden guiar y motivar el trabajo profesional de los arquitectos hacia prácticas mas eficientes compatibles con el buen diseño. Además, tanto la metodología de diseño propuesta como los sistemas de evaluación utilizados, pueden ayudar a los distintos profesionales implicados en el sector de la construcción, a tomar decisiones concretas adecuadas sobre la mejora de la eficacia energética de las practicas constructivas habituales.

Palabras clave: diseño de fachadas eficientes | diseño integrado | fotovoltaico integrado en el edificio | diseño de bajo impacto medioambiental | arquitectura sostenible | análisis multi-criterio

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The energy transition is a pathway toward the transformation of the global energy sector from fossil-based to zero-carbon by the second half of this century. It focuses on reducing energy-related CO_2 emissions to limit climate change. To achieve this, the energy transition is based on the use of renewable energy and the implementation of energy efficiency measures to potentially achieve 90% of the required carbon reductions [IRENA 2019a].

1. Introduction

Context: global warming

Since 1990, the Intergovernmental Panel on Climate Change (IPCC) has been studying the consequences of global warming, providing the scientific input to international climate policymaking [IPCC 2019]. IPCC's fifth assessment report (AR5) states that *continued emission of greenhouse gases (GHG) will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems. Limiting climate change would require substantial and sustained reductions in greenhouse gas emissions, which, together with adaptation, can limit climate change risks* [IPCC 2014].

Environmental Protocols: reduce GHG emissions

The United Nations Framework Convention on Climate Change (UNFCCC) is the main multilateral forum on fighting climate change. Since 1992, different protocols [UNFCCC 1997, 2015] have established a limit to GHG emissions for all UNFCCC parties. Among the latter, the European Union (EU) is committed to drastically reduce GHG emissions by 2050: levels should be 80-95% lower when compared to 1990 [European Commission 2012]. This challenge is addressed from all energy-consuming sectors, setting the framework of the energy transition[1], which is generally defined as a long-term structural change in energy systems.

Challenges: growing population leads to intense construction activities

Targeting GHG emission reduction objectives is a major challenge in the context of a continuing population and economic growth [OECD 2011; OFEN 2017]. Hosting this growing population in a quality urban-space involves an intense activity in the construction sector, which is the largest single energy consumer in Europe and accounts today for 36% of the EU's GHG emissions [European Commission 2019].

Policies: construction sector's energy efficiency

In Europe, the reduction of GHG emissions associated with the construction sector is addressed through the publication of new energy directives regarding energy efficiency [Directive 2012/27/EU 2012] and building performance [Directive 2010/31/EU 2010]. These European directives focus on reducing GHG emissions and the undesired reliability on non-renewable resources by establishing building energy efficiency measures.

Switzerland: *Energy Strategy 2050* and 2000-Watt Society

In Switzerland, a long-term energy policy has been developed under the name of *Energy Strategy 2050* (ES 2050), which restructures the Swiss energy system [SFOE 2014]. This new energy policy focuses on the consistent exploitation of existing renewable energy potentials. Likewise, another Swiss energy economy initiative – the 2000-Watt Society – proposes limits to both energy consumption and CO_2 emissions related to one person's annual activity [Suisse Energie 2015]. These person-based limits have been translated to building's energy efficiency targets and gathered in the Swiss construction recommendation: SIA 2040 [SIA 2040 2017].

Energy efficiency: the potential of the building envelope

The new building energy efficiency directives focus on lowering both operational energy and embodied energy. To this end, they highlight the potential of the building envelope to decrease the building's operational energy demand and provide it with clean and decentralised electricity. This means that the building's operational energy efficiency can be significantly improved through the increase of the building envelope's thermal insulating properties [Ruggieri *et al.* 2013]. In addition, on-site building energy generation can be achieved by incorporating renewable energy generation systems such as photovoltaics (PV) [Bonomo *et al.* 2015]. However, the integration of high-performant thermal insulators and PV systems into the building envelope entail certain embodied environmental impacts. For this reason, energy efficiency construction recommendations propose a combined evaluation of the building's energy performance where on-site energy generation can compensate for the energy generation system's embodied impacts.

On-site energy generation: Photovoltaics

The *Energy Strategy 2050* establishes that by 2050, 20% of the total Swiss energy consumption has to be generated by PV systems [SFOE 2014]. To achieve this target, the integration of PV systems into buildings is being promoted by the Swiss Energy Law (LEn) [AFCS 2018].

Recent and on-going researches are pushing forward PV technology by improving its performance and lowering its price. PV performance improved from 12% to 17.5% between 2007 and 2017 [IRENA 2017] and will soon reach efficiency values near 30% with technologies such as the new tandem perovskite PV cells [CSEM 2016]. At the same time, PV prices have dropped by around 80% since 2009, reaching today 0.45 CHF/PV cell [DETEC 2017; IRENA 2019b; Perret-Aebi 2019a]. As a consequence of PV performance improvement and PV price decrease, PV electricity price offers a competitive alternative compared with the electricity produced by a generation plant [SFOE 2014]. Notwithstanding, PV electricity has a potential cost-reduction of 59% by 2025, according to the International Renewable Energy Agency [IRENA 2016].

Photovoltaics in buildings: Building-integrated photovoltaics (BIPV)

A promising offer of PV technology consists of the architectural and constructive integration of PV elements into buildings, called the Building-integrated photovoltaics (BIPV) [Osseweijer *et al.* 2018]. The latter has been identified as a performant carbon mitigation option [Edenhofer *et al.* 2014] that has an architectural function and an electric generation capacity [SUPSI 2019]. It also presents numerous advantages compared to a centralised PV power plant or a traditional Building-attached photovoltaics (BAPV) installation because it enables to reduce material use, initial investment costs and energy transportation losses [SUPSI 2019]. BIPV systems can be incorporated into the building envelope as a real construction material: integrated into roof and façade cladding systems, window glazing, solar control systems or other façade components such as balustrades.

Development in photovoltaics technology began reasonably early (1839), although it is only since the 1970s that photovoltaic elements have been installed into building envelopes [Hegger *et al.* 2008]. PV building application started in 1973 with a BAPV roof in Delaware, and the first BIPV façade was presumably realised in Aachen in 1991 [Crassard *et al.* 2007]. Still, almost three decades later and despite its constant evolution, BIPV technology is not exploited to the best of its potential and does not benefit from widespread use in construction practices [Heinstein *et al.* 2013].

BIPV barriers

The BIPV integration depends mainly on the architect, who oversees the building design and coordinates the whole building construction process. However, architects often justify the lack of BIPV use in their designs by the unconvincing expression of existing solutions [CSEM *et al.* 2015; Ballif *et al.* 2018] and the lack of information regarding BIPV products and systems [Azadian *et al.* 2013; Bonomo *et al.* 2015; Yang 2015; Yang *et al.* 2015]. An unsufficient expressive quality of certain BIPV solutions can be restrictive in BIPV façade design because of their public exposure [Farkas *et al.* 2009]. The smaller number of convincing BIPV examples in terms of architectural integration and the lack of information are identified, among others, as architectural barriers for widespread BIPV use, hindering its potential and revealing a real gap between technology and architecture in current façade design and construction practices [Farkas *et al.* 2012].

Architectural design to foster building's energy efficiency

To contribute bridging the gap between technology and architecture in the context of energy transition, this research aims at developing a new façade design to provide buildings with an energy-efficient solution and contribute meeting the latest energy requirements while dealing with their architectural expression and construction complexity issues. To this regard, contemporary façade design, energy-efficient construction requirements and BIPV architectural features are analysed to foster BIPV incorporation into energy-efficient architectural practices. Accordingly, this research is developed explicitly within an architectural design approach.

This design approach generates energy-efficient design solutions, which are presented with an architectural language and assessed within an architectural perspective. The outcome of this process aims at providing architects with energy-efficient architectural references for residential façades that integrate passive and active energy design strategies. These architectural references are expected to be a concrete contribution to the work of architects, motivating energy-efficient façade design as well as supporting emerging practices to foster the evolution of professional architecture practices towards the energy transition.

Interdisciplinary research process

Bridging this gap intrinsically involves an interdisciplinary research process. In this line, ultra-high efficiency BIPV technologies are incorporated into the design research process through collaboration with BIPV developers. The new BIPV panels are multi-functional construction elements which increase the energy performance and visual acceptance of BIPV technology for its widespread use [Perret-Aebi 2019b]. In a like manner, collaborations with embodied environmental impact specialists, façade construction professionals, construction product developers and architecture practitioners; provide the architectural research process with reliable technical support, in order to contribute bridging the gap towards energy efficiency.

Research framework: Switzerland

The extent of this research work is limited to the Swiss context, with punctual references to worldwide construction practices and European energy directives. As a matter of fact, European and specifically Swiss construction practices significantly differ from international ones, the Swiss regulation being particularly demanding regarding the building's energy consumption. However, beyond the numerical results, the approach and the methodology developed in the research are transposable to another context.

Research framework: collective residential buildings

Switzerland has a total of construction-land (built or not) of 228 478 hectares. 47% of this surface is qualified as residential, and between 17% and 24% of this residential area is not yet constructed [ARE 2012]. Knowing that the growing population phenomenon also affects Switzerland [OFS 2015], these statistics results forecast an intense activity of the building industry for constructing collective residential buildings to cover the housing demand in the following decades [Riera Perez 2015; Wüest & Partner 2015]. For this reason, the current research focuses on energy-efficient architecture design strategies applied to collective residential buildings.

Research framework: façades

Residential building's energy efficiency is regulated by Swiss norms and recommendations published by the Swiss Society of Engineers and Architects (SIA) [SIA 112/1 2004; SIA 380/1 2009; SIA 2010; SIA 180 2014; SIA 112 2017; SIA 2040 2017]. The latter set high energy efficiency standards to meet the European GHG emissions reduction target by the year 2050. The building envelope, and specifically the façade, given its large surface in collective residential buildings, has the potential to contribute towards reaching the efficiency standards of the energy transition [Osseweijer *et al.* 2018].

This work aims at exploring the façade's potential to improve the building's energy efficiency from an architectural design approach. Similarly, the outcome of this research is expected to guide architects through the integration of energy-efficient façade design principles, with a specific focus on the integration of the latest BIPV technologies and low embodied impact construction principles dealing with façade design and construction requirements as well as energy and economic performance.

Research methodology

To explore the façade's energy-efficient design potential, the work is developed through a research by design process. The latter is designed to analyse the energy transition context and the state of the art of the research, to later develop an energy-efficient façade design that meets the latest energy requirements gathered in the previously mentioned building directives and construction recommendations. This energy-efficient façade is implemented into an architectural design process which generates building scenarios that can be subject of an assessment process. Through interdisciplinary collaborations with different construction sector stakeholders, the assessment process evaluates the façade's energy and economic performance as well as its transfer potential towards architecture professional practices. Ultimately, this process aims at defining the design potential of collective residential façades to contribute to the energy transition.

Structure of the thesis

This thesis presents the above-mentioned research process and structures its content in six further chapters. The following chapter, Chapter 2, contextualises the research and argues for the need to investigate energy-efficient design strategies in the building sector. This argumentation concludes in the establishment of the research question and the research methodology designed to answer it.

Chapter 3 presents a critical review of the energy transition requirements, which enables a better understanding of the focus of this research on energy-efficient façades, specifically BIPV and low embodied environmental impact construction. This chapter contains a description of low embodied impact concepts and BIPV systems to enable a comprehensive and critical lecture of the document. In this regard, the chapter aims to provide architects with passive and active energy economy strategies, frequently ignored or unknown among construction professionals. Ultimately, Chapter 3 analyses the state of the art of BIPV façade design research and practice.

Chapter 4, 5 and 6 constitute the core of this research work containing the assessed design outcome of this work. Chapter 4 presents Phase I of the research by design process. It develops the Advanced Active Façade (AAF) concept from an in-depth analysis of contemporary façade and BIPV design practices as well as energy-efficient design and construction requirements. The chapter presents the AAF construction system and its implementation into the AAF building scenarios, which can be further simulated and assessed regarding energy and economic performance. All the content of this chapter is represented with architectural graphic language: 2D plans, 3D axonometric and 3D architectural visualisations, in line with the aim of this thesis of guiding architects through the energy transition. The following phases help, within an iterative research and design process, to optimise the AAF as the research outcome of the design approach.

Chapter 5 presents Phase II of the research by design process, which consists of the energy and economic efficiency assessment of the AAF façade. The assessment chapter sets the framework to confront the design outcome's energy performance to common practices and energy efficiency limit values established by the 2000-Watt Society and defined by the norm SIA 2040 [Suisse Energie 2015; SIA 2040 2017]. Similarly, the economic performance of the AAF is assessed considering the higher initial investments associated with BIPV installations and the savings associated with the incorporation of an energy-efficient façade that generates on-site renewable energy.

Chapter 6 presents Phase III of the research methodology and evaluates the transfer potential of the AAF towards professional practice. For this, a series of interdisciplinary interactions are organised to confront different building stakeholders to the design results. First, the construction of a real scale façade demonstrator generates an innovative collaboration with façade constructors and BIPV producers, enabling the optimisation of the AAF design. Second, the AAF is presented to architecture experts, professionals and non-professionals to evaluate their acceptance of the AAF proposed design. Third, the AAF construction system is integrated into an architectural educational process through the organisation of an architectural competition for students aiming to foster knowledge transfer and to test the design potential of the AAF. Ultimately, this chapter evaluates the AAF's acceptance, its design potential and it transfer potential towards architecture professional practices.

In light of the results of the design and assessment phases, Chapter 7 presents a final discussion, recommendations and closing conclusions of the current study as well as a brief prospect for further research.

2. Research question

The research question is an inquisitive statement, which is often the starting point for scientific reasoning. It emerges from a series of initial findings and a research hypothesis [Tétreault 2015]. This chapter introduces the initial findings that have motivated the formulation of the research question leading this doctoral work. From the research question, a hypothesis and fundamental objectives are articulated. Then, the structure of the research and the adopted methodology is exposed.

2.1. Initial findings

A context of climate change

The Intergovernmental Panel on Climate Change (IPCC) defines climate change as *a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period* [IPCC 2001]. IPCC's fifth assessment report warns that global temperatures will further increase if GHG emissions are not reduced. This can have irreversible negative impacts on people and ecosystems, as described in the 2018's report, and must be urgently addressed by taking actions for mitigating GHG emissions [IPCC 2014; IPCC 2018].

Approaches to mitigate GHG emissions include energy demand reduction, energy efficiency, low-carbon technologies and fossil fuel use reduction [Yang *et al.* 2015a]. Among these actions, the IPCC states that energy efficiency plays a significant role in attaining climate stabilisation targets because today, most of the energy consumption comes from non-renewable sources [IPCC 2014]. This is to say; energy efficiency has the potential to reduce energy consumption and hence, GHG emissions. In line with this affirmation, the International Energy Agency (IEA) estimated that energy efficiency strategies could achieve more than 40% of the GHG mitigation required to reach its climate goals [IEA 2018].

Since 2011, energy roadmaps have been developed pursuing the decarbonisation of Europe's energy system to lower GHG emissions by 80-95% of the emissions registered in 1990 [European Commission 2012]. More recently, the Paris Agreement set new energy objectives with the ambition of limiting global warming below 2°C compared to preindustrial levels [UNEP 2015].

Issues and challenges

The drastic population increase forecasted for the following decades and the growing energy demand that it entails set a challenge for the targeted GHG emission reduction. In addition, higher comfort requirements and increasing electrical equipment use, accelerate the increase of global energy consumption [Hestnes 1999; OFS 2018].

This growing population issue is a worldwide matter, which raises the subject of hosting the increasing population in a quality urban-space [UN 2016]. It is expected that the growing population perspectives lead to intense activity in the building sector, which is already the largest single energy consumer in Europe accounting for 40% of the EU's energy consumption and 36% of its GHG emissions [Ritzen *et al.* 2014; European Commission 2019].

> *No other sector of industry uses more materials and energy, produces more waste and contributes less to material recycling than the building industry* [Hegger *et al.* 2008].

In Switzerland, more than eight million people were registered as Swiss permanent residents in 2015 (Figure 2.1). According to the Swiss Federal Office of Statistics (OFS), the Swiss population will continue to increase up to more than ten million people by 2045 [OFS 2015b]. Within the building sector, the residential construction sector is the most active one. As illustrated in Figure 2.2, 47% of the Swiss construction land (228 478 hectares) is qualified as residential, where the growing population will need to be accommodated [ARE 2012]. In 2018, 68% of the private construction expenditure was invested in housing development [OFS 2018]. The latter has been encouraged by favourable mortgage rates in the last decade [OFS 2011]. These facts define the Swiss residential construction sector as a dynamic one that will maintain and even intensify its activity in the next decades, defining a challenge to improve the energy efficiency of the building sector.

As a consequence of the intense activity in the construction sector here presented, the economic growth and the increasing use of electrical equipment, energy consumption is expected to continue increasing in the following years by an annual average of 2.3% until 2040 [Hestnes 1999; DOE/EIA 2017; Prieto *et al.* 2017; OFS 2018]. In Switzerland, the average energy consumption per person has decreased by 14% since 1990, but the population has increased by 23%, resulting in a total energy demand increase of 5% [OFEN 2017a]. An effective application of energy economy strategies can slow down the escalation in the world primary energy consumption, which increased only by 1% in 2016 [BP 2017]. Nevertheless, predictions elaborated by the US Energy Information Administration (EIA) show that by 2040, world energy consumption will increase by 48% compared to the 2012 consumption record, mostly due to the population increase [DOE/EIA 2016].

Evolution of energy policies

International concerns about climate change have raised awareness about energy issues setting the context of energy transition and focusing on energy efficiency [Morvaj *et al.* 2010]

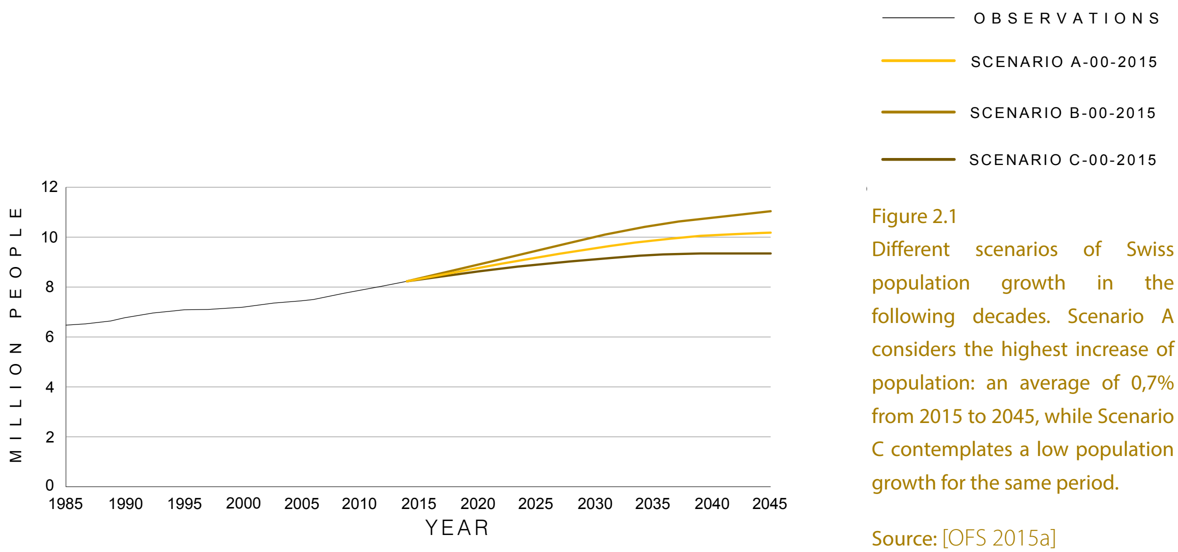


Figure 2.1
Different scenarios of Swiss population growth in the following decades. Scenario A considers the highest increase of population: an average of 0,7% from 2015 to 2045, while Scenario C contemplates a low population growth for the same period.

Source: [OFS 2015a]

Europe is considered as one of the largest energy-consuming regions of the world with an unsustainable growing energy demand based on fossil fuels. More precisely, 70% of Europe's energy consumption comes from fossil energy sources, mostly imported [Welsch *et al.* 2017]. To lower the non-renewable energy demand, European governments have developed new energy performance and economy directives to improve the EU's security of supply, reduce greenhouse gas emission, and thereby to mitigate climate change [2010/31/EU 2010; Directive 2012/27/EU 2012; European Commission 2012].

These directives target the use of energy from renewable resources, the limitation of global temperature rise below 2°C, the reduction of GHG emissions, and the security of European energy supply. To this end, they affect the building sector through their focus on avoiding excessive use of energy, reducing energy losses, monitoring and managing energy consumption [Directive 2010/31/EU 2010; Morvaj *et al.* 2010; Directive 2012/27/EU 2012; Niederle 2016].

Despite these objectives, energy systems have not yet been designed to deal with the above-mentioned energy efficiency challenges and must be transformed by 2050. This means that a new energy model is needed to make energy systems secure, competitive and sustainable in the long-run, setting the context of energy transition [European Commission 2012].

In Switzerland, energy demand is also growing, being consumed mainly in the form of oil fuels (51%), electricity (25%) and wood (4%) [OFEN 2017a]. The growing energy demand and the new restrictive European energy directives have motivated a readjustment of the energy systems, bringing the Swiss energy supply to a turning point [SFOE 2014]. In 2011, in response to the nuclear reactor accident in Fukushima, the Federal Government developed a new national energy strategy to be implemented until 2050: the *Energy Strategy 2050* (ES 2050). The latter restructures the Swiss energy system and defines the energy transition [SFOE 2014]. The ES 2050 has three main objectives: 1) increase the use of renewables, mainly hydro and solar power, 2) foster the energy efficiency of buildings, machinery and transportation, and 3) progressively withdraw from nuclear power [SFOE 2014]. This energy policy targets a 16% energy consumption reduction per capita by 2020 and a 43% energy consumption reduction per capita by 2035, comparing values to the ones registered in 2000 [OFEN 2018].

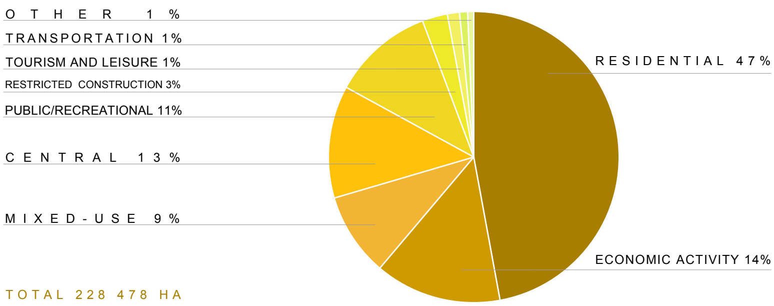


Figure 2.2.
Swiss construction land qualification.

Source: [ARE 2012]

The first step in the implementation of the ES 2050 was the overhaul of the Swiss energy law, which is effective since January 2018. This revision contains an energy transition program, regarding energy and building, focused on reducing energy consumption and CO_2 emissions from the Swiss real estate stock, as well as proposing economic and fiscal incentives to refurbish old buildings [OFEN 2017b]. The ES 2050 encourages the exploitation of renewable energies, such as solar, wind, geothermal and biomass, in addition to the already well-developed Swiss hydropower grid. The ES2050 forecasts a 60% consumption of hydropower and a 40% consumption of other renewable resources by 2050 [SFOE 2014].

Energy transition of the building sector

Within this framework, a series of encouragement and research programs are set up in order to transform the national energy systems and guide interdisciplinary professional practices through the imminent energy transition.

Regarding buildings' energy efficiency, the building sector benefits from several energy efficiency promotion programs and construction recommendations. Some examples are: the label *Minergie*, which fosters energy-efficient construction providing construction solutions, certifications and guidance [Minergie 2019], the *Programme bâtiments*, which subsidises energy-efficient building designs [Suisse Energie 2017], or the *Programme RPC/Pronovo*, which subsidises the integration of photovoltaic systems in buildings [Pronovo 2019].

Meanwhile, recent research has highlighted the potential of the building envelope to optimise the building's energy efficiency through passive and active energy strategies [Ruggieri *et al.* 2013]. The former can lower the building's operational energy demand and embodied environmental impacts, and the latter can provide the building with on-site renewable energy generation. The result is a lower energy balance improving the overall building's energy efficiency.

Among building active energy efficiency strategies, solar technologies have the highest potential [Jelle *et al.* 2012; Reijenga *et al.* 2012; Perlin 2013]. More precisely, photovoltaic (PV) technology is one of the most promising sources, which must cover 20% of the total electricity consumption in Switzerland by 2050, according to the ES2050 [SFOE 2014]. Consequently, PV technology is rapidly improving and becoming more and more efficient. The cost of PV modules has been divided by five times in the last six years, and the cost of full PV systems has been divided by almost three [Perret-Aebi 2019a].

A promising offer of PV technology consists of the architectural and constructive integration of PV elements: Building-integrated photovoltaics (BIPV) [Osseweijer *et al.* 2018]. The latter has been identified as a performant carbon mitigation option that has both an architectural function and an electric generation capacity [Edenhofer *et al.* 2014; SUPSI 2019]. It also presents numerous advantages compared to a centralised PV power plant or a traditional building-attached PV (BAPV) installation because it enables to reduce material use, initial investment costs, and energy transportation losses [SUPSI 2019]. BIPV systems can be integrated into the building envelope as a real construction material being part of the roof and/or the façade[1]. However, the roof is being increasingly solicited to host building services, green surfaces or recreational and public spaces. Hence, there are advantages to letting it free of other technological devices avoiding incompatibilities.

1

Façades are defined in the literature as the building's external walls which, like a separating filtering layer, protect the interior spaces from the weather and control the interior climate. Façades define as well the way the building is perceived from the exterior [Herzog *et al.* 2004; Knaack *et al.* 2014].

It can be understood from this definition that the term façade refers to both vertical façades and roof. For brevity's sake, the use of the term façade throughout the thesis refers explicitly to vertical façades – forming an angle equal to or greater than 60° with a horizontal plane [Sanchez-Ostiz Gutiérrez 1996].

For this reason, façade surfaces have a high potential to integrate BIPV systems as cladding systems, window glazing, solar control systems or other façade components such as balustrades. As identified in the initial findings, 47% of the Swiss construction land is qualified as residential. This implies that there is a large percentage of Swiss residential façades with significant potential to contribute to the energy transition.

A successful BIPV integration depends mainly on the architect, who leads and coordinates all the building design and construction stages. BIPV must be incorporated into the architectural design process at an early stage. However, architects often avoid incorporating BIPV in their designs because of the unsatisfactory visual aesthetic qualities of existing BIPV solutions, which notably affect façade design given its public exposure. Also, BIPV façade design can be affected by façade composition zoning standards [Farkas *et al.* 2009]. Thus, BIPV's poor aesthetics is identified as an architectural barrier blocking widespread BIPV use [Farkas *et al.* 2012]. Similarly, the initial findings show that architects complain about the lack of available information on BIPV technology and its design potential. This lack of information leads to a lack of BIPV use among architectural practices defining another barrier blocking the architectural integration of BIPV into design practices [Azadian *et al.* 2013; Bonomo *et al.* 2015; CSEM *et al.* 2015; Yang 2015; Yang *et al.* 2015b; Ballif *et al.* 2018].

Ultimately, BIPV façade design entails the incorporation of high embodied impact elements: the BIPV panels. From a combined energy assessment perspective, this impact can be totally or partially compensated through passive and active energy design strategies. On the one hand, compensating this impact involves considering the PV energy generation, which is expected to offset its embodied energy largely. On the other hand, an energy-efficient façade design that incorporates low embodied impact construction principles and high-performance insulation has the potential to improve further the building's combined energy efficiency towards the energy transition.

2.2. Research question

Even though the BIPV's widespread use has been hindered by different barriers, revealing a gap between technology and architecture in current façade design and construction practices, its potential is still significant. Its strategic integration into collective residential building's façade could find a place in the energy transition global challenges. In light of these initial findings, a fundamental research question arises, motivating this research work:

How can the architectural design of collective residential façades contribute to the energy transition?

To bridge the gap between technology and architecture, residential façade design must provide buildings with energy-efficient solutions that meet the latest energy requirements while dealing simultaneously with their architectural expression and construction complexity issues. These considerations allow identifying a targeted need, knowing that it falls into a field already explored by numerous researches. From there and in order to answer the research question, this work is based on the hypothesis that ***integrated façade design has the potential to contribute bridging the gap between energy-efficient technologies and architectural practice towards the energy transition***.

Based on this hypothesis underpinned by the research question, this doctoral research work adopts an architectural approach based on the principles of research by design. The underlying goal is to develop a new façade construction system that meets the latest energy requirements, and that is transferable towards professional practices. In addition to shedding light to the research question, this doctoral work also concerns the contribution that this research work intends to bring to the architects and, more broadly, to the evolution of building design practices.

Fundamental objective

The fundamental objective of the present research is, therefore, a concrete contribution to the work of architects, providing them with an assessed constructive solution that supports the design of energy-efficient buildings. This constructive solution aims at being taken as an energy-efficient façade architectural reference, contributing to the evolution of architectural practices that must be urgently adapted to the latest energy efficiency requirements to reduce the GHG emissions of the building sector.

To foster the evolution of current construction practices towards energy-efficient ones, the present work focuses on maximising the knowledge transfer potential towards professional architectural practices. Eventually, the knowledge transfer of the research outcome supports the existing emerging practices of façade sustainable design.

2.3. Structure of the research and methodology

Before providing answers to this research question, the existing building energy efficiency norms, recommendations, technologies and guidelines are studied in the research framework. Then, within an architectural approach, the research by design methodology is defined in three main phases: Phase I- Design approach, Phase II - Quantitative assessment, and Phase III - Transfer potential towards architectural practice.

Research framework

The analysis of the initial findings opens a variety of research tracks; for this reason, the scope of the research must be circumscribed. Indeed, the main topics discussed, namely the energy transition, energy efficiency, BIPV, low embodied impact construction and façade's architectural design, cover a wide range of applications.

This research takes the architectural façade design process, within the energy transition scenario, as the thread of the research framework analysis. The focus of this research on façades is due to the high potential of the building envelope to lower the operational energy demand of a building [Ruggieri *et al.* 2013]. More particularly, in urban areas, façades account for the largest part of the building envelope, between 60% to 80% [Redweik *et al.* 2013; Zammit *et al.* 2017]. In addition, integrating energy efficiency strategies into façades is a real challenge for architects because of their public exposure, which generates the urban landscape. This exposure requires to find a harmonious design coherence among the energy-efficient systems and the façade composition [Herzog *et al.* 2004; Hindrichs *et al.* 2006].

The initial findings above-described highlight the growing population perspectives and the need for further development of quality and affordable housing [OFS 2015b; Riera Perez 2015; Wüest & Partner 2015]. For this reason, this research studies collective residential building façades in particular, in sight of the intense activity perspectives in this sector. In addition, a preliminary study of existing BIPV projects reveals that the residential building typology is a minority and might require more considerable attention.

Following this thread, the research framework presented in Chapter 3 starts by introducing the increasingly demanding façade construction requirements in the energy transition context. Then it analyses the latest building energy efficiency directives and their main objectives: lowering the building's embodied energy and lowering the building's operational energy. These two objectives are the focus of the study of the state of the art reported throughout Chapter 3. It presents the existing technologies, barriers, and construction principles generated towards the energy transition, as well as recent research and practice incorporating energy-efficient façade design.

Research by design methodology

Synthetically, research by design is a research process where knowledge is produced through the act of designing. It includes investigations where the design takes a significant part of the research process. In the context of this current research work, the design is understood as an iterative process which enables an architect to provide complex solutions to a problem [Hauberg 2011].

RESEARCH METHODOLOGY

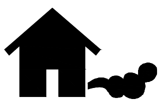
PHASE I : DESIGN APPROACH

Development of a energy efficicient façade to Incorporate BIPV into façade design practices

- Analysis
  - Contemporary collective residential façades
  - Existing BIPV façades
- Design
  - The Advanced Active Façade (AAF)
- Implementation
  - The AAF building scenarios

PHASE II : QUANTITATIVE ASSESSMENT

Multidisciplinary quantitative assessment of the design approach output

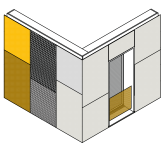


- Energy efficiency
  - Embodied energy assessment
  - Operational energy assessment
  - Combined energy assessment

- Economic efficiency
  - Life cycle cost (LCC)
  - Net present value (NPV)
  - Internal rate of return (IRR)
  - Discounted payback (DPB)

PHASE III : TRANSFER POTENTIAL

Multidisciplinary integrations to evaluate the research outcome transfer's potential towards architectural professional practices



- Constructing a façade demonstrator

- Presenting the AAF
  - Architecture practitioners
  - Architecture experts
  - Non-Experts

- Organising an architecture competition for students

Research by design is a particularly suitable approach in projects regarding complex environmental challenges. It involves investigating strategies, testing of ideas, materials and technologies; and studying cultural, social, economic, and aesthetic issues [Strand 1997; Roggena 2017]. Within the research by design, the architectural design process is the primary means through which new knowledge is generated. For this reason, architectural research by design results are reached through experience in practice [EAAE / AEEA Research centre 2016].

Ultimately, design-driven research offers a range of solutions for a specific issue, which in this case is the energy-efficient façade. The research by design process aims at generating architectural references that can inspire and motivate architects incorporating similar design processes into their professional creative process [Prost 1992; Goldschmidt 1998; Rey 2018].

Due to the topicality of the use of solar energy, along with the imperativeness of the energy transition, this work takes a practical *modus operandi*, supported by the research by design methodology. This methodology is designed based on existing research by design approaches [Roggena 2017] and relies on real architectural and construction design experiences, as well as on interdisciplinary interactions with the professional sector. Ultimately, this process enhances the potential application of the research's theoretical content to professional practices with the objective of providing an answer to the above-mentioned research question.

From this angle, three main iterative research phases structure the present research by design methodology: a design phase, an assessment phase and a transfer phase, where the outcome of the latter phases optimises the outcome of the former phase. Consequently, the structure of the research by design methodology is presented as follows: Chapter 4, Phase I - Design approach; Chapter 5, Phase II - Quantitative assessment; and Chapter 6, Phase III - Transfer potential towards architectural practice.

Phase I: a design approach to energy-efficient façades

The research framework outlines the energy requirements that a contemporary façade must meet. It also presents the energy efficiency technologies with the highest potential and their architectural barriers. Within a design approach, Phase I is presented in **Chapter 4** and focuses on the incorporation of BIPV technology into energy-efficient façade design practices. To this end, the design process is divided into three steps:

- **The Analysis step** focuses on the study of existing contemporary façade and BIPV design practices to define how both can be combined into an energy-efficient architectural design process.

  Design practices are analysed to identify: 1) façade design aspects affecting the optimal integration of BIPV and 2) BIPV architectural features affecting the façade design and construction. This process results in the identification of two façade design aspects – façade composition and façade morphology – which affect the way BIPV can be incorporated into the façade, and two BIPV architectural features – visual features and functional features – which affect façade design and architectural expression.

  Energy-efficient façade construction practices and BIPV system's construction requirements are also analysed in this phase to define the façade's constructive solution that integrates passive and active energy design strategies.

- **The Design step**'s objective is to design a façade that meets the contemporary design currents and complies with the construction and energy requirements presented in Chapter 3. This process results in the definition of the Advanced Active Façade (AAF), which integrates passive and active energy strategies to optimise the building's energy efficiency. The AAF construction system is defined as a highly-insulated and low embodied impact façade that incorporates BIPV as an integral component to generate on-site renewable energy.

- **The Implementation step** integrates the design outcome (the AAF construction system) into an architectural design process generating the AAF building scenarios. To do so, three successive actions take place: 1) the definition of an urban context; 2) the identification of a representative Swiss collective residential building; and 3) the active façade design.

  An existing plot, currently subject to an urban densification project, is identified as the urban context of the research project. This plot is located in Lausanne, which is a medium size-city that can be considered a representative Swiss city regarding climate and density. Then, the identification of a representative building provides the base to evaluate the energy efficiency of the AAF building scenarios and compare the results with current construction practices. Eventually, the AAF is implemented into the architectural design process following the contemporary design and construction trends identified throughout the analysis step. This design process generates the AAF building scenarios which can be considered as energy-efficient architectural references and can be subject to further analysis.

The design approach outcome: the AAF, is taken as the objective of the quantitative assessment (Phase II) and transferring potential evaluation (Phase III). In line with the aim of providing architects with an energy-efficient façade design reference, all the content developed through this research phase is presented with an architectural graphic language: 2D plans, 3D axonometric and 3D architectural visualisations. Ultimately, Phase I aims at fostering the evolution of current architectural practices towards energy-efficient architectural practice.

According to this objective, the performance of the AAF is provided through the assessment of its energy and economic efficiency, which is assessed in the next phase of the research.

Phase II: Quantitative assessment of the AAF's energy and economic efficiency

For Phase II (**Chapter 5**), the AAF building scenarios are assessed based on a comparative assessment method regarding energy and economic performance. The comparative framework is defined by the AAF building scenarios and two non-active façade construction current practices: *Common practice* (CP) and *Best practice* (BP). In addition, different PV technologies, BAPV integration and storage systems are also simulated and evaluated.

- **The energy efficiency assessment** is performed through the simulation and calculation of the different building scenario's embodied energy and operational energy. Ultimately, the combined energy analysis is also performed to confront its results to the energy efficiency limit values defined for the year 2050 by the norm SIA 2040 [SIA 2040 2017].

  The embodied energy analysis implies the quantification of the building's embodied impacts through the Life Cycle Assessment (LCA) method. This analysis is based on the façade and building's embodied impact calculations taking as reference the Swiss KBOB's database [KBOB 2016]. The operational energy analysis concerns the building's energy demand and generation to quantify its associated operational environmental impacts. To analyse the operational energy efficiency, energy simulations are performed through the building simulator tool Design-Builder (DB). Eventually, the combined energy analysis is required in most energy efficiency assessments where high embodied impact technologies are integrated into the building to lower its operational energy [SIA 2040 2017]. This is the case of integrating active energy strategies into the building envelope such as BIPV, which, despite its high embodied impact, is assumed to lower the building's combined energy balance.

- **The economic efficiency assessment** is performed to evaluate the economic impact of the AAF on the final building cost, and the benefits associated with the higher initial investment in the façade's energy efficiency upgrade. Despite the higher cost of the AAF compared to current façade construction practices, investing in an energy-efficient building can be a profitable long-term investment [Rütter-Fischbacher *et al.* 2010].

  A simplified economic efficiency assessment is performed for 10-year and 30-year investment periods through different economic-evaluation methods: 1) the life cycle cost (LCC), which enables the different scenario comparative regarding initial investment and operational costs; 2) the net present value (NPV), which indicates the sum of all cash flows at the end of the investment period; 3) the internal rate of return (IRR), which indicates the annual return on the initial investment; and 4) the payback time (PBT), which indicates the elapsed time between the time of an initial investment and the point when the revenues generated by the building reimburses that investment.

Phase III: Transfer potential towards the architectural practice

Phase III (**Chapter 6**), is the last phase of the research by design methodology. Developed simultaneously with Phase II, it analyses the applicability of the research outcome of Phase I: the Advanced Active Façade (AAF), as well as its transfer potential towards architectural practice.

This phase includes three interactions between the AAF and different audiences and contexts formulated as follow: 1) constructing a real-scale façade demonstrator; 2) presenting the AAF to different focus groups; and 3) organising a specific architectural competition for students. Within an iterative research process, Phase III focuses on optimising the AAF design, evaluating its design acceptance and assessing its design and transfer potential.

- **Constructing a façade demonstrator** transfers the research results in the context of architectural practice and professional construction processes. The demonstrator design and construction gather together an interdisciplinary group of professionals who provide feedback on the design and construction processes. This enables the AAF optimisation and applicability appraisal.

- **Presenting the AAF** is intended for three different professional and non-professional focus groups: architecture practitioners, architecture experts and non-experts. The architecture practitioners is a group of 50 construction professionals who visit the AAF demonstrator and provide feedback on its design, efficiency, and cost perception. They also evaluate how the visit of the AAF demonstrator affects their interest and motivation towards integrating energy-efficient façades into their projects. The architecture experts are 5 Swiss architecture experts who are selected based on their architecture awards, experience, and publications. Personal interviews are conducted with these architecture experts who allow testing the accordance of the work developed in this thesis with contemporary construction practices in Switzerland. The third group, the non-experts, are addressed through a national survey on generalised BIPV acceptance that is carried out in collaboration with the Institute of Sustainable Development of the Zurich University of Applied Sciences (ZHAW). This process aims at measuring the overall social acceptance of the AAF building scenarios.

- **Organising an architectural competition for students** aims at studying the applicability of the AAF into architectural practice. Students are asked to design a collective residential building that incorporates the AAF construction system. This competition enables testing the design potential of the AAF and achieves a knowledge transfer objective by introducing the research output into an architecture educational process.

These three research phases are integrated into an iterative design process where assessment results (Phase II) and professional practitioners' feedback (Phase III) are considered to optimise the performance, applicability, and acceptance of the AAF, consisting in the design approach output (Phase I).

3. Research framework

As highlighted in the initial findings presented in Chapter 2, this doctoral work is developed within the Swiss energy transition context. The research framework here presented takes as a starting point the increasingly demanding energy efficiency requirements and the challenging objective of meeting them within the building sector for its large and growing energy demand. Then, it focuses on the potential of façade design to improve the building's energy efficiency through passive and active energy design strategies. Among the passive energy design strategies, highly insulated façades and low embodied impact construction principles are explored. Among the active energy design strategies, the incorporation of BIPV systems and their potential to foster the building's energy efficiency are studied regarding existing research and current practices.

Ultimately, exploring the potential of energy-efficient façade design to contribute to the energy transition of the building sector gives way to the research by design approach developed in Chapters 4, 5 and 6. The objective of this research by design process is to contribute to overcoming the existing gap between energy-efficient technology and architectural practices.

3.1. Energy efficiency towards the energy transition

Since the 1970s, building design efforts have focused on reducing the building's energy consumption as a reaction to the oil crisis and the consequent fuel price increase. The awareness of the limited non-renewable resources drove to a sensible energy consumption [Cooke *et al.* 1994; Knaack *et al.* 2014a] leading to the first energy consumption regulation, *the Energy Conservation Act* in 1977 [Richarz *et al.* 2008], which motivated multiple façade insulation improvements. In Switzerland, the first energy consumption recommendation was drafted in the late 1980s to promote a rational economy of energy. As far as the construction sector is concerned, this recommendation referred to the building services performance as a way to lower the building's energy demand [Conseil Fédéral Suisse 1988, 1990; Aksoezen *et al.* 2015].

Today, the reduction of energy consumption is no longer driven by the scarcity of fossil fuels, but by an environmental concern that directly relates energy consumption to global warming and its negative environmental impacts [Akadiri *et al.* 2012]. As a consequence of global warming, numerous protocols and directives are promoting the reduction of GHG emissions internationally [European Commission 2012; Edenhofer *et al.* 2014; Satterthwaite 2014; IPCC 2019]. In Switzerland, the Swiss *Energy Strategy 2050* (ES 2050) published in 2014 and presented in the previous chapter, aims at restructuring the Swiss energy system defining the energy transition [SFOE 2014].

3.1.1 Requirements

As introduced in the initial findings (Chapter 2), the energy transition requires high levels of energy efficiency in every energy-consuming sector in order to drastically lower GHG emissions. It also requires a decrease in energy consumption per person and an increase in the use of renewable energy, specifically hydro and solar power [SFOE 2014]. As a reminder, the ES 2050 requires that energy consumption from photovoltaic (PV) will represent 20% of the total electricity consumption of the country by 2050 [SFOE 2014].

With the same objective and focused on the sustainable use of energy, the Swiss Federal Institute of Technology (ETH) in Zurich has developed the concept of the 2000-Watt Society as a model of energy policy. This energy model establishes that it is possible to limit the annual energy consumption per person to 2000 Watts by the year 2100. In addition, the 2000-Watt Society requires that 75% of this energy consumption must come from renewable resources to limit the annual GHG emissions per person to 1 tonne of CO_{2eq}[1] [Stadt Zürich 2008; Ettlin 2013]. These energy consumption requirements are based on the study of the maximum energy consumption that worldwide energy reserves permit annually per capita, and are justifiable in terms of environmental impact [Volland *et al.* 2011].

The 2000-Watt Society sets an intermediate objective for 2050, which defines a maximum annual consumption per person of 3500 Watts of primary energy (PE), 2000 Watts of non-renewable primary energy (NRPE) and 2 tonnes of $CO_{2eq.}$ These requirements are set to the total energy consumption of all sectors (construction, mobility, industry and systems) [SIA 2040 2017]. Primary energy consumption per capita and CO_2 emissions associated have been decreasing since 2000, when values over 6200 Watts and 8.5 tonnes of CO_{2eq} per person were registered. More recently, in 2017, a PE consumption of 4710 Watts and 6.5 tonnes of CO_{2eq} per person were registered [Suisse Energie 2018].

These energy policies and their energy efficiency requirements are integrated into Swiss construction norms and recommendations, defining the building's energy efficiency target values for the year 2050 [Suisse Energie 2015; SIA 2040 2017].

3.1.2 Standards

Since January 2018, the new **Swiss Energy law (LEn)** regulates the above-mentioned requirements and defines mandatory measures to increase the energy efficiency of buildings, mobility, industry, and systems. It also integrates measures and incentives to further develop the electric supply from renewable sources (Section 3.1.3) and improves the legal framework conditions [AFCS 2018; OFEN 2018].

Similarly, the ***Model of the cantonal energy requirements*** **(MoPEC)** in the canton of Vaud (CH) gathers a set of energy requirements and aims at ensuring a high degree of harmonisation in the area of cantonal energy regulations. Regarding new building construction, MoPEC establishes that from 2020, all new buildings will be heated autonomously with a reasonable part of electricity and that from 2050, no fossil fuels will be used in building heating [EnDK 2018].

Ultimately, the above-mentioned energy requirements established by the 2000-Watt Society have been converted by the Swiss Society of Engineers and Architects (SIA) into building energy efficiency targets, to foster the application of the 2000-Watt Society requirements. This is the norm **SIA 2040:2017: *Towards energy efficiency*** [SIA 2040 2017], which is a non-mandatory construction recommendation fostering building's energy efficiency through the balance of three energy flows: embodied, operational and mobility.

1
A carbon dioxide equivalent or CO_2 equivalent, abbreviated as $CO_{2\,eq}$ is a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential [Eurostat 2017a].

The embodied energy flow includes the primary energy needed for the building's construction, the required element's replacement and the building's disposal. The operational energy flow includes the building's primary energy use for heating, ventilating, cooling, lighting, and other buildings services. The mobility energy flow includes the primary energy required for daily mobility related to the location of the building and the corresponding infrastructures [SIA 2040 2017].

The norm SIA 2040: 2017 transforms the 2000-Watt Society's energy efficiency targets per person into energy efficiency targets per square meter, depending on the building typology (e.g. it establishes an average of 60 m^2 per person in residential buildings). These energy efficiency targets are defined with two different indicators: The Non-renewable Primary Energy (NRPE)[2] and Global Warming Potential (GWP)[3], which are represented in Table 3.1. These energy efficiency targets show that the consumption of non-renewable energy entails the emission of GHG, expressed in CO_{2eq}.

Energy efficiency targets

Due to the specific focus on façade design and construction, the research framework introduces here the embodied and operational primary energy flows, leaving mobility aside. The norm SIA 2040:2017 contemplates this option of not integrating the mobility energy flow, providing additional target values for the combination of embodied and operational energy balances [SIA 2040 2017].

Embodied energy refers to the total amount of NRPE required for all upstream processes, from the extraction of raw materials to the manufacturing and transformation processes, as well as for disposal. The consumption of embodied energy, depending on its origin, entails the emission of GHG quantified as kilograms of carbon equivalent (kg CO_{2eq}), which is one of the most comprehensive impact measurement of GWP indicator [Pomponi *et al.* 2016].

Today, low embodied impact targets begin to have an increasing priority in building construction requirements [SIA 2032 2010; SIA 112 2017; SIA 2040 2017]. Consequently, the building process and construction material production are expected to be more energy-efficient.

Embodied carbon accounts approximately for 30% of the total lifetime carbon footprint of the residential building sector [Lane 2010]. More specifically, building façades can represent up to 21% of the embodied impact of a building (including windows) [Cheung *et al.* 2015]. In Switzerland, opaque façades

2
It is the total amount of non-renewable primary energy required for all upstream processes, from the extraction of raw materials to the manufacturing and processing processes. It includes also the primary energy required for the material disposal, including transport [SIA 2032 2010].

3
GWP is linked to the anthropogenic emissions of greenhouse gases (e.g. CO_2, CH_4, CFCs) and their effects on the atmosphere [John 2012].

RESIDENTIAL BUILDING NEW CONSTRUCTION	ENERGY EFFICIENCY TARGET VALUES NRPE kWh/m² yr	 GWP kg CO2-eq/m² yr
Embodied	**30**	**9**
Operational	**60**	**3**
Mobility	30	4
Combined target value	120	16
Additional required performance: Embodied + Operational	**90**	**12**

Table 3.1
Target values for the «residential building» category for a standard surface area per person based on the duration of one year and the energy reference area (ERA).

Source: [SIA 2040, 2017]

account on average for 9% of the annual embodied NRPE of the building and 11% of the annual embodied carbon [SIA 2032 2010] as displayed in Figure 3.1.

The most extended way to measure the embodied energy and the embodied carbon of a building is the Life Cycle Assessment (LCA) of a building [Gantner *et al.* 2018]. The latter is defined in the Construction Products Regulation as *The assessment of the consecutive and interlinked stages of a construction product's life, from the raw material acquisition or generation from natural resources to final disposal [EU 305/2011 2011].* This method provides information about different environmental impacts and has been regulated by the International Standard Organization: ISO 14040, ISO 14044 and ISO 14025 [ISO 2010, 2016a, 2016b] to ensure the comparability of results.

LCA provides data on the environmental impacts caused by a building all along its lifespan. For this reason, it is a useful method that can facilitate decisions regarding design focused on reducing the embodied impact of buildings. Indeed, it is used by numerous researches that are working on lowering the embodied energy of buildings. Further information on LCA is presented in Section 3.2.1.

Operational energy concerns the buildings energy demand for its function and the on-site energy generation if it exists. Similarly to embodied energy consumption, the operational energy consumption entails negative environmental impacts, depending on its origin, that are also quantified with NRPE and GWP indicators [Pomponi *et al.* 2016]. The latest energy efficiency targets concerning operational energy are as well presented in the norm SIA 2040 [SIA 2040 2017].

The reduction of the building's operational energy is mainly achieved through the increase of the thermal insulating material's performance, by augmenting the layer thickness and/or by lowering its thermal conductivity [Ruggieri *et al.* 2013]. It can also be achieved through the improvement of the energy efficiency of the different building services [Kleinert *et al.* 2016; Rasmussen *et al.* 2016] or the incorporation of on-site energy generation systems.

On-site building's energy generation can be achieved through different means. For example, solar thermal systems are widely used mainly for producing domestic hot water (DHW) and space heating, wind power can also be used as a local renewable source, especially in rural areas where the average wind speed is higher than in cities [RIBA 2009], and PV systems, which have the highest

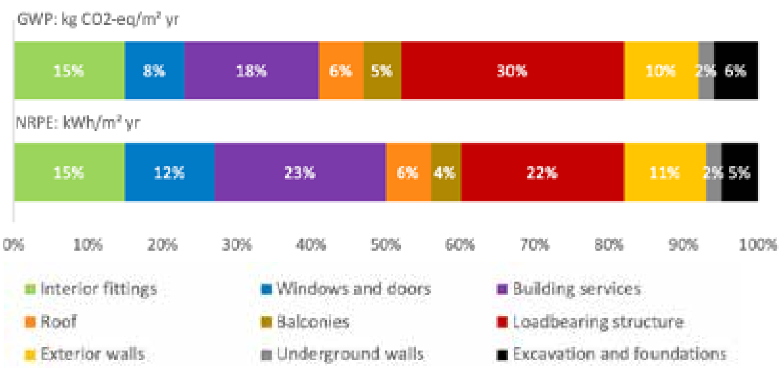


Figure 3.1
Building embodied energy distribution.

Source: [SIA 2032, 2010]

energy generation potential [Jelle *et al.* 2012; Perlin 2013], are installed on roofs and require little maintenance [RIBA 2009].

Solar technologies have been well explored for many years. Today, solar thermal (ST) and solar photovoltaic (PV) are regarded as the most feasible renewable solutions for building application, especially on façades [Zhang *et al.* 2015].

Optimising the building's energy efficiency requires an integrative and holistic approach to all aspects affecting energy performance within the context of the local climate while ensuring comfortable and healthy conditions for occupants. Optimising a building's energy efficiency is a combination of reducing energy demand, embodied energy and providing energy supply from renewable resources [Jones *et al.* 2015]. These practices are not yet widespread among construction professionals [Koezjakov *et al.* 2018]. However, the state of the art of energy-efficient façades presented in Section 3.2 shows a large development of embodied energy-efficient design strategies as well as building applied photovoltaics to improve the building's operational energy.

3.1.3 Promotion of energy efficiency

Current mandatory construction standards refer to energy efficiency limit values that are far from the energy transition objectives [SIA 380/1 2009]. To encourage and accelerate the building's energy efficiency upgrade, there are several economic incentives involving subsidies, feed-in-tariffs (FIT) and fiscal incentives. Similarly, to discourage the non-efficient-use of energy, the Swiss government applies additional taxes for large energy consumers.

To encourage energy efficiency in buildings, the Swiss Confederation has presented the *Programme Bâtiments,* which focuses on reducing the energy consumption and CO_2 emissions of the Swiss real estate stock [OFEN 2017]. This incentive program subsidises mostly energy renovation processes. Regarding new collective housing buildings, this incentive program subsidises energy-efficient constructions with up to 100 CHF per square meter of energy reference area (ERA) [Suisse Energie 2017].

Regarding renewable energy generation, the Swiss Confederation, through the entity *Pronovo,* subsidises the incorporation of PV systems into buildings to improve their energy efficiency. *Pronovo's* subsidies can reach up to 30% of the total costs of the PV installation [Pronovo 2019].

At a cantonal level (Vaud), there are additional encouraging programs such as *100 millions pour les énergies renouvelables et l'efficacitée énergétique* (100 million for renewable energies and energy efficiency). The most recent measure implemented by this program aims at promoting self-consumption of PV installations using batteries as energy storage, by subsidising up to 50 000 CHF of the storage installation [DGE 2018].

It is also worth mentioning that from 2020, a fiscal incentive will make a deduction on the demolition costs of buildings to construct new and energy performant ones [OFEN 2017].

Another method of energy efficiency promotion is to discourage the non-efficient use of energy. That is to say, by implementing taxes on large energy consumers and fossil fuel consumers. To illustrate this, the Swiss population approved in 2017 a grid electricity price increase, which is included in the new energy law [AFCS 2018]. This measure increases by 0.8ct./kWh the grid energy price and aims at promoting electricity savings in buildings [OFEN 2017].

Ultimately, building energy efficiency certification is also a way to promote energy efficiency in buildings. The Swiss *Minergie* construction label for new or renovated buildings is a non-mandatory energy efficiency certification, which can be required to apply for public subsidies (*Programme Bâtiments*). There are three types of *Minergie* labels, which reflect the building's final energy demand per energy reference area: *Minergie*, *Minergie-P*, and *Minergie-A*. These labels certify that a building consumes less than 90kWh/m^2, 80kWh/m^2 and 35kWh/m^2 per year, respectively. Additionally, the label ECO can be combined with the three above-mentioned *Minergie* labels, referring to a healthy and sustainable construction [Minergie 2019]. Moreover, *Minergie* provides architects with energy-efficient envelope construction solutions and details to promote the building's energy efficiency through simplifying the façade and roof design processes [Binz *et al.* 2014].

3.1.4 Façade potential towards the energy transition

The building envelope provides protection, which is fundamentally its primary and most important function [Herzog *et al.* 2004; Knaack *et al.* 2014a]. Today, the building envelope is a combination of relatively sophisticated components, which, adequately placed, will provide a satisfactory result regarding physical, visual, thermal, humidity and acoustic protection [Sanchez-Ostiz Gutiérrez 2003].

Existing research indicate that the building envelope, and specifically façades for their larger surface area [Lassandro *et al.* 2017], plays a critical role controlling the operational energy demand of a building and can contribute to lower its total embodied energy [Herzog *et al.* 2004; RIBA 2009; Ruggieri *et al.* 2013; Binz *et al.* 2014; Zemella *et al.* 2014, 2014; Ihara *et al.* 2015].

The façade is required to provide interior comfort regarding temperature, humidity, lighting, air quality, and sound level. It is also required to provide a visual relationship with the external surroundings and protect privacy. It provides protection against weather, mechanical damage, and fire. This complexity of requirements must be achieved, maximising the energy efficiency of the building [Herzog *et al.* 2004].

Today's façade design is at a significant transition point, given the way enclosures must respond to increasing performance requirements, environmental issues, and energy consumption reductions. Understanding the building envelope as a factor of the overall building performance has significantly changed how we perceive and deal with façades since they are no longer considered passive elements that provide protection based only on the material. Instead, building envelopes are adaptive systems that respond to changing conditions in a daily, seasonal or even life cycle [Boswell 2013].

On the one hand, façades can integrate adaptive systems to minimise buildings' energy demand; these are the kinetic façades that react to changing stimuli, such as the weather, changing its morphology and proprieties to better regulate interior temperature, light, and ventilation [Zaera-Polo *et al.* 2014]. Façades can also be designed as active systems that support the actual operation of the building by generation and thus providing energy [Boswell 2013].

On the other hand, as a main component of the building, façades are responsible for part of its embodied impacts. In the case of residential façades, they account for at least 10% of the building's embodied impacts – windows and doors not included –, although it strongly depends on the façade and the building design [SIA 2032 2010]. Therefore, lowering the embodied impact of façades affects the total embodied impact quantification of the building towards energy efficiency.

Ultimately, building façades have a high potential to optimise the building's energy efficiency through the integration of high-performance insulation and adaptive systems to lower the operational energy demand. Additionally, façades can host on-site energy generators such as PV, which can further improve the building's energy efficiency [Edenhofer *et al.* 2014]. The low embodied impact façade design can further optimise the building's energy efficiency, compensating for the high embodied impact associated with PV [Finnegan *et al.* 2018].

FAÇADE REQUIREMENTS

PROTECTION

The origin of Architecture dated when humans changed from a nomadic to a sedentary lifestyle. At this point, people built their shelters using local materials to protect themselves against the weather and enemies. Protection is hence the primary and most important reason for building.

Until the Modern Movement, most façades, which had massive construction, constituted an enclosure and part of the loadbearing structure. The later determined that wholes in façades were small and mainly for ventilation purposes. Once the Romans invented the arch, façades started to be more permeable, and windows could have larger dimensions for better lightning, although conditioned by the exterior weather conditions.

The use of glass for construction permitted to open larger holes in the façade and keep interior spaces protected from the weather.

COMFORT

During the industrial revolution, new technologies and advances in the building industry permitted to fulfil new façade requirements oriented to enhance comfort. At this time, there was an improvement of thermal and acoustic insulation as well as humidity and sunlight control.

To meet hygienist requirements, the "cavity wall" was developed controlling humidity and condensation in the interior spaces. After that, insulating materials began to be introduced in this cavity to improve the thermal comfort of interior spaces.

These innovations, driven by the Modern Movement, were accompanied by the dissociation of structure and enclosure. This dissociation led to façade design freedom, which started to incorporate large glass surfaces. The latter brought up the problem of interior overheating, which led to the development of façade solar control systems.

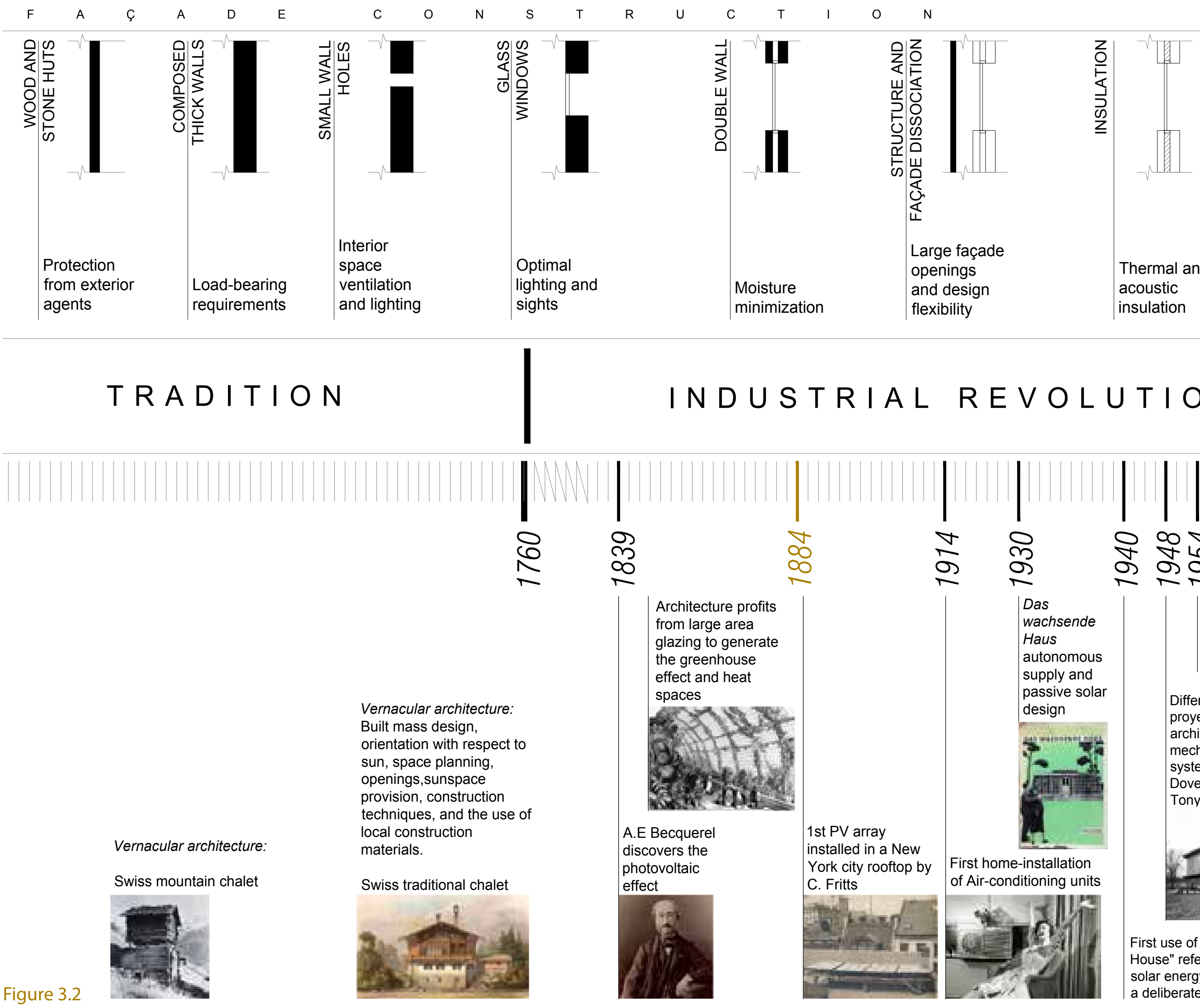


Figure 3.2
Residential façade requirements and façade construction systems evolution.

Source: [Schittich 2006; Herzog *et al.* 2004; Adjemian Oria 2011; Knaack 2011; Boswell 2013; Denzer 2013; Herzog *et al.* 2014; Knaack 2014;

E C O N O M Y | S U S T A I N A B I L I T Y

Since shelter and comfort façade requirements where met, new concerns appeared and motivated further façade development. These requirements were related to the First oil crisis, which motivated a search for energy economy in buildings due to the fuel's shortage and price increase.

Within this context, façade thermal insulation improved significantly and became mandatory in many countries.

In line with this requirement, adaptive and bioclimatic façades were also developed with the objective of controlling and reducing the building's energy consumption.

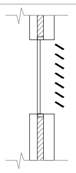
Today's façade design is at a significant transition point, given the way enclosures must respond to increasing performance requirements, environmental issues, and energy consumption reductions.

The building envelope is considered as a significant factor for regulating the buildings energy consumption regarding embodied and operational energy.

At this point, building façades are required to reduce its embodied energy at the time of reducing the operational energy consumption of the building. These requirements can be met through low-embodied-impact construction principles and the incorporation of energy-generating technologies such as BIPV.

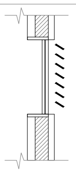
Ultimately, highly energy-efficient façades must lead architectural design to the construction of net-zero or positive energy buildings.

SOLAR CONTROL



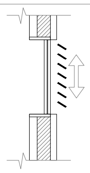
Thermal and acoustic insulation

HIGH-PERFORMANCE INSULATION



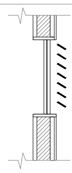
Lower energy consumption

ADAPTIVE FAÇADES



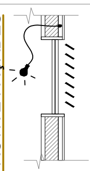
Lower energy consumption

LOW-CARBON CONSTRUCTION



Embodied impact minimization

ACTIVE FAÇADES



On-site renewable energy generation

HIGHLY ENERGY-EFFICIENT FAÇADES

d

…N

FIRST OIL CRISIS

E N E R G Y T R A N S I T I O N

1954 — Bell laboratories produces market-ready solar PV cells

…rent *Solar House* …ects marrying …tecture and …anical solar heating …ems.

…r Sun House. Photo: … Denzer

… the term "Solar …rring to the use of …y for space heating in … creative manner.

1970 — Fred Keck recognized as the father of the passive Solar House

1973 — 1st PV installation in a residence: "Solar One"

1977 — 1st energy consumption regulation: *The energy conservation act*

1979 — BAPV roof installed in the White House

1991 — 1st BIPV façade in Aachen (Germany)

1996 — Launch of coloured solar cells on the market

2000 — 1st integration of transparent crystalline cells

2011 — Accepted and recognised architectural references of BIPV façade design.

AGC Technovation center

2014 — Publication of the Swiss Energy Strategy 2050 (ES 2050)

2018 — Total global solar capacity: 405GW

New Swiss Energy Law

2035 — ES 2050 intermediate goal: Decrease in energy consumption per person of 43% (compared to values registered in 2000)

2050 — ES 2050: 20% of the energy consumption must be provided by PV

2000 Watts Society intermediate goal: Maximum annual consumption per person of 3500 Watts of primary energy.

2100 — 2000 Watts Society goal: Maximum annual consumption per person of 2000 Watts of primary energy.

…FOE 2014; Lynch 2015; OFEN 2018]

3.2. Energy-efficient façade design

The form and function of present-day wall and façade construction are the results of a long development process. The functional, technical, and design-related requirements outline the resulting forms of façades as well as their future developments [Knaack *et al.* 2014b]. Within the construction system, the façade can be defined as the sub-system of the vertical building envelope, which forms an angle equal to or greater than 60 ° with a horizontal plane [Sanchez-Ostiz Gutiérrez 1996].

The façade evolution presented in Figure 3.2 shows the successive steps of the façade construction developments involved to satisfy the performances required to the building envelope [Schittich 2006]. Façades have responded to different requirements as the construction industry has provided products and systems that made it possible. Figure 3.2 displays information of the different requirements – protection, comfort, energy economy and sustainability – as well as the agents and construction systems that affect the façade design evolution [Herzog *et al.* 2004; Adjemian Oria 2011; Lynch 2015]. Against this backdrop, we present here an overview of façade design in terms of meeting current energy transition targets. Then, different passive and active energy-efficient façade design strategies are detailed.

Façade design overview

Meeting the energy transition targets mentioned in Section 3.1 to improve the building's energy performance has a direct impact on the façade design as it must adapt to incorporate the new energy efficiency requirements with affordable construction solutions. Today, energy efficiency in buildings is mostly achieved through increasing façade thermal insulation [Ruggieri *et al.* 2013]. The latter entails an additional cost and additional complexity regarding the façade cladding construction solution, which is further separated from the traditional loadbearing wall. This construction complexity limits the options of façade cladding materials to lightweight façade cladding elements [Dahl Rocha *et al.* 2014].

The sustainable façade design is understood as a process of building *wrap up* where, to avoid thermal bridges, no structural elements are directly connected to the façade design due to the continuous insulation layer — this primary description results in buildings as monoliths with windows as holes. However, as an aesthetical heritage of the modern movement, façades are articulated with different elements that aesthetically invoke a constructional logic. Among the latter are the horizontal slabs of the different floors or the window dimension along the façade [Dahl Rocha *et al.* 2014].

This resource of articulating the façade with constructional logic provides the building with a human scale, especially in residential buildings where storey height is mostly standardised *[RLATC,* 1987, art. 27]. Human scale can be perceived through the repetition of *human-scale-elements,* e.g. window, storeys or balconies. The dimensions of these elements are commonly known and directly relate to the human average size [Ortelli 2016]. Additionally, the façade design articulates the previously-described human-scale with the building's scale, referring to the building's volume, and with the urban context scale, referring to the building's context [Marchand 2016]. These facts describe the complexity of the façade design, which must respond to energy efficiency requirements as well as to composition and aesthetic requirements.

Financial aspects also play an essential role in façade design, which tends to integrate pre-fabricated modules to shorten construction times. The study of façade modularity is being progressively incorporated into today's façade design processes which directly affects its architectural expression [Abriani 1998]. As an example, the joints between prefabricated modules must be considered and taken cared of at an early design stage.

Façade design today mostly depends on the energy efficiency and comfort requirements that must be met within a given budget [Boswell 2013]. The façade is one of the most expensive elements of a building, and its design significantly affects its final cost [Arnold 2005]. The façade design is intrinsically linked to the use of the interior spaces, and their requirements regarding lighting, solar control or exterior use often lead to the design of loggias or balconies [Bassand 2005; Lapierre 2005]. Additionally, the urban context of the building affects the façade design, especially if there are specific municipal regulations on façade design [Grand Conseil GE 1988; Commune de Val-d'Illiez 2018].

Ultimately, the *sustainable aesthetics*[4] of contemporary façades combine the constructional logic with the modern-architecture heritage, as well as space and cost constraints. The contemporary façade design must be further analysed to explore the façade's energy efficiency potential within an architectural approach[5].

Energy-efficient façade design strategies

To meet the previously mentioned energy efficiency requirements (Section 3.1.1), the study of state of the art has identified two main façade energy design strategies: passive energy design strategies and active energy design strategies. The formers improve the building's energy efficiency with no electrical or mechanical systems, maintaining acceptable levels of interior comfort. Among these passive strategies, we can mention performant insulation, low embodied impact construction, the study of solar gains, external shading, or thermal mass. Active energy design strategies involve the electrical or mechanical optimisation of the interior comfort and the building's energy efficiency such as the previously mentioned BIPV systems [Brown 2010; Sadineni *et al.* 2011; Stevanović 2013; Rodrigez-Ubinas *et al.* 2014; Kang *et al.* 2015].

3.2.1 Passive energy design strategies

Façade's passive energy design strategies consist of constructional concepts that can help minimise the energy consumed by buildings, including operational and embodied energy [Zeng *et al.* 2017]. Operational energy savings consist of minimising the heat losses in winter, avoiding overheating in summer, providing natural ventilation, and maximising daylight utilisation [Richarz *et al.* 2008]. Embodied energy savings consist of minimising the energy required for the façade's assembly, maintenance and disassembly as well as the energy required for producing the materials that compose it [Lupíšek *et al.* 2015].

Lowering operational energy involves passively benefitting from free available energy sources and using energy as efficiently as possible to heat, light and ventilate interior spaces. It implies mostly the heating requirement, which is made up to the following factors: heat losses through transmission, heat losses through ventilation, heat gains through incident solar radiation, and heat gains through the room utilisation. Therefore, the heating requirement depends on the façade's thermal transmittance value, the size and orientation of the

4
Sustainable aesthetics has been referred by several authors and largely discussed in the book 'Aesthetics of Sustainable Architecture' [Lee 2011]. *Throughout this research, the façade's sustainable aesthetics refer to the result of constructing the building's façade as a high-performant skin. This skin has been described by Dahl Rocha as a thick insulating wrapper which does not necessarily express, either literally or metamorphically, the structural and constructional concept of the building* [Dahl Rocha *et al.* 2014].

5
The contemporary façade analysis is performed in Phase I (Chapter 4) of this research project's methodology, within an architectural approach.

windows, the façade's air permeability and the interior heat charges [Richarz *et al.* 2008]. In residential buildings, the heating requirements are mostly affected by the opaque façade design; and the ventilation and daylight requirements are mostly affected by the window design.

While most architects are familiar with strategies for saving operational energy, embodied energy efficiency is a less well-researched area [Pomponi *et al.* 2016] and it is rarely applied in common architectural practices [Häkkinen *et al.* 2015]. According to some researchers, this might be due to a lack of comparable methodologies, information and regulation [De Wolf *et al.* 2017].

It is generally assumed that the emissions generated by the building's energy consumption – operational – are higher than its embodied emissions. By consequence, it can be noticed that most directives and efforts focus on reducing operational energy [Lützkendorf *et al.* 2015]. For this reason, as the literature is already sufficiently abundant, it is not further developed within this research framework, which rather focuses on low embodied impact design as a passive façade design strategy.

Low embodied impact façade design

Low embodied impact design requires particular attention given that operational energy reduction measures often lead to an increase in materials use (e.g. more insulation) and energy demand for their production. While efforts are focused on decreasing operational energy, embodied energy might increase if not considered during the design process [Ibn-Mohammed *et al.* 2013].

Low embodied energy building design involves a specific consideration of all building aspects regarding energy efficiency (Table 3.2): from site planning to building-services, going through the study of the building's form and fabric [Jones *et al.* 2015]. The design of the building envelope and the orientation of the building volume are the most influent factors of the embodied energy efficiency of a building [RIBA 2009].

Embodied impact evaluation

There are three major streams of life cycle studies to evaluate a building's embodied impacts. The first one focuses on energy use: Life Cycle Energy Assessment (LCEA). The second one focuses on CO_2 emissions: Life Cycle Carbon Emissions Assessment (LCCO2A). Finally, the third and most common one focuses on assessing the buildings' total environmental impact over its entire lifetime: Life Cycle Assessment (LCA) [Finnegan 2018]. The latter defines the amount of energy and material used, and the emissions released into the environment. This assessment includes the entire life of the product: material

LOW EMBODIED IMPACT DESIGN APPROACH

SITE PLANNING	BUILDING FORM	BUILDING FABRIC	BUILDING SERVICES
		MATERIALS	
		INSULATION	HEATING
LOCATION ON SITE	SHAPE FACTOR	SOLAR CONTROL	COOLING
ORIENTATION	BUILDING LAYOUT	DAYLIGHT PENETRATION	LIGHTING
SITE FACTORS	CONSTRUCTION PROCESSES	AIR TIGHTNESS	VENTILATION

Table 3.2
A low embodied impact design approach.

Source: [Jones *et al.* 2015]

extraction and process, manufacture, transportation, use, maintenance, recycling, and final disposal [Glaumann *et al.* 2010; Chau *et al.* 2015]. However, due to the anticipated material lifetime analysis, LCA cannot accurately predict the environmental impact of every material [John 2012]. LCA is based on assumptions that are regulated by ISO standards: ISO 14040 and ISO 14044 [ISO 2016]; and in the standard TC350 (European Standards Committee). These standards provide material producers with a methodology and a common basis to perform the construction products' LCA [Finkbeiner *et al.* 2006]. The level of complexity of the LCA is defined by the following methodology stages: 1) scope and system boundary definition; 2) inventory analysis; 3) impact assessment; and 4) interpretation as defined in the ISO standards [Finnegan 2018].

A simplified LCA concept is represented in Figure 3.3. It shows the resources inputs (energy, water and materials), the transformation, construction, operation and disposal processes, and the environmental loadings output (GHG emissions and waste).

LCA results depend on the system boundary definition and the stages included in the analysis, which are gathered in Figure 3.4 [Moncaster *et al.* 2018]. When assessing the life cycle of a building, the system boundary must be clearly defined at the beginning of the process so that environmental impacts can be reported: *cradle-to-cradle*, *cradle-to-gate*, or *gate-to-gate* [Souto-Martinez *et al.* 2018].

LCA results can be expressed in many different environmental indicators: climate change, acidification, ozone depletion, atmospheric aerosol loading, eutrophication, air pollution, ionising radiation, photochemical ozone formation or chemical pollution indicators, among others. The choice of the appropriate indicators to express the LCA results depend on the objective of the assessment process [Dong *et al.* 2017].

In the Swiss context, the Swiss Association of Engineers and Architects (SIA) has published the norm SIA: 2032 *L'Énergie Grise des Bâtiments* [SIA 2032 2010], which tackles embodied energy and its assessment. Other norms with related content are the SIA 112/1 [SIA 112 2017] and the SIA 380/1 [SIA 380/1 2009], which give recommendations on sustainable construction of buildings, and guidelines for calculating a building's energy performance, respectively. These norms express their limit values and targets in primary energy (PE), non-renewable primary energy (NRPE), and global warming potential (GWP).

A significant number of LCA tools are available to calculate environmental impacts. The goal here is not to make an exhaustive survey of these tools but rather to refer to researches that have classified and explained the topic of embodied carbon assessment methods. In this way, the article entitled

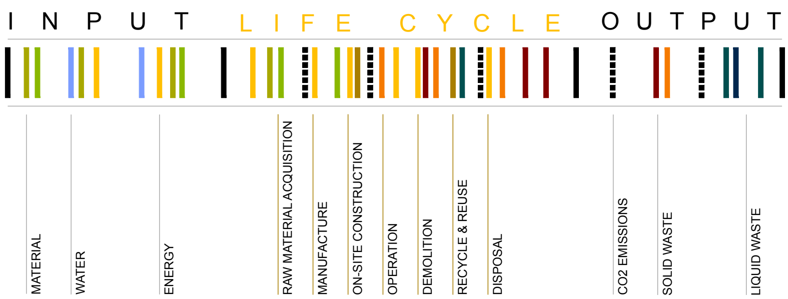
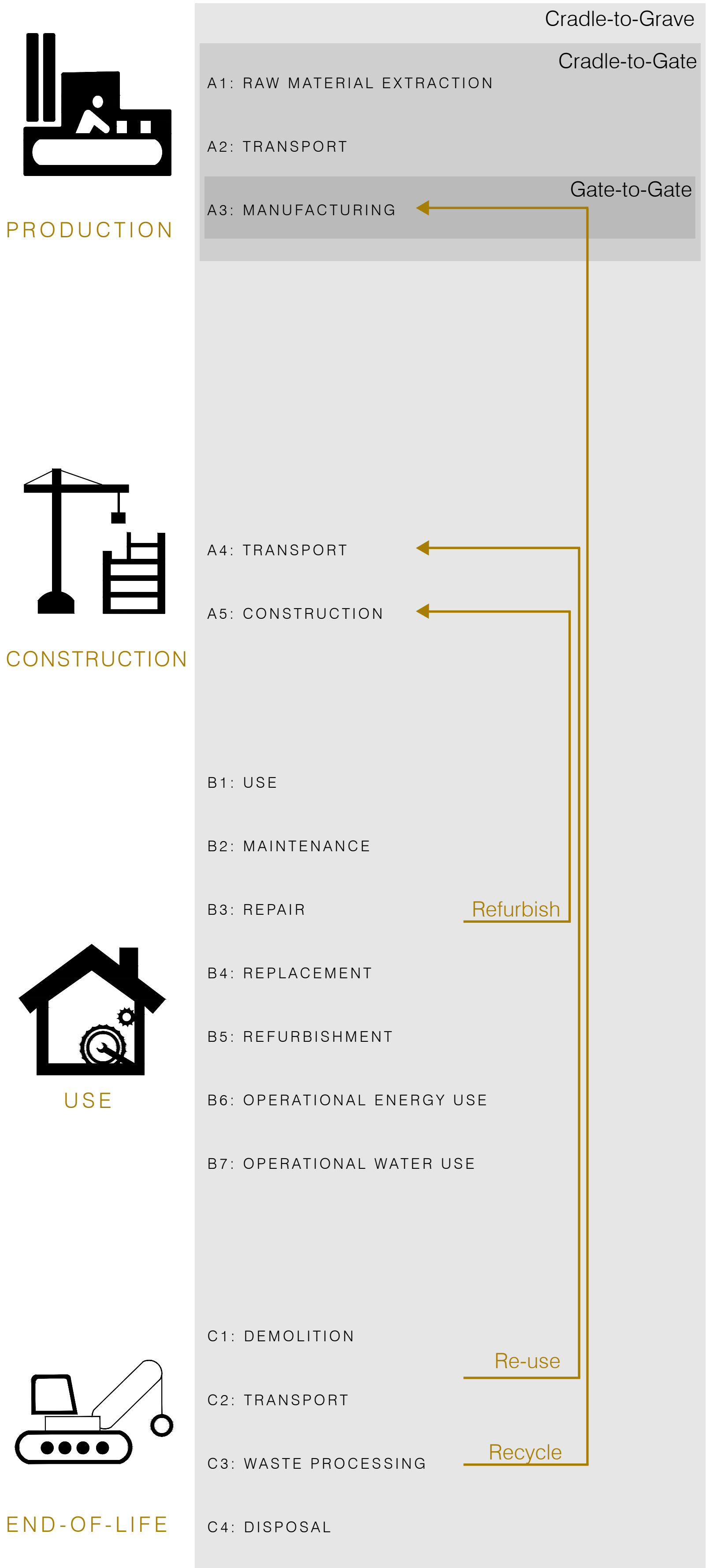


Figure 3.3.
Simplified concept of LCA. Different transport phases shall be added to this scheme.

Source: [Chau *et al.* 2015]



CRADLE TO GRAVE:
Full LCA from resource extraction 'cradle' to use phase and disposal phase 'grave'.

CRADLE TO CRADLE:

Specific Cradle to Grave where the product's end of life disposal step is a recycling process.

CRADLE TO GATE:

Assessment of a practical product life cycle from resource extraction 'cradle' to factory gate. The use phase and disposal phase of the product are omitted in this phase.

GATE TO GATE:

Is a partial LCA looking at only one value-added process in the entire production chain.

Figure 3.4
LCA Cycle stages and phases of a building product life cycle.

Source: [Souto-Martinez *et al.* 2018]

Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice by Catherine De Wolf, Francesco Pomponi and Alice Moncaster, from the University of Cambridge [De Wolf *et al.* 2017], presents a complete and structured presentation of LCA tools and methodologies [Häkkinen *et al.* 2015]. Another complete review of LCA tools is contained in John's doctoral thesis [John 2012]. These documents are considered as a reliable source of information.

State of the art of the research

Low embodied impact design research offers numerous design and construction principles to lower the embodied energy and embodied carbon of a building. Through the study of state-of-the-art, these design and construction principles are often repeated or formulated in similar ways. The highlights of this study are presented here as a list of low embodied impact design and construction principles, classified according to the simplified life cycle phases presented in Figure 3.4: production, construction, operation, end-of-life. These principles are further discussed and presented in the following paragraphs:

Production

- Fewer materials: When designing a low embodied impact façade, the first and most straightforward way to minimise embodied impacts is by optimising the use of construction materials. Accurate calculations and detailed design can determine the exact thickness and resistances of construction products to avoid over-dimensioning. In a like manner, the choice of lighter materials involves the design of smaller loadbearing façade sub-structures. Light construction simplifies façade fixations systems, general building structure, transport, and on-site work [Connaughton *et al.* 2011; Birgisdottir *et al.* 2017].

- Natural materials: An effective way to reduce the embodied impacts of a wall frame structure is to move from traditional construction highly-processed materials – such as steel or concrete – to organic and natural materials [Connaughton *et al.* 2011]. Table 3.3 shows the environmental performance of some common construction materials.

  Natural products have some advantages over conventional materials: they are made from renewable and organic resources, which lead to a low embodied impact, they can usually be reused and recycled, they are fully biodegradable, they are non-toxic, allergen-free, and can be safely handled and installed [Eco-innovation action plan 2011; Arrigoni *et al.* 2017; Gray 2019].

Table 3.3.
Energy and environmental performance of different common construction materials. NRPE for Non-Renewable Primary Energy, GWP for Global Warming Potential.

Source: [KBOB 2016]

LOADBEARING CONSTRUCTION MATERIALS	NRPE kWh/kg	GWP kg CO2-eq/kg
Ceramic bricks	0,79	0,25
Concrete	45	16,8
Steel	3,55	0,68
Wood	0,5	0,1

- Local materials: It is widely acknowledged that the use of local materials and construction products has a lower embodied impact than the use of imported ones [Eco-innovation action plan 2011]. The environmental impact of transportation depends on the distance, vehicle type, and weight of the deliverables [Van Fan *et al.* 2018]. Air transport has, by far, the highest environmental impact, then road transport, rail transport, and ultimately sea transport, which has the lowest environmental impact [Delcampe *et al.* 2012; EEA 2016].

- Alternative materials: When natural and locally sourced products are not available, there are other options to lower a building's embodied impact. These options involve utilising alternative materials, which can be highly recycled synthetic materials or component substitutes [WRAP 2014; Mundy 2015; Birgisdottir *et al.* 2017]. For example, choosing recycled aluminium profiles instead of regular aluminium products saves more than 90% of the energy that would otherwise be required by primary production [Bull 2014]. Similarly, cement substitutes can significantly lower concrete's embodied impact. These substitutes are pulverised fuel ash (PFA) or ground granulated blast-furnace slag (GGBS), which are carbon and cost-effective but require a longer concrete curing. Concrete's environmental impact can also be lowered when using recycled aggregates [Mundy 2015].

  Following this same low embodied impact construction principle, the use of light façade materials and systems as an alternative to traditional heavy systems – such as stone cladding or brick enclosure – reduces the load requirements of the main load-bearing structure. This results in a reduction of the bearing sections of the latter. In addition, lighter materials usually have a simpler installation process than heavy ones [Birgisdottir *et al.* 2017].

- Alternative processes: This principle refers to the way materials are produced. The footprint of cement, for example, could be reduced by changing clinker's production process, its main component. This would be possible by switching to renewable energies and improving technologies to operate furnaces at a lower temperature [WRAP 2014].

- Standardised labels: The use of the Environmental Product Declarations must be encouraged to communicate the environmental impact of each of construction product because *information enables choice* [Eco-innovation action plan 2011].

Construction

- Prefabrication: It is the main construction method in northern and central Europe to ensure accuracy and efficiency. This method lowers buildings' environmental impact by reducing on-site construction work to the assembly of prefabricated building elements. Prefabricated façades can save up to 50% of on-site waste [Connaughton *et al.* 2011]. However, environmental costs such as transport and factory energy consumption must be considered when comparing on-site construction with prefabrication processes. All in all, the global impact is lower when building components are prefabricated because processes are optimised and replacements minimised [Birgisdottir *et al.* 2017].

- Lightweight materials: this practice can lower the environmental impact of the construction phase due to the less carbon-demanding transportation and construction processes required [Birgisdottir *et al.* 2017].

Operation

- Optimisation of the building envelope performance: As mentioned above, the most efficient way to reduce the operational energy demand of a building is by improving the thermal insulation properties of the building envelope. Optimal ventilation, natural lighting and cooling must also be studied to lower the operational embodied impact of a building [Richarz *et al.* 2008].

- The durability of materials and systems: One of the most critical factors in whole-life carbon analysis is the replacement and refurbishment cycle. Façades are often replaced before the end of the operational life of a building [SIA 2032 2010]. For this reason, selecting materials and systems with high durability and reliability can control the risk of failure and consequently decrease the amount of maintenance and replacements necessary to ensure the building's performance during its lifecycle [Kuittinen *et al.* 2013]. In this view, a balance between long-lasting and low embodied impact features must be found [BRE 2016].

- Flexible design: The contemporary need for flexible buildings, which require rapid and multiple changes in their use, involves considering proper strategies to simplify renovation and replacement activities as much as possible [Nehasilova *et al.* 2016].

End-of-life

- Deconstruction plan: Preparing a plan for building changes, reconfiguration, and deconstruction is an efficient way to lower façades' embodied impact [Kuittinen *et al.* 2013]. If building components can easily be deconstructed with regular machinery and key materials can be recovered to reuse them, then the environmental impact is minimised in the last phase of its lifecycle.

- Reuse: To enhance material reuse, the connections between different construction products must guarantee a neat separation of the different construction products without damage [Eco-innovation action plan 2011; Akinade *et al.* 2017; Eckelman *et al.* 2018].

- Recycle: When construction products cannot be directly reused, they should be recycled[6]. Although recycling processes involve energy consumption, they extend the materials' lifecycle. Moreover, recycling construction materials is a more energy-efficient process than transforming them into waste [Connaughton *et al.* 2011].

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According to A. Lang, recycling means any recovery operation by which waste materials are reprocessed into products, materials or substances, whether it is for its original or new purposes [Lang 2004].

- Waste management: In the context of the reuse and recycle issue, it is essential to consider waste management and its recyclability because construction and demolition waste (CDW) accounts for 46% of the total waste [Eurostat 2017b]. Most waste from on-site construction is initially regarded as non-recyclable due to the inclusion of impurities [Zabalza Bribian *et al.* 2011; Galvez-Martos *et al.* 2018]. However, *clean* waste, which is usually generated during the prefabrication processes, can be reused or recycled [Cruz Rios 2015].

  The *Waste & Resources Action Programme* (WRAP) presents a complete set of strategies and guidelines to lower the embodied impact of buildings [WRAP 2014]. It also includes an estimated percentage of the carbon emissions saved when applying the correspondent low embodied impact construction guidelines for building design and construction.

  The energy waste and the consequent carbon emissions associated with the maintenance, reparation, replacement and disposal of construction materials over the lifetime of the building can be calculated. Even though they are usually treated separately, they need to be considered when designing with low embodied impact objectives [Akinade *et al.* 2017; Eurostat 2017b; Galvez-Martos *et al.* 2018].

Ultimately, adopting good practice in building construction can reduce up to 50% waste and up to 20% of material excess. Construction companies usually order more material than needed in prevision of breakages and careless manipulation. Good practice can minimise these unforeseen material wastes and hence, the final embodied impact of construction practices [Connaughton *et al.* 2011].

All these design and construction principles must be interpreted and applied to each specific context. As stated by most of the reviewed embodied impact mitigation researches, the use of locally sourced or produced products is an essential factor when lowering environmental impact. These principles refer to the whole process of building design. However, this research focuses on residential building façade design in the Swiss context, which implies that some of these principles are more relevant and easily applied than others. Further developments on the incorporation of low embodied impact design and construction principles are presented in Chapter 4.

3.2.2 Active energy design strategies

Active façade design strategies have two different definitions in the literature. The first one implies the incorporation into the façade of technical installations that generate energy to meet the building energy needs [Kuhn *et al.* 2014]. The second one implies the incorporation into the façade of technical installations that require energy to help achieve the interior comfort conditions [Richarz *et al.* 2008]. This research framework adopts the first definition and considers an active façade as *a multifunctional energy generating component of the building* [Kuhn *et al.* 2014].

The most popular technical installations that can be incorporated in façades to generate renewable energy benefit from solar power and are solar thermal and photovoltaic technologies. As previously mentioned, PV technology has a high potential to generate electricity as an active design strategy when incorporated into the building envelope [Jelle *et al.* 2012; Reijenga *et al.* 2012; Perlin 2013]. According to the *active façade* definition, the integration of PV technologies into the façade transforms a regular façade into an active façade.

3.2.2.1. Photovoltaics

Photovoltaics (PV) is a way of generating electrical power by converting solar radiation into direct current (DC) electricity through the use of semiconductor technologies thanks to the PV effect. The PV industry is growing more than 70% per year, improving existing PV technology and developing new ones [Crassard *et al.* 2007].

The most common materials presently used for PV include Monocrystalline silicon, Polycrystalline silicon, amorphous silicon, cadmium telluride, and copper indium gallium selenide/sulphide. All these technologies differ both in terms of employed material and structure, consequently influencing the efficiency of the energy conversion. The cell types can be grouped into three categories: the traditional crystalline silicon cells – wafer-based –, the Thin-Film cell – made from different semiconductors materials –, and the nanotechnology-based solar cells [Jelle 2016].

PV cells must be interconnected to form a PV module. PV modules combined with a set of additional components – e.g., inverters, electrical components, and mounting systems – form a PV array. Ultimately, a composition of PV arrays forms a PV system [Munari Probst *et al.* 2012].

This section gathers an introductory and non-exhaustive overview of solar cells either available on the market or at a research stage. There are several classifications of available technologies, depending on their cell composition, mechanical proprieties or performance. This classification is the one used in SHS's task 41 [Munari Probst *et al.* 2012] and presented in the Handbook of Solar Energy [Tiwari *et al.* 2016]. It refers to the cell's composition in a chronological order to provide the reader with an overview of PV technology.

First-Generation: Wafer-based crystalline silicon cells (Monocrystalline and Polycrystalline cells)

Silicon crystals or ingots are grown and then sliced into semiconductor wafers, which form the crystalline silicon PV cells (Si-wafer). These are the most extensively used. In 2017, 95% of the total PV generation was Silicon wafer based [Tiwari *et al.* 2016; Fraunhofer ISE 2019].

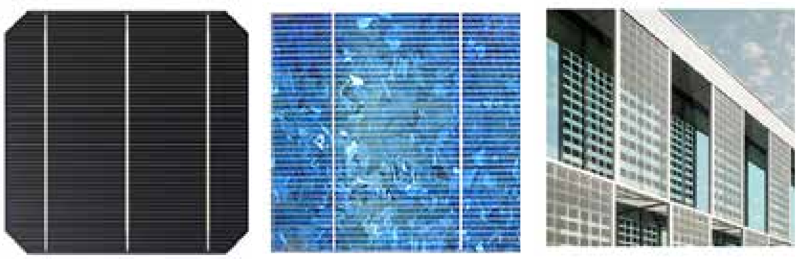

Figure 3.5.
Monocrystalline and
Polycrystalline technology.

Source: AGC

Si-wafer cells are usually square and measure 150 x 150 mm. There are two types of crystalline silicon, easily recognisable thanks to the difference of colour between them. The first one, Monocrystalline silicon cells, are made from pure black Monocrystalline silicon. They have higher efficiencies and higher prices. The second one, Polycrystalline silicon cells, are produced using ingots of multi-crystalline silicon. Due to a simpler manufacturing process, the Polycrystalline silicon cells are less expensive, but also less effective. They are recognisable by the shiny blue colour that comes from the many small crystals [Munari Probst *et al.* 2012; Tiwari *et al.* 2016].

These wafer-based technologies have average efficiencies that vary between 14% and 24%[7] [Jelle *et al.* 2012]. Among crystalline silicon technologies, Monocrystalline PV cells are at least 6% more efficient than Polycrystalline solar cell, because of the perfect crystal structure of the former that stimulates electron flow [Husain *et al.* 2018]. Crystalline modules are optimised for 1000W/m^2 radiance, but this performance lowers significantly in lower irradiance [Polysolar 2015].

The latest crystalline module performances are 24.4% for a Monocrystalline photovoltaic module and 19.9% for a Polycrystalline photovoltaic module [Green *et al.* 2018]. However, an average of respectively 21% and 18% can be considered for energy simulations [Interview with G. Cattaneo, 2018].

Second-Generation: Thin-Film cells

Thin-Film cells and their contacts are deposited directly on large area substrates, such as glass panels, stainless steel, polymers or foils. Thin-Films can be seen as a microscopically thin layer of 'disordered' photovoltaic material that gives the module surface a uniform appearance [Tiwari *et al.* 2016].

This technology has a low-cost potential because its manufacture requires only a small amount of material, and the production process requires less energy than in the case of crystalline technology – production process requires a temperature of 200° to 500°C vs 1400°C for c-Si. They can also tolerate higher impurities than Crystalline, thus needing less expensive purification of raw materials [Tiwari *et al.* 2016].

Thin-Film solar cells are usually categorised according to the PV material used: amorphous silicon (a-Si), which is the most common one; Copper Indium Gallium Selenide (CIS or CIGS), which achieves the highest conversion efficiencies; and Cadmium Telluride (CdTe), which promises the lowest production costs. Cell colour depends on the type of the PV material and varies among brownish or reddish-brown, reflective dark green, dark grey and black [Tiwari *et al.* 2016].

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PV cell efficiency is higher that PV module efficiency due to the small losses associated with inter-cell connections and the energy conversion efficiency.

Figure 3.6.
Thin-Film technology.

Source: Onyx Solar

Efficiencies differ among technologies: between 4% to 10% for a-Si, from 9,4% to 14.7% for CdTe, and an interval of 11-18,7% for CIS/ CIGS. The most efficient CIS/CIGS modules have efficiencies of approximately 13% [Jelle *et al.* 2012; Jelle 2016]. Regarding their optimal operation radiance, Thin-Film technologies operate optimally at 700-800W/m^2 radiance and continue working down to very low radiance levels. Thin-Film does not require direct sunlight to generate energy; Thin-Film modules are capable of generating electricity with ambient and reflected light [Polysolar 2015].

In 2017, 5% of the total annual production corresponded to the Thin-Film technologies market share [Fraunhofer ISE 2019].

Third-Generation: Emerging and novel PV technologies

Third-generation PV cells aim at improving the energy-conversion efficiency and lowering the production cost of the first- and second-generation solar cells. Among the emerging PV technologies, organic solar cells offer the prospect of very low-cost active layer material, low-cost substrates, low energy input, and easy up-scaling. Their usual efficiencies range from 4% up to 10% and have recently reached 11.5% in 2015 [Munari Probst *et al.* 2012; Jelle 2016; Tiwari *et al.* 2016].

Novel technologies also include dyes that imitate photosynthesis and PV materials that can be mixed in solution to become ink or paint, lending themselves to printing or to being brushed or sprayed onto a surface. This is the case of the Dye-sensitized solar cells (DSSC), which can reach 11% efficiency in diffuse daylight [Perlin 2013; Tiwari *et al.* 2016].

Other innovative technologies approach the production of solar cells as a combination of different technologies. This is the case of technologies known as sandwich or stack solar cells [Jelle 2016], which achieve a maximal harvest of solar radiation by combining different material layers with different spectral absorbances. Technology combinations have the potential for reaching high efficiencies, which in 2014 were close to 30% in laboratory conditions [Ballif 2014].

With a completely different objective, there is a particular interest in achieving transparent solar cells due to the architectural integration potential that would represent. Researchers from Michigan State University have developed a solar cell that is completely transparent. This research found out that solar harvesting is possible through small organic molecules that absorb specific nonvisible wavelengths of solar radiation [Mourant 2014].

Ultimately, the National Renewable Energy Laboratory of the U.S. (NREL) regularly publishes the evolution of the best research-cell efficiencies for a

Figure 3.7.
DSSC technology.

Source: H.Glass and LAST

range of PV technologies, bringing details and information about state-of-the-art PV cells [NREL 2019].

Photovoltaics' combined energy efficiency

The study of the energy efficiency of PV systems is related to the concept of energy payback time (EPBT). The latter refers to *the time in which the energy input during the PV system life-cycle is compensated by the electricity generated by the PV system* [de Wild-Scholten 2009]. The EPBT depends on the embodied energy of the PV system and its lifetime output, which in turn depends on the PV panel performance and its solar irradiation [de Wild-Scholten 2009].

De Wild-Scholten research shows that Thin-Film PV technologies have lower EPBT than crystalline PV technologies. For their part, SUPSI / ISAAC state that the average EPBT for all PV systems is three years, varying from 1.0 to 4.1 years on rooftop PV systems, depending on PV technology and module solar irradiation [de Wild-Scholten 2009; Bhandari *et al.* 2015; Fraunhofer ISE 2019; SUPSI 2019a].

The cradle-to-gate life cycle analysis (See Figure 3.4) of a PV system includes raw material acquisition and processing, PV module manufacture, PV system operation, and end-of-life management [Bhandari *et al.* 2015]. Recycling PV panels has the potential to reduce their EPBT because it reduces the energy demand for harvesting and refining PV materials [Goe *et al.* 2014].

Recycling

Indeed, most PV embodied energy is required by the PV material refinement process to achieve the minimum purity required for performance. For this reason, recycling PV material has a significant potential to lower the embodied energy and hence, the energy PBT of PV systems [Goe *et al.* 2014].

Lowering the EPBT of PV systems is not the only advantage of PV recycling. According to Sykorova *et al.*, 60 million tons of PV waste will be produced by 2050. This fact is promoting the development of PV recycling policies [Sykorova *et al.* 2019]. In Switzerland and other European countries, the *PV Cycle* organisation

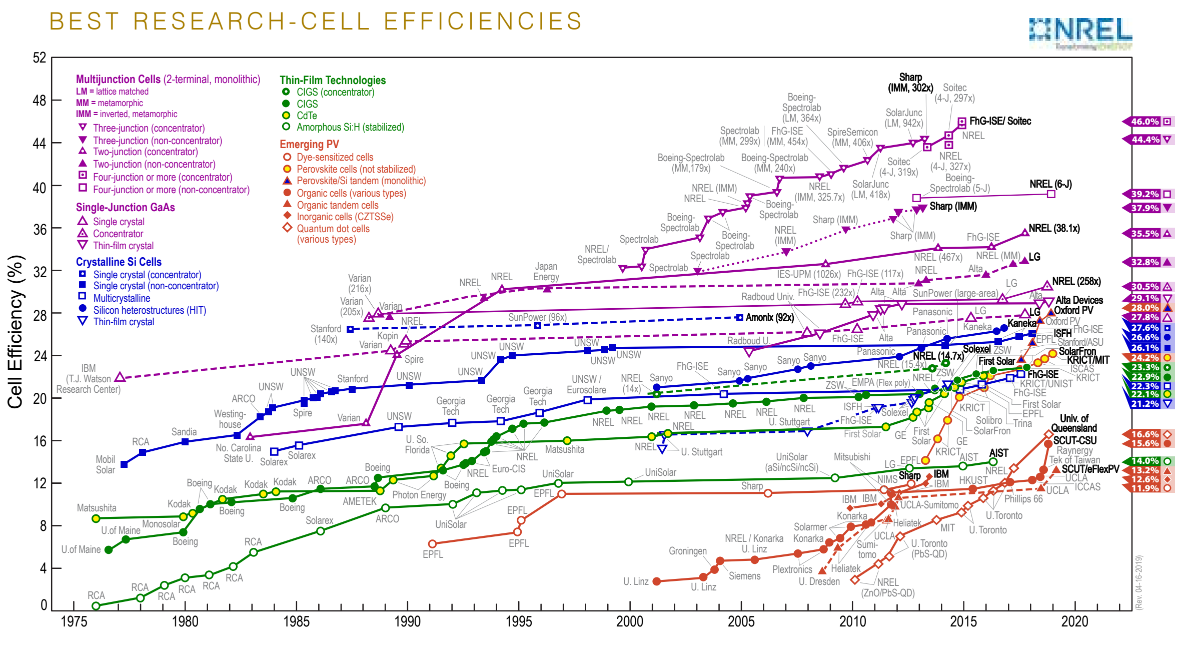

Figure 3.8
Best research-cell efficiency chart.

Source: [NREL, 2019]

offers, since 2007, adapted waste management services for PV products, which are defined as e-waste by the *Waste Electrical and Electronic Equipment* (WEEE) directive [EU 2012; PV cycle 2019; Sykorova *et al*. 2019].

Today, PV recycling can reach 96% recycling efficiency. The process involves the disassembling of the module to separate its components: Glass elements can be reused and metallic parts can be re-shaped into cell frames, while silicon cells can be cleaned and directly reused in the production of the new PV panel. This process involves the separation of the different module layers without damaging the wafer. Research shows that solar cells manufactured with recycled Si-wafers have an equivalent efficiency to that produced with new Si-wafers. Broken wafers can be melted and used to manufacture new ones. This process results in an 85% recycling rate of the silicon material. Similarly, Thin-Film PV panels can achieve 95% reuse rate of the semiconductor material [Shin *et al.* 2017; Sykorova *et al.* 2019].

Sica *et al.*'s publication gathers a complete review of PV end-of-life management and presents the different recycling methods for the different PV technologies, providing details on the different PV technologies and modules recycling [Sica *et al.* 2018].

Photovoltaics in buildings

PV applications for buildings appeared in the 1970s, usually connected to constructions in remote areas with no electric grid connection [Eiffert *et al.* 2000]. More recently, the interest in PV technology is rapidly growing and is increasingly focused on the use of building surfaces for its installations. For this reason, numerous applications of PV technology in buildings have emerged.

In Europe, PV construction products[8] must fulfil three fundamental aspects according to the construction product regulations (CPR): 1) the technical quality – PV technology, constructive and functional characteristics – , 2) the deference for the environment – energy efficiency and health –, and 3) the guarantee and safety in the use of the building's materials [European Parliament 1988; EU 305/2011 2011]. More recently, the European norm EN 50583-1 *Photovoltaics in buildings* applies to PV modules used as building construction products. It focuses on the PV properties that affect the building requirements specified in the European CPR [EN 50583-1 2016].

There are two different ways a PV system can be installed on the building's envelope, depending on their level of integration and on the different architectural functions that they perform: Building-attached photovoltaics (BAPV) and Building-integrated photovoltaics (BIPV).

Building-attached photovoltaics (BAPV):

BAPV refers to the building-mounted PV modules that are exclusively used for generating energy. They are mounted on top of the building's existing structure and do not replace or perform as a construction component. BAPV may be part of the architectural composition of the building or not, and they may be assembled, coplanar or not, to the building envelope on roofs, façades, atria or shading devices (Figure 3.9) [Cronemberger *et al.* 2014]. Most of the time, BAPV are not considered during the architectural design phases and are added to the building once the construction phase is finished [Montoro *et al.* 2011].

BAPV represented 76% of PV building-installations in Switzerland in 2014 [Hüsser *et al.* 2015].

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As defined on the Construction Products Regulation: A construction product is any product which is produced and placed on the market for incorporation in a permanent manner in construction works or parts thereof and the performance of which has an effect on the performance of the construction works with respect to the basic requirements for construction works [EU 305/2011 2011].

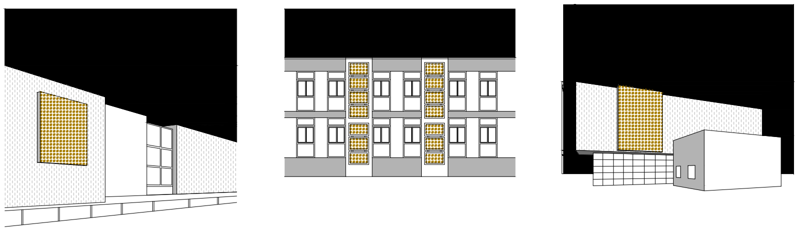


Figure 3.9.
Façade Building-attached photovoltaics (BAPV) examples.

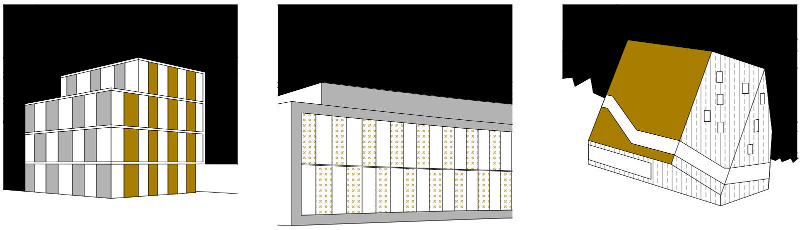


Figure 3.10.
Façade Building-integrated photovoltaics (BIPV) examples.

BIPV MOUNTING CATEGORIES A-E

CATEGORY A	SLOPED ROOF-INTEGRATED NOT ACCESIBLE FROM WITHIN THE BUILDING	THE PV MODULES ARE MOUNTED IN THE BUILDING ENVELOPE AT AN ANGLE BETWEEN 0° AND 60° WITH A BARRIER UNDERNEATH PREVENTING LARGE PIECES OF GLASS FALLING ONTO ACCESIBLE AREAS BELOW
CATEGORY B	SLOPED ROOF-INTEGRATED ACCESIBLE FROM WITHIN THE BUILDING	THE PV MODULES ARE MOUNTED IN THE BUILDING ENVELOPE AT AN ANGLE BETWEEN 0° AND 60°.
CATEGORY C	NON-SLOPED VERTICALLY-MOUNTED NOT ACCESIBLE FROM WITHIN THE BUILDING	THE PV MODULES ARE MOUNTED IN THE BUILDING ENVELOPE AT AN ANGLE BETWEEN 60° AND 90° WITH A BARRIER BEHIND PREVENTING LARGE PIECES OF GLASS OR PERSONS FALLING TO ADJACENT LOWER AREA INSIDE THE BUILDING.
CATEGORY D	NON-SLOPED VERTICALLY-MOUNTED ACCESIBLE FROM WITHIN THE BUILDING	THE PV MODULES ARE MOUNTED IN THE BUILDING ENVELOPE AT AN ANGLE BETWEEN AND INCLUDING BOTH 60° AND 90°.
CATEGORY E	EXTERNALLY INTEGRATED ACCESIBLE OR NOT FROM WITHIN THE BUILDING	THE PV MODULES ARE MOUNTED ONTO THE BUILDING AND FORM AN ADDITIONAL FUNCTIONAL LAYER EXTERIOR TO ITS ENVELOPE (E.G. BALCONIES, BALUSTRADES, SHUTTERS, AWNINGS, LOUVRES, BRISE SOLEIT, ETC.).

Table 3.4
BIPV mounting categories.

Source: [EN 50583-1 2016]

Building-integrated photovoltaics (BIPV):

BIPV modules are used for generating electricity as well as fulfilling at least one of the façade's functions as the exterior layer of the building envelope. These functions can be one or more of the following [EN 50583-1 2016]:

- Mechanical rigidity or structural integrity
- Primary weather impact protection: rain, snow, wind, hail
- Energy economy, such as shading, daylighting or thermal insulation
- Fire protection
- Noise protection
- Separation between indoor and outdoor environments
- Security, shelter or safety

BIPV modules are installed replacing one traditional construction material, and therefore, performing at least the substituted material's architectural function – in addition to the function of generating energy (Figure 3.10). According to European Norm 50583-1: *Photovoltaics in buildings,* BIPV can be mounted in buildings in five different ways, presented in Table 3.4.

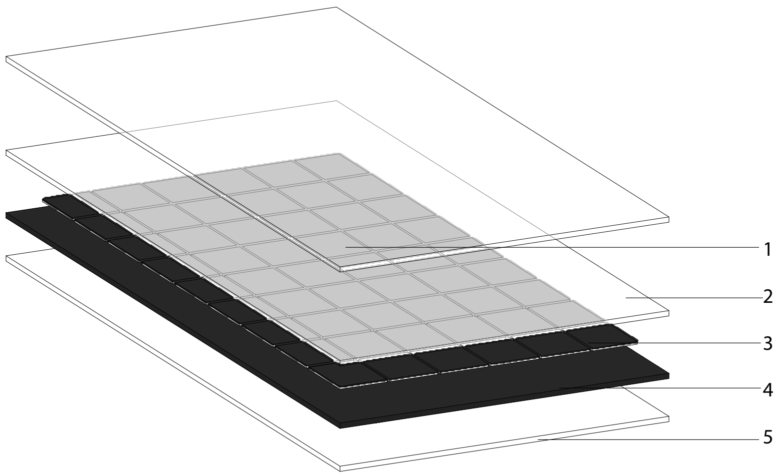
Constructed in Aachen (Germany) in 1991, the first BIPV façade integration was designed as a curtain wall façade with insulating glass [Benemann *et al.* 2001]. Today, BIPV is a globally expanding market with an annual estimated growth rate of 18.7% [Espeche *et al.* 2017]. There is a large variety of BIPV products available on the market, which makes it possible to integrate BIPV fulfilling different architectural façade functions such as cladding, protection or glazing. [Attoye *et al.* 2017]. In Switzerland, 24% of the total PV installations in buildings were considered as BIPV in 2014 [SUPSI 2019a].

As an active construction component, BIPV elements must be integrated into the early phases of the design process in order to achieve an affordable and coherent architectural result with enhanced energy performance [Munari Probst 2008; 2012b; Bonomo *et al.* 2017].

As mentioned, BIPV modules are integrated into the building envelope replacing conventional building materials, rather than being installed after the completion of the building construction. These systems enable to reduce the material and the initial investment costs, compared to traditional construction where PV systems are independent and aggregated to the building [Munari Probst 2008; 2012b; SUPSI 2019a].

46.6% of BIPV products at a market-ready stage are roof components. Façade BIPV products represent only 11.6% of the market share. The remaining market segments are urban furniture (31.7%) and other various custom-designed BIPV elements (10%) [Scognamiglio 2017].

BIPV elements are composed of glass layer structures. There are two main categories: the glass-film BIPV modules and the glass-glass BIPV modules. The former combines a front layer of glass with a rear layer of film that is usually a metal or a plastic film. The latter integrates PV cells with different layers of glass, defining different types of BIPV panels [Odersun 2011]. This BIPV panel composition is illustrated in Figure 3.11.



1- FRONT GLASS

2- CLEAR INTERLAYER

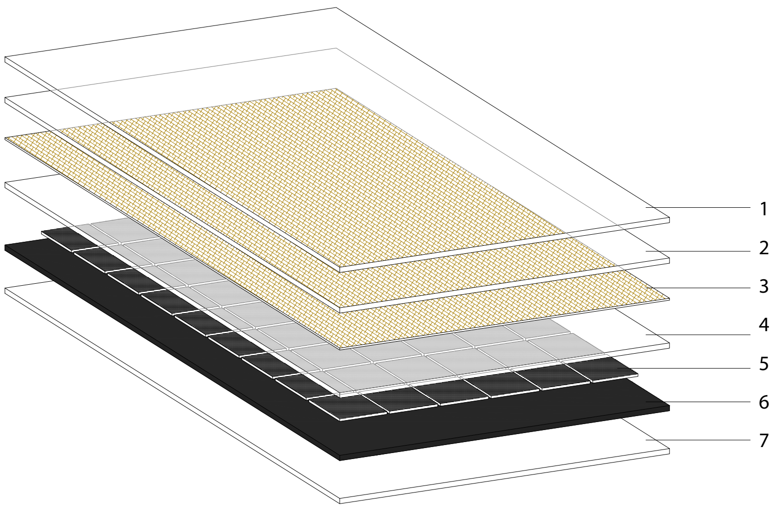
3- PV CELL MATRIX

4- BACK INTERLAYER

5- BACKGLASS

Figure 3.11
BIPV panel composition.

Source: CSEM



1- FRONT GLASS

2- CLEAR INTERLAYER

3- COLOUR AND TEXTURE FILTER

4- CLEAR INTERLAYER

5- PV CELL MATRIX

6- BACK INTERLAYER

7- BACKGLASS

Figure 3.12
CSEM's new BIPV panels composition.

Source: CSEM

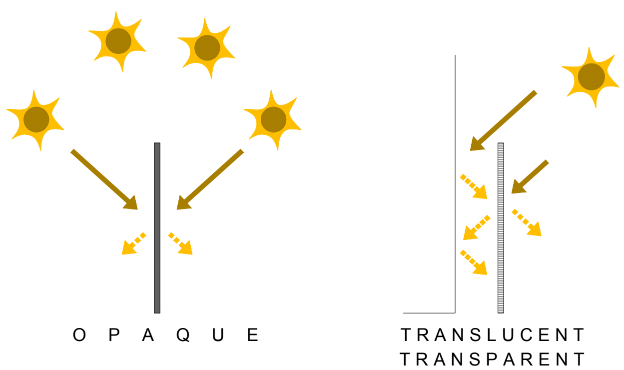


Figure 3.13
Bifacial BIPV concept.

According to the SHC Task 41, BIPV elements must comply with three main building requirements: functional, constructive, and formal requirements. The former refers to the fact that BIPV elements replace one or several building construction materials, taking up its envelope's functional requirements. The constructive requirement refers to the compliance of the BIPV element with all building construction standards and regulations. Ultimately, the formal requirement refers to the BIPV system's design flexibility and harmonisation with the existing construction materials [Munari Probst 2008; Farkas *et al.* 2013].

Novel BIPV panels

Novel BIPV panels incorporate texture and colour filters to foster the aesthetic potential of BIPV systems [Perret-Aebi *et al*. 2013]. This is the case of CSEM's latest BIPV panels which incorporate a filter (number 3 in Figure 3.12) into a regular glass-glass Monocrystalline BIPV panel offering a new aspect to the panel compared to the usually black c-Si panels, with a variety of textures, colour, and reflections. This type of transformative panels represents a technological solution that modifies the visual appearance of a standard BIPV module to enhance its architectural integration potential [Jolissaint *et al.* 2017; Ballif *et al.* 2018].

Different filters are chosen based on the range of their original colours and textures, avoiding artificial colouring and searching innovative textures. These filters enrichen BIPV panel's architectural expression and define a new construction material. However, as they partially cover the PV cells, they reduce the sun radiated PV surface and hence, the BIPV panel's performance.

Novel BIPV panels can be designed to collect photons from the incident and albedo irradiation, reaching both the front side and the backside of a solar module. These are the *Bifacial* BIPV panels that have been under research since the 1960s and can raise by up to 30% the energy output of a regular BIPV module [Guerrero-Lemus *et al.* 2016; Hansen *et al.* 2017].

To optimise the bifacial functioning of BIPV systems, the colour of the mirroring surface has to maximise the amount of light reflected. According to R.Gerrero-Lemus *et al.*, white acrylic paint can have a high reflection index in the air and good light scattering properties [Guerrero-Lemus *et al.* 2016]. When a BIPV system is designed with a bifacial generation function, the distance between the active surface and the back reflector must optimise the light reflection to maximise the energy output. According to Chin Kim Lo *et al.*, the optimal distance between the solar cells and the mirror in a bifacial BIPV system is 15.8 cm [Chin Kim Lo *et al.* 2015].

BIPV energy management strategies (EMS)

Due to the mismatch between the building's energy demand schedule and the PV generation schedule, emerging energy management technologies aim at minimising the problems associated with this mismatch and maximising the building's self-sufficiency. These energy management involves demand-side energy management strategies (DSEMS), energy storage and smart grids[9], to increase the share of self-consumed PV energy and minimise the current feed-in tariff's fluctuation problems [Weibel 2011; Song *et al.* 2016; SolarPower Europe 2017].

EMS is usually paired with BIPV generation forecasts [El-Baz *et al.* 2018] and integrates storage systems [Jiang *et al.* 2107] such as batteries and fuel cells [Rekioua 2018]. Ultimately, EMS integrates BIPV systems in a smart grid as a local energy generation centre.

9

As defined by the IEA, a Smart Grid is an electricity network that uses digital technology to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end-users. The aim of smart grids is to maximize the system reliability, resilience and stability and minimize costs and environmental impacts by coordinating the needs and resources of end-users and generation, grid and market operators [IEA 2011].

Demand Side Energy Management Strategies (DSEMS)

Owing to variable meteorological conditions that determine the output of PV power, solar-generated electricity cannot be reliably dispatched or accurately forecasted. Additionally, residential buildings have a peak energy demand in the evening that PV generation cannot directly supply and a peak energy production during the day, depending on the BIPV orientation. Such timely mismatch enforces the need to export a significant part of the locally generated energy to the grid, even though energy is later imported back from the grid [Vieira *et al.* 2016].

DSEMS can balance the building's energy demand and supply [Aghajani *et al.* 2107]. In BIPV scenarios, they are focused on improving PV's energy efficiency by overcoming the intermittency and energy demand-generation mismatch [Barbato *et al.* 2012]. DSEMS can also help to increase the BIPV system's reliability [Guichi *et al.* 2018], and can be adjusted to different objectives: minimise cost, maximise comfort or minimise CO_2 emissions [El-Baz *et al.* 2017].

Recent researches have focused on this topic and have developed different strategies. [Khan *et al.* 2015; Ali *et al.* 2018] present a thorough DSEMS literature review, the different available technologies, and recent developments. In the residential BIPV energy management context, DSEMS integrate home automation which has the potential of peak shaving and load shifting to better meet PV generation schedule [Barbato *et al.* 2012; Wu *et al.* 2015; Gellings *et al.* 2016]. These shiftable loads are principally heat pumps and electric vehicles [El-Baz *et al.* 2017].

Energy storage technologies

Due to the characteristic intermittence of renewable energy sources, affordable and available energy storage technologies are indispensable to contribute to the energy transition objectives, breaking with the fossil fuel dependence [Chamberlain *et al.* 2016]. The output of PV power is determined by variable meteorological processes outside the control of the generators or the system operators. Solar-generated electricity cannot be reliably dispatched or accurately forecasted.

The widely employed method to improve PV performance and minimise the building's energy demand and PV generation mismatch is to incorporate batteries. Batteries can help to mitigate the intermittency of renewable energy generation and increase the self-sufficiency ratio (SSR) of the building [Zhang *et al.* 2016a]. With a battery system, the excess PV electricity during the day is stored and later used at night. In this way, buildings equipped with a PV battery system can reduce the amount of electricity drawn from the grid and therefore increase their self-sufficiency.

Energy can be stored in different ways as thermal, mechanical, potential or electrical energy. Table 3.5 presents a classification of the existing main energy storage technologies [Christiansen *et al.* 2015; Goswami *et al.* 2016].

Nowadays, PV building installations are usually coupled with Lithium-ion batteries [Vieira *et al.* 2016], as they are superior at achieving higher

SSR with the same Life Cycle Cost (LCC) and due to its decreasing price – ca. 14% annually from 2007 to 2014 [Zhang *et al.* 2016b].

Batteries cannot store energy for long seasonal periods. Therefore, it is not an adequate solution for situations in which a building has a large energy surplus during the summer period and requires a significant amount of grid power during the winter period. However, other energy storage systems can accommodate seasonal energy storage issues. For example, hydrogen storage is a promising method that is suitable for long term storage [Zhang *et al.* 2016a]. The optimal choice must be assessed in each particular case, knowing that hybrid solutions are also feasible options [Zhang *et al.* 2016b].

According to Kousksou *et al.*, energy storage is a crucial factor for renewable energy resources to become utterly reliable as primary sources of energy. Essentially, energy from these renewable resources must be stored when there is an excess of production and then released when there is a building energy demand. The authors present a detailed review of the state of the art of these systems in their work that gives insightful information on energy storage systems [Kousksou *et al.* 2014].

Energy storage systems can improve energy self-consumption by up to 50%. Some studies demonstrate how the integration of a battery in a BIPV system can reduce more than 75% of the energy sent into the grid and by 78% the energy consumed from the grid [Luthander *et al.* 2015; Nyholm *et al.* 2016]. The energy storage industry had a learning curve growing 19-24% per year from 1985 to 2012, and it is expected to further increase due to the demand created by the electric vehicles industry [de Oliveira e Silva *et al.* 2016]. As a consequence of these optimistic facts, some researchers have developed a tool for the economic assessment of battery energy storage [Khalilpour *et al.* 2015].

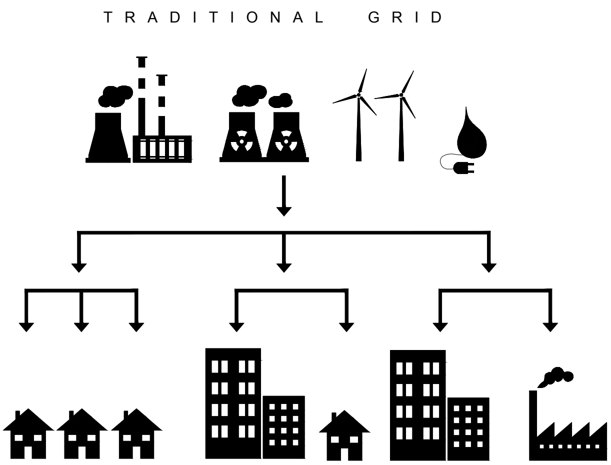
In an ideal energy storage scenario, buildings would generate and consume the same amount of energy, minimising energy exchanges on the grid. For this to happen, the surplus must be stored when the BIPV system generates an energy surplus during peak solar irradiance hours. [Santos *et al.* 2014]. However, Santos' research results showed that energy storage systems have annual energy loses up to 24.24%. To compensate energy storage loses, they state that *to be completely grid-independent, PV generation has to be higher than the building demand*.

Table 3.5
Existing main energy storage technologies.

Source: AECOM Energy Storage Study [Christiansen *et al.* 2015]

ENERGY STORAGE TECHNOLOGIES

MECHANICAL	ELECTRICAL	ELECTRO-CHEMICAL	CHEMICAL	THERMAL
PUMPED HYDRO (PHS)	CAPACITORS	CONVENTIONAL BATTERIES (LEAD ACID/ NiCd / NiMh /Li)	HYDROGEN	MOLTEN SALTS
COMPRESSED AIR ENERGY STORAGE (CAES)	SUPERCONDUCTORS	HIGH TEMPERATURE (NaS / NaNiCl)	METHANE	CHILLERS
FLYWEEL		FLOW BATTERIES (REDOX FLOX / HYBRID FLOW)		



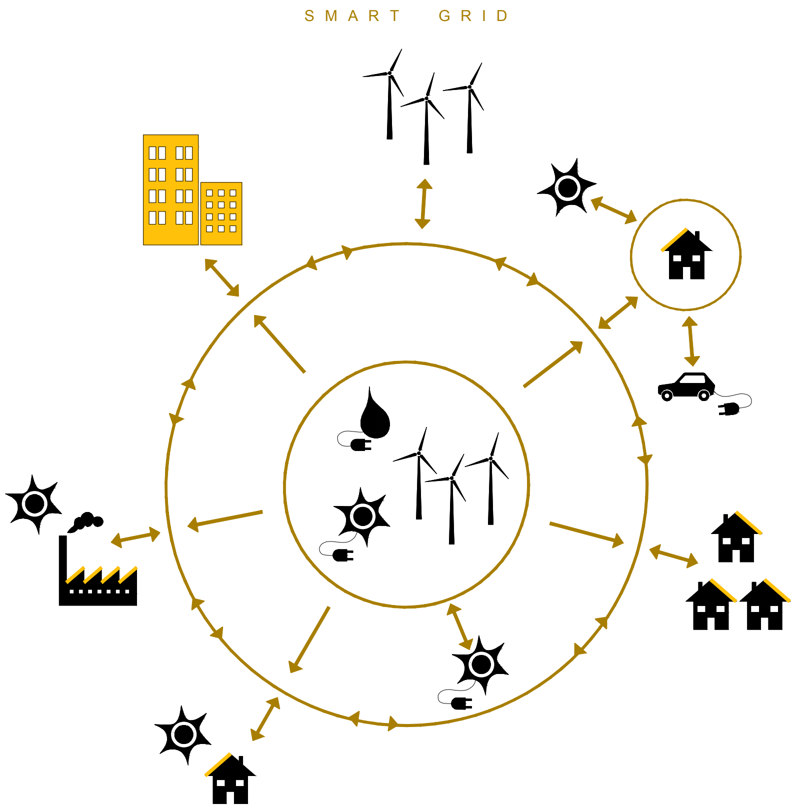


Figure 3.14
Traditional and smart grid schemes.

Source: ABB

Smart grid

The existing unidirectional system of energy supply is evolving towards a bidirectional energy distribution system [Moura *et al.* 2013; Bouhafs *et al.* 2014], which integrates multiple energy producers as well as different energy storage systems [Miao 2016; Godina *et al.* 2018] (Figure 3.14). These energy flows are regulated by EMS, incorporating smart communication technology, which defines the smart grid [Khan *et al.* 2015].

The smart grid is a promising solution to the problems resulting from the growing energy demand, the growing pollution rates, and the ageing power grid infrastructure [Vardakas *et al.* 2015].

A smart grid is an electric network that automatically coordinates the production, consumption and storage of electric energy. This type of network allows a demand-driven electricity generation system to be converted into a supply-based electricity consumption system [Bouhafs *et al.* 2014]. This means that the consumption patterns are adapted to random variations in wind and solar energy production. A smart grid contributes to improving supply security, reducing electrical distribution cost, integrating renewables into the grid and increasing the efficiency of the entire system [AES 2018].

The increasing share of variable renewable energy resources, which are mainly solar PV and wind power, is leading to significant challenges to the electricity grid stability, security, and reliability [Euroelectric 2011]. These challenges are due to the intermittent and not accurately predictable electrical output of renewable energy resources. Controlling the consumption together with storing energy ensures the needed flexibility to better match the energy generation with the energy consumption schedule.

The smart grid represents a novel electric grid paradigm that breaks with the basis of the traditional electric grid. Its implementation at a national scale is being studied in Switzerland [Ali *et al.* 2018].

The development of these BIPV EMS defines two different ways to approach BIPV design: a *conservative* approach and an *innovative* approach. The first one, the *conservative* approach, limits BIPV integration to areas where energy generation matches the building energy demand schedule. The approach takes into consideration that buildings consume on-site BIPV-generated energy when needed, and the rest is exported into the grid. The second one, the *innovative* approach, maximises the building's active surfaces to boost energy generation. This approach is based on the hypothesis that BIPV systems can incorporate EMS to minimise the energy generation mismatch and hence, energy export.

These two approaches have different design consequences. On the one hand, a *conservative* design requires a detailed study of the building envelope surfaces with high solar radiation matching the building's energy demand schedule. The *conservative* approach limits the number of active square metres to avoid energy overgeneration and optimise the active façade cost. This approach is discussed in Aguacil's PhD thesis, which studies BIPV potential in building renovation [Aguacil 2019]. On the other hand, an *innovative* design focuses on maximising energy generation, which can be achieved by enlarging the active surfaces size and performance.

For the time being, the *conservative* approach is the most realistic one due to the expensive existing storage systems and the small scale of existing smart grids [Deign 2017]. However, the increasing energy demand, which is expected to grow 56% by 2040 [US Energy Information Administration 2016], motivates this research to take for hypothesis the need to maximise on-site energy generation to meet the increasing energy demand predictions. In addition, the hypothesis that a national smart grid is a close reality has also led to the *innovative* approach of this research's design process. As a matter of fact, it would increase the environmental and economic profit of maximising the on-site renewable energy generation. For this reason, this research framework defines an *innovative* BIPV design approach for the architectural design process, involving that the totality of the on-site generated BIPV energy can be locally consumed based on EMS development in the near future.

3.2.2.2. BIPV design approach: BIPV façades

As presented in Table 3.4, BIPV can be integrated into the building envelope in different ways. Broadly speaking, BIPV can be part of the roof and/or façades. These two different options carry different panel orientations, different electrical output, different energy generation profiles, different architectural requirements, and different social façade perception. In central Europe, panels must be oriented south and with an inclination of around 35° (equal to the location's latitude) to achieve the maximum annual electrical output. However, slight angle variations between 20° and 45° and slight orientation variation to the east or west result in minor radiation losses [Odersun 2011; Zomer *et al.* 2013].

The maximal solar radiation is easier to achieve in BIPV roofs than in BIPV façades due to their natural morphology: surfaces between 60° and 0° are considered roofs and surfaces between 90° and 60° are considered façades [Sanchez-Ostiz Gutiérrez 1996; Scognamiglio *et al.* 2014]. For this reason, BIPV façades have between 20% and 40% lower energy potential outputs per square meter than BIPV roofs [Heinstein *et al.* 2013]. However, façades can include external devices such as solar control systems, which can be inclined and oriented to maximise BIPV electrical output [Svetozarevic *et al.* 2019]. According to recent works, the façade orientations that deliver the maximum energy yield for central and southern Europe are the southeast and the southwest façades [Kylili *et al.* 2014].

Figure 3.15 and Figure 3.16 show the solar radiance potential of the different building envelope inclination and orientation. Pitched roofs have the highest solar radiance potential, although the integration of BIPV surfaces into building's façades has some advantages to consider when designing an active envelope [Sozer *et al.* 2007]:

- In cities, façades usually have more available exposed area than roofs. Mainly because they have a bigger surface, but also because roofs are mostly devoid of building infrastructures such as chimneys, elevator engines or building services like ventilators or air-conditioning units. It is estimated that in urban areas, around 60 to 80% of the building envelope corresponds to façades.

- In line with this point, freeing the roof surface from additional technical devices – BAPV roof – can avoid technical incompatibilities and provide an adequate surface for the neighbours to develop leisure activities, urban agriculture, and

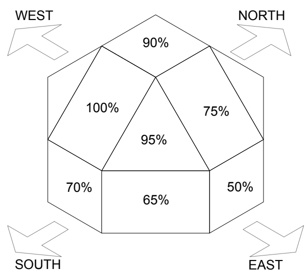


Figure 3.15
Solar radiance distribution on the building envelope regarding inclination and orientation, in an European context.

Source: Polysolar

other recreational activities. [Redweik *et al.* 2013; Zammit *et al.* 2017].

- Façades have a better maintenance condition than roofs since vertical surfaces do not accumulate so much dirt. Besides, in the Swiss context, snow accumulation is also a problem on horizontal and tilted surfaces, while it hardly affects vertical surfaces. In the same line, breakage risk due to hailstorms is reduced [Redweik *et al.* 2013].

- Façades have a better distribution of the solar radiation over the year; this means that those façades provided with PV have a more regular annual energy production than photovoltaic roofs. Buildings with BIPV façades can benefit from PV electricity production more homogeneously throughout the year when combining different orientations [Sanchez *et al.* 2015; Salem *et al.* 2015].

- At the urban electrical grid-scale, roof peak production at noon can derive into grid overloads. In BIPV façades, the generation peak is lower, which means that less energy may be injected in the grid when not demanded by the building. Some researches state that until energy storage systems are affordable and reliable to integrate into buildings, it is more interesting to focus on matching the building's energy demand – to maximise self-consumption – rather than on the maximum output of the system – to maximise self-sufficiency [Sanchez *et al.* 2015].

- At the building scale, the daily generation profile of PV installed on façades fits better the specific residential building's hourly energy demand. When buildings do not have an energy storage system, matching energy generation and demand profiles becomes more critical than maximising total annual energy output [Gutschner *et al.* 2002; Sanchez *et al.* 2015].

- In Switzerland, according to the IEA's PVPS programme, residential buildings have the highest BIPV potential. Moreover, they state that roof surfaces of high tilts and façades facing east and west have better solar yields when energy production needs to match specific daily or hourly loads [Gutschner *et al.* 2002].

- The economic aspect is also an important factor in favour of BIPV façades. In general, façade cladding materials are more expensive than roof finishing materials, which are mostly ceramic clay in tilted roofs or gravel in flat roofs. This means that replacing an expensive material with another expensive material is, under the economic point of view, more interesting than replacing a cheap material with an expensive one [Verberne *et al.* 2014].

- Façade design with PV is a real challenge for the architect and a marketing opportunity for the owner. The façade has the public dimension that the roof does not usually have. This implies a larger visible impact of a PV façade than a PV roof, affecting the social acceptance and requiring higher integration quality [Munari Probst *et al.* 2007; 2019]. In consequence, a significant effort has to be made to achieve a design in harmony with the rest of the project. However, a successful BIPV façade design increases the

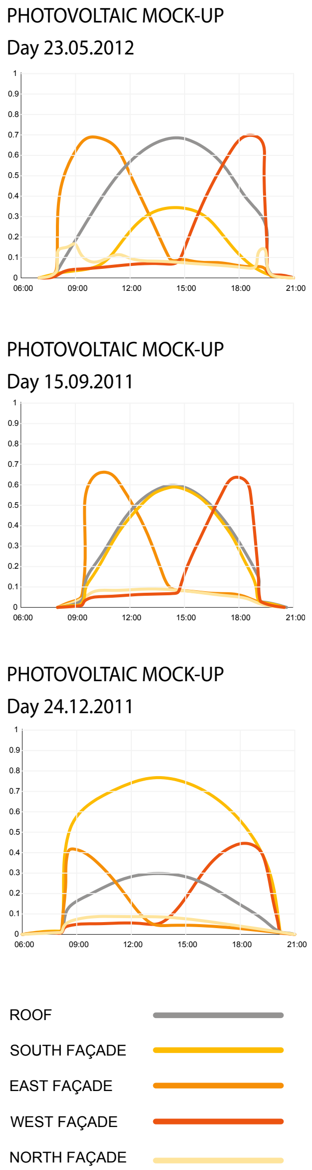


Figure 3.16
Annual energy production of roof, south façade, east-façade, west-façade and north façade of a simulated building.

Source: [Sanchez *et al.* 2015]

general social acceptance and likeability of the building due to its *sustainable aesthetic*, which could be translated into economic BIPV benefits [Herzog *et al.* 2004; Hindrichs *et al.* 2006].

- Ultimately, active roof PV output is often insufficient to meet the energy demand of high-rise buildings of five or more storeys. This corresponds to the size of the most common residential buildings in medium-dense urban areas [Kuhn *et al.* 2014; Verberne *et al.* 2014; SUPSI *et al.* 2015, 2017].

Despite the higher annual electrical output of BIPV roofs, BIPV façades have additional advantages regarding energy generation, socio-cultural aspects and economic factors that can be complementary to BAPV roofs as a potential solution to improve the building's energy efficiency [Scognamiglio *et al.* 2014].

3.2.2.3. BIPV façade's integration barriers

The introduction of solar technologies into the built environment has not been widely accepted despite BIPV's potential to improve the building's energy efficiency. In recent years, several researches have focused on identifying BIPV barriers and analysing the barriers themselves.

In the first place, a literature review reveals that some BIPV barriers have been overcome over the past years. Indeed, in 1999, van Mierlo identified barriers in BIPV's legal and regulatory framework as well as recycling issues that today have already been overcome [van Mierlo *et al.* 1999]. However, recent research results highlight other barriers such as BIPV cost, aesthetics and lack of information and knowledge, among others, that continue to pose challenges [Sozer *et al.* 2007; Farkas *et al.* 2012a; Azadian *et al.* 2013; Heinstein *et al.* 2013; Bonomo *et al.* 2015; Karakaya *et al.* 2015; Yang *et al.* 2015; Prieto *et al.* 2017].

The most extensive work on the identification of barriers blocking the expected widespread use of BIPV within the construction sector can be found on the IEA SHC program on its task 41 (T.41.A.1), published in 2012. This report gathers a detailed and extensive literature review from 1994 to 2011 about Solar

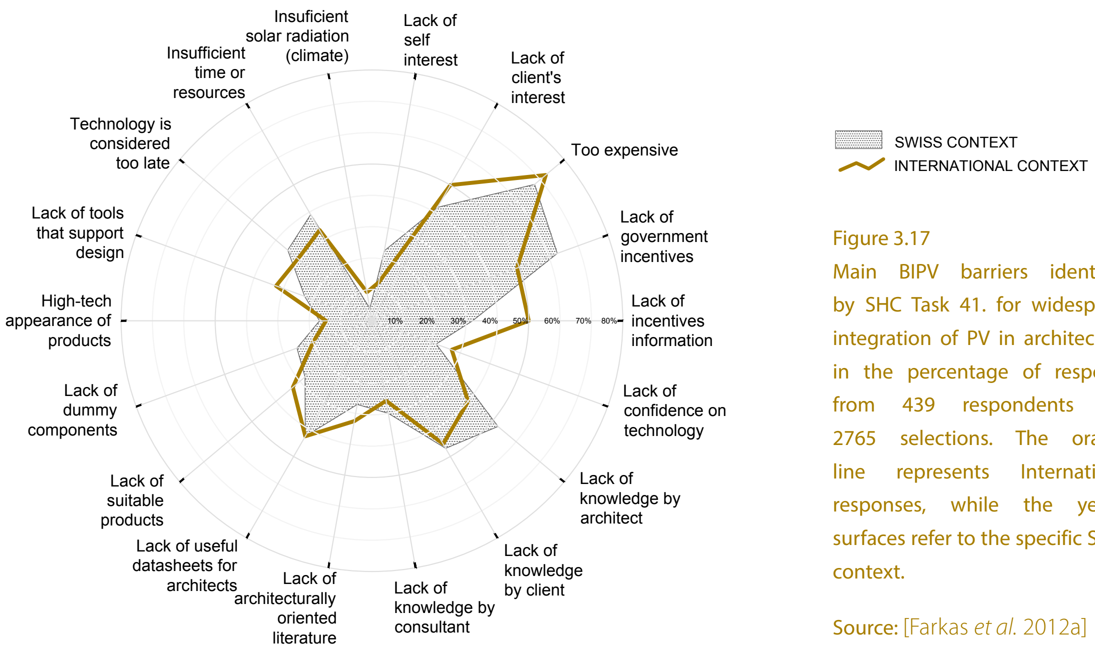


Figure 3.17
Main BIPV barriers identified by SHC Task 41. for widespread integration of PV in architecture, in the percentage of response from 439 respondents and 2765 selections. The orange line represents International responses, while the yellow surfaces refer to the specific Swiss context.

Source: [Farkas *et al.* 2012a]

Thermal and Photovoltaics integration barriers. The SHC program has carried out the biggest international survey at the time – 439 respondents – regarding PV in buildings addressed to construction professionals: 78% architects, 13% engineers, 1% physicist and 7% of other building professionals were interviewed. The T.41.A.1 report goes through a detailed analysis of its survey results and proposes 18 identified barriers classified into six groups: Interest, economy, knowledge, information, products and process. They discovered that 73% of the respondents believed that a PV integration was not economically justifiable; around half of the respondents complained about the lack of technical knowledge by architects, and 50% of the interviewed subjects stated that there was a lack of general interest on BIPV technology. Results regarding BIPV barrier identification from SHC task 41's research are displayed in Figure 3.17 [Farkas *et al.* 2012a].

Barriers such as low efficiency and high costs of active solar technologies are being gently overcome in recent years due to the technological advance of PV, its cost decline and the constant fluctuation of oil and gas prices. However, architectural integrability and formal expression of BIPV products are still a challenge for future BIPV research. Authors of the SHC task 41 report highlight that, even if architects referred to architectural integration and lack of knowledge as the main obstacles, little work has been done towards overcoming this impediment [Wall *et al.* 2012].

In 2013, CSEM's research team in Neuchâtel analysed BIPV barriers after several pioneer companies in BIPV products either stopped or abandoned development in the field. According to them, *there are technical, legal, administrative, and market barriers to be considered, all of this is accompanied by disputes on aesthetics, and above all on calculations of cost-efficiency*. Their work identified a wide range of barriers and needs for widespread use of BIPV: legal barrier, lack of experienced installers, social barriers, high costs, inconsistent subventions, lack of information and BIPV products with poor architectural qualities [Heinstein *et al.* 2013].

Other researches refer to more technical barriers such as durability and reliability of the panels. They also mention the complex BIPV maintenance and replacement processes, which is a consequence of not considering these issues from the early design stage of the project. The lack of specific BIPV standards and building codes was also highlighted as an issue that is now being overcome since the publication of the new European BIPV standard EN50583: *Photovoltaics in Buildings* in 2016. Similarly, other more specific technical barriers such as BIPV

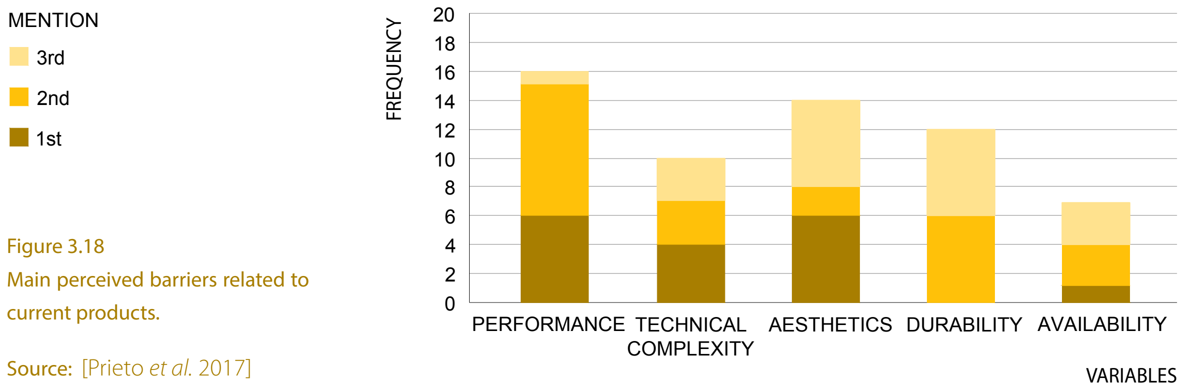


Figure 3.18
Main perceived barriers related to current products.

Source: [Prieto *et al.* 2017]

system choice, overcharging of loadbearing structures, and mechanical stress on BIPV are subject of research for being overcome [Yang 2015].

Another noteworthy and more recent research is the one developed by Prieto from Delft University. In 2015, they addressed professionals to conduct a survey and identify the main barriers for façade integration of solar technologies. Their work presents the perceived barriers and compares the findings along with similar research experiences on the topic, among them the results obtained in 2012 by the SHC Task 41. High BIPV costs stand out among the identified barriers, which include BIPV aesthetics, the performance of the systems, and the knowledge to design, implement or operate them [Prieto *et al.* 2017].

In Prieto's survey, the most mentioned barriers were product related. For this reason, an analysis of this barrier was carried out to identify specific research topics. These are represented in Figure 3.18 according to the number of mentions referring to product performance, technical complexity, aesthetics, durability and availability.

As mentioned above, some BIPV barriers are being overcome like BIPV's legal and regulatory framework as well as recycling issues. This is also the case of the general interest in BIPV identified by Farkas and Horvat [Farkas *et al.* 2012a]. In fact, among Prieto's research results, it is relevant to note that the lack of interest is no longer identified as a BIPV barrier. This is a result of good marketing of renewable energies; people are becoming aware of the advantages of a BIPV installation and are more concerned about energy issues, in the current context of the energy transition [Prieto *et al.* 2017].

High costs are the primary concern of BIPV potential users, although BIPV producers are succeeding in drastically lowering product prices through performance improvement, material reduction and material recycling [Biyik *et al.* 2017]. Moreover, recent researches mention additional economic benefits associated with BIPV. These benefits include the environmental and health aspects through the reduction of carbon emissions, as well as economic viability for society [Yang *et al.* 2015]. Additionally, some studies have monetised the cost of carbon emissions, which allow to include those estimations in the BIPV cost assessment equation, tilting the balance in favour of BIPV use [Lazos *et al.* 2012]. Eventually, Sozer *et al.*'s research focuses on BIPV façade design to overcome the high-cost barrier. It concludes that trained professionals on BIPV design and the integration of PV application at the beginning of the architectural design process can optimise the cost of BIPV façades [Sozer *et al.* 2007]. The fact is that research is rapidly pushing forward, and PV building integration is getting more affordable and advantageous [SUPSI *et al.* 2017].

Apart from BIPV cost, research surveys show that what mainly concerns architects are two facts: the lack of knowledge about BIPV technology and the unsufficient expressive quality of certain BIPV solutions. It can be assumed that these two facts are closely linked. The lack of sufficient information and knowledge about BIPV products is what mainly limits the formal expression possibilities of architectural projects. As for the architect's lack of knowledge, the main concern is the lack of experience and the general know-how of architects about PV. Bonomo *et al.* noted in 2015 how the available BIPV information is mainly technical and how this is a real problem for architects. Designers do not know the architectural features of BIPV and find it very difficult to integrate all the technical data in the design process. For a more extensive BIPV architectural use, Bonomo *et al.* recommend developing information about materials and systems compatibility, integrating technical elements and maintenance instructions. Regarding this same problem, the use of architectural language[10] is vital for BIPV to start being part of the architectural design process as a construction material and not as an additional technical device [Scognamiglio *et al.* 2014; Bonomo *et al.* 2015].

In regards to façade aesthetics, several researches have worked on developing guidelines and identifying systems that can meet architectural requirements. Munari Probst, in the cotext of SHC's Task 41, highlighted how delicate interventions in façades are, as they are the public face of architecture [Munari Probst *et al.* 2007; 2012]. Most BIPV façade researches are mainly focused on the functional integration of BIPV. Among them, several have identified different façade classifications and have matched existing BIPV products with existing façade systems [Munari Probst *et al.* 2012; Farkas *et al.* 2013; FOSTEr inMED 2015; Prieto *et al.* 2017]. Some of these authors refer to existing BIPV installations and analyse the advantages and disadvantages of the chosen installations, in ways similar to a catalogue. These approaches help to demystify the complexity of BIPV technical integration and advance towards an architectural comprehension of BIPV. However, there is still room for improvement because BIPV integration is not yet a common architectural practice. For this reason, aesthetical barriers cannot be considered overcome, meaning that more work in this field is required [Heinstein *et al.* 2013].

3.2.2.4. Active façade design: existing research

The previous section has presented several obstacles for the integration of BIPV in common architectural practices identified in the BIPV literature review. Some of them need to be addressed from the product developers' sector, some from the national legal regulation system, and others form the collective of architecture professionals. Among the latter, the architectural integration of BIPV in façade design has been defined as a real challenge for the PV industry. BIPV façade design must integrate scientific parameters – energy output – and interpretative aspects – aesthetic, spatial, visual and cultural – finding the optimal balance to meet the building requirements [de Berardinis *et al.* 2011].

Since the late '90s, PV development towards its building application has been widely investigated [Scognamiglio *et al.* 2014]. The International Energy Agency (IEA) has funded several programs [SHC 1995, 2013, 2014; PVPS 2016, 2019] and the literature has produced numerous handbooks [Sick *et al.* 1996; Randall 2001; Roberts *et al.* 2009; Munari Probst *et al.* 2011] and papers on the topic [Hestnes 1999; Zanetti *et al.* 2010; Frontini *et al.* 2012; Reijenga *et al.* 2012; Bonomo *et al.* 2015; Shukla *et al.* 2016; Attoye *et al.* 2017; Yang *et al.* 2017; Hachem-Vermette 2018], among the most relevant. In addition, public authorities have also published PV design and construction recommendations to foster and support the integration of BIPV in early design stages.

This section presents an overview of the existing research focused on the energy-efficient façade dealing with BIPV architectural integration issues as a building application. Among the reviewed researches, this section refers to the most relevant existing work regarding this research framework, sharing an architectural approach.

International and national research programs

The IEA focuses on guaranteeing the use of affordable and reliable clean energy through securing the supply and, therefore, fostering environmental awareness. Since 1974, the organisation develops strategies to respond to

10
Architectural language refers to the use of 2D and 3D plans and images as well as the use of the common measuring units among construction professionals: meters and square meters over kilowatts, kilowatts peak and other units used among electric engineers to describe BIPV systems.

oil supply disruptions towards renewable energy efficiency [IEA 2019]. There are mainly two programs established by the IEA that tackle the issue of PV. These are the Solar Heating and Cooling Programme (SHC) [SHC 1977] and the Photovoltaic Power Systems Programme (PVPS) [PVPS 1993]. Both programmes have developed some of the most extensive research projects regarding BIPV, referred to as *Tasks*.:

- IEA SHC Task 16, *Photovoltaics in Buildings [SHC 1995]*

  The main outcome of this research project is the publication of the design handbook: *Photovoltaics in buildings,* which addresses architects and engineers. It introduces PV technology as well as PV system components and limitations. This handbook presents different requirements regarding weather, structural, occupant and design requirements. It defines PV architectural design as a multidisciplinary approach. In its Chapter 13, Sick *et al.* provide façade morphology design concepts that illustrate the integration possibilities of PV panels into the façades minimising the internal energy loads while maximising PV energy output. These design concepts that maximise PV's energy output include *sawtooth* curtain wall, *accordion* curtain walls, *sloping* curtain walls, and PV awning systems, among others. Ultimately, this handbook provides built PV integration examples as well as its construction details and maintenance recommendations (Figure 3.19) [Sick *et al.* 1996].

- IEA SHC Task 41, *Solar Energy and Architecture [SHC 2014]*

  This task defines the architectural integration quality of PV systems as *the result of a controlled and coherent integration of the solar collectors simultaneously from all points of view,* considering three features: formal, functional and constructive integration. The former refers to the BIPV features affecting the building appearance and façade design, the second to the function of the BIPV as a construction material, and the latter to the constructive requirements of the façade [SHC 2014].

  Within the SHC task 41's work, formal, functional and constructive building requirements are identified. Moreover, a set of integration recommendations for architects and a system development

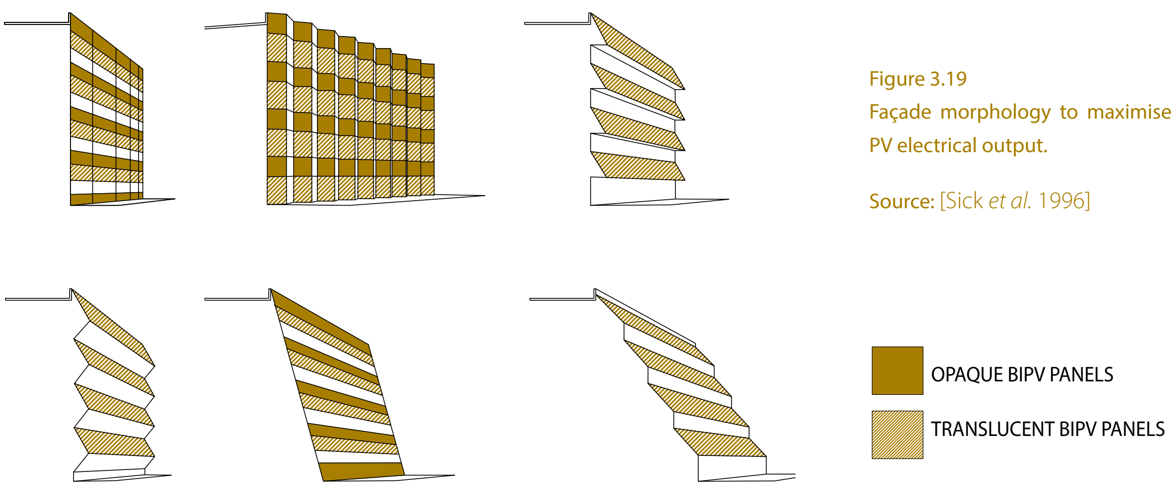


Figure 3.19
Façade morphology to maximise PV electrical output.

Source: [Sick *et al.* 1996]

methodology is provided for product system developers to meet formal architectural requirements. These are the coherence among the architectural composition and the BIPV systems dimension, shape, and position; the coherence among all materials composing the building envelope and the BIPV system regarding colours and textures; and the specific design of jointing, framing and matching with other building materials. Regarding functional and constructive aspects, load transmission issues, weather and fire resistance, as well as impact risk, must be considered according to the Task 41's research team [Munari Probst *et al.* 2012; 2014; Farkas *et al.* 2013].

SHC Task 41 gathers a catalogue of BIPV products classified by building elements – e.g. solar window shutters, PV louvres, etc – and provides building integration examples, construction details as well as its *integrability* characteristics [Horvat *et al.* 2012b; Farkas *et al.* 2013].

Ultimately, the SHC Task 41 provides information about existing tools for solar design and guidance through Solar marketing to help to spread the advantages of BIPV integration in buildings [Hagen *et al.* 2012; Horvat *et al.* 2012b, 2012a; Munari Probst *et al.* 2014;].

- IEA PVPS Task 7, *Photovoltaic power systems in the built environment [PVPS 2016]*

  This task is an international collaborative effort focusing on BIPV, linking developments in IEA countries worldwide. The overall objective of Task 7 is to enhance the economic viability, the architectural and the technical quality of photovoltaic power systems in the built environment. This research – concluded in 2001 – has an essential content of BIPV barrier identification as well as non-technical barrier assessment [van Mierlo *et al.* 1999].

  Task 7 proposes a methodology to approach the BIPV project assessment. In a similar way to the work developed within the SHC Task 41, PVPS Task 7 proposes architectural criteria to integrate BIPV. According to them, BIPV should be integrated in a natural way, which is architecturally pleasing, respects a good composition and is in harmony with the context [Schoen *et al.* 2000]. In addition, researches of PVPS developed an approach to calculating the available area for PV suitability, including the area in the building stock suitable for PV use, referred as the BIPV potential [Gutschner *et al.* 2001, 2002; Schoen *et al.* 2001]. Among the results of this research, it is interesting to note that residential buildings represent 48,5 % of the BIPV area potential for façades in Switzerland [Haas *et al.* 2002]. The PVPS Task 7 also assessed BIPV reliability and developed BIPV maintenance guidelines [Laukamp *et al.* 2002] as well as developed market deployment strategies to improve BIPV economic viability [Eiffert *et al.* 2002; Haas *et al.* 2002].

- IEA PVPS Task 15, *Enabling framework for the development of BIPV [PVPS 2019]*

  Within the PVPS research program, Task 15 aims *to create an enabling framework to accelerate the penetration of BIPV products in the global market of renewables, respecting mandatory issues, aesthetic issues, reliability and financial issues* [IEA PVPS 2016]. Task 15 includes BIPV environmental assessment issues, architectural and aesthetic evaluation, and field testing, in an international context [Eder *et* *al.* 2017]. This research targets the large scale market penetration of BIPV products while contributing to an aesthetically pleasing built environment and coping with the challenge to realise zero energy buildings [Ritzen *et al.* 2014].

The research methodology includes: 1) the development of a BIPV project database, 2) the identification of business models of BIPV to foster the development of BIPV projects in different countries, 3) the identification of BIPV requirements at an international level to foster standardization, 4) the investigation of BIPV environmental benefits within an assessment methodology comparable to other construction material's assessment methodology, 5) the demonstration of BIPV technologies and applications, and 6) the dissemination of the research findings [PVPS 2019]. This research is on-going and results publications are expected in the following years.

On a national level, the Active Interfaces interdisciplinary research project, specifically within its design subproject, aims at *crossing over the limits of the current practice and to develop a holistic strategy for BIPV-adapted solutions in urban renewal design processes in the Swiss context,* as specified in activeinterfaces.ch [ACTIVE INTERFACES *et al.* 2019]. It represents a strategic potential in terms of transferability and is expected to have positive repercussions for the urban, architectural and constructive design practices. In the context of this project, the team developed architectural design strategies, through real case studies, for promoting the integration of BIPV in urban renewal processes. The work targets the design of façade renovation strategies mainly focused on improving the building's energy efficiency while ensuring architectural integration.

The University of Applied Sciences and Arts of Southern Switzerland (SUPSI) is one of the most active research institutes in BIPV development in the Swiss context [SUPSI 2019b]. In collaboration with Swiss Energy, they have created a website that gathers all information regarding BIPV technology, products and examples: bipv.ch [SUPSI 2019a]. Their researchers have actively participated in several of the above mention research projects and regularly publish about BIPV research in scientific journals. Among their most relevant research outcome regarding BIPV façade design, Frontini *etal.* present BIPV integration criteria for roofs which can be extended to façades and refer to co-planarity to the building envelope, respecting the outline lines of the construction, integration into the construction system and consideration of the building urban context [Frontini *et al.* 2012]. For its part, Bonomo *etal.* consider BIPV as a construction material that can find its expression in contemporary architecture. Part of their research focuses on overcoming the lack of information barrier to foster BIPV design, providing BIPV data compared to existing construction materials, and fostering an integrated design approach for BIPV design [Bonomo *et al.* 2015].

At the EPFL, the research carried out by Munari Probst since 2004 identified implicit criteria shared by architecture professionals that can determine the architectural quality perception of a solar system (thermal and PV) incorporated into the building envelope. These criteria refer to the fact that all the formal characteristics of a solar system must be coherent with the building's design concept. This coherence involves the panel shape, its size and its position into the building envelope. It involves as well the visible materials, their colours and textures, and the jointing system [Munari Probst 2008]. More recently, these criteria have been integrated into a method to assess the integration of solar collectors into the built environment considering its quality, sensitivity and visibility: *the LESO-QSV method* [Munari Probst *et al.* 2019]. This method evaluates the geometry of the system – considering its size, shape and positioning –

the coherence of the system materiality – considering colour, texture and reflexivity – and rates the coherence of the modular pattern – considering the jointing system – to provide a global qualitative evaluation of the solar collector integration.

Other researches

Apart from these international and national research programs, the study of the literature has highlighted several papers addressing the issue of the architectural façade design towards energy transition, which relates to the current research framework.

Already in 1999, Hestnes stated the importance of focusing on the whole building design rather than in BIPV technologies, as this is the way architects work. According to the author, the architectural approach starts with general building requirements – aesthetic, programmatic, performance, etc. Only then, architects will study the available technologies to match the building needs. The paper provides a collection of BIPV examples and analyses them from an architecture point of view, mainly focused on design coherence and *aesthetic compatibility* [Hestnes 1999].

Apart from these considerations, several research papers have produced BIPV design guidelines. Among them, Reijenga *et al.* research focus on the urban requisites and conditions for an optimal BIPV façade incorporation. Their research provides guidelines for PV integration, among which they recommend integrating PV into the building's structure or composition logic. They also suggest that the PV system should be in harmony within the context of the building as well as PV's colours and textures should match with global building design. Eventually, the PV panel dimension must fit into the *composition grid* of the façade [Reijenga *et al.* 2012].

Zanetti *et al.* propose five recommendations to foster the architectural quality of BIPV systems. These are: the coplanarity of the solar installation with the building envelope, the respect of existing building lines, the shape of the BIPV system – which must be coherent with the building itself –, the grouping of the BIPV elements rather than scattered, and the accuracy of the construction details to guarantee a satisfactory design result [Zanetti *et al.* 2010].

In their paper, Shukla *et al.* present a PV technology review as well as a series of steps to the technical and structural designs for BIPV. These steps are presented as *instructions* to technically integrate PV in buildings and consider technical energy building issues such as building peak shifting and integration possibilities such as incorporating BIPV in shading devices. Regarding BIPV structural integration, they provide one example with its corresponding construction details [Shukla *et al.* 2016].

Yang *et al.* acknowledge the urgent need for reducing GHG and recognise BIPV potential to design high energy-efficient buildings. They propose a list of *checkpoints* to consider BIPV as a *viable design solution.* These *checkpoints* relate to the building irradiation, cost, incentives, and social benefits [Yang *et al.* 2017].

In line with the SHC task 16 research outcome [Sick *et al.* 1996], Hachem-Vermette explores different façade design morphologies to maximise the electrical output of a residential building façade. She proposes variations of geometry to define a flat façade, a folded-plate façade – horizontal and vertical saw-tooth variants – and folded-plate units as pyramid units. The research concludes that energy efficiency can be improved by the particular design morphology of the

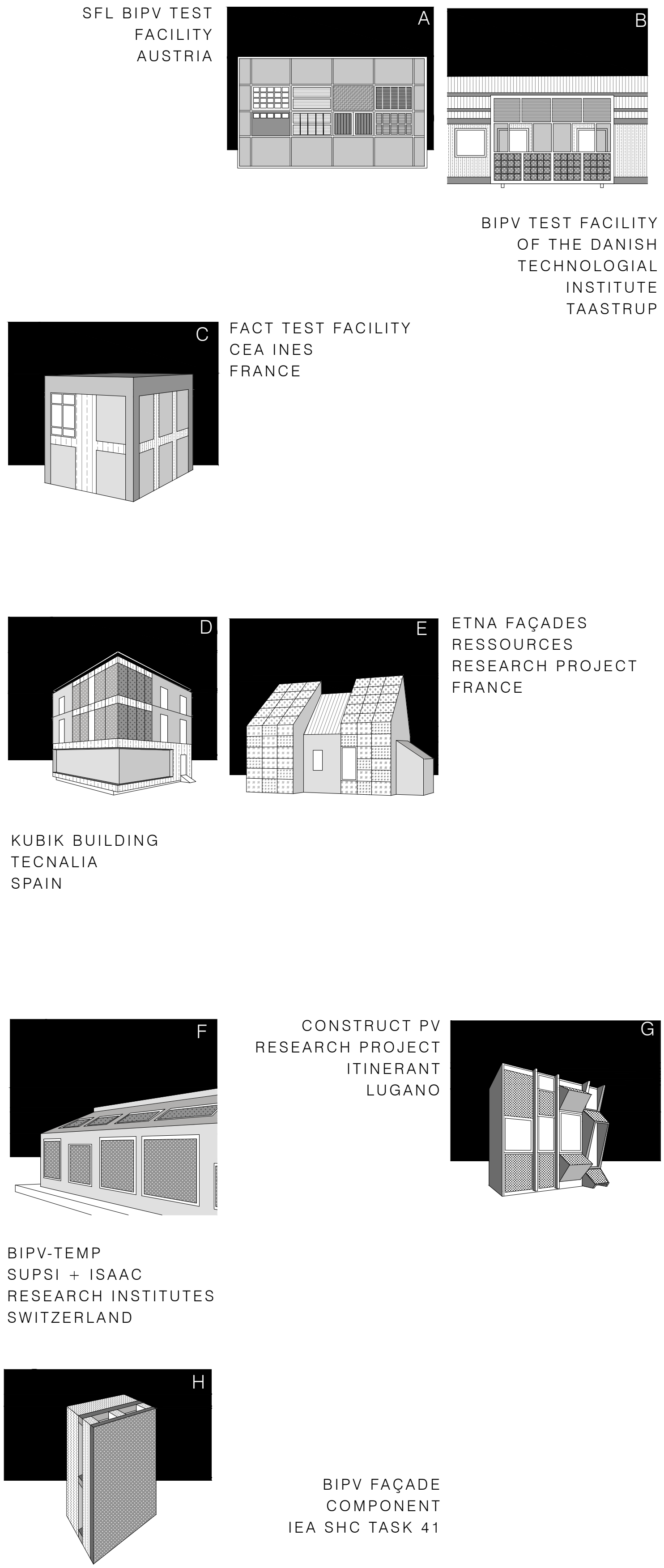


Figure 3.20
Different BIPV façade R&D facilities.

Source: [Farkas *et al.* 2013; Gaillard *et al.* 2014; Loonen *et al.* 2015; Chatzipanagi *et al.* 2016; Vadillo 2016; Eder *et al.* 2017; Construct PV 2018; PV sites 2018] façade, mainly because a multi-faceted façade increases the total available surface for BIPV integration [Hachem-Vermette 2018].

Ultimately, Farkas *et al.* follow an architectural approach to façade design and consider BIPV as a real construction material. They introduce photovoltaic materials and analyse its architectural features, for example, the shape and size of PV materials, its texture, colours, optical reflections, and possible patterns. Economic issues are also discussed as they are considered a key topic, also from an architectural approach. As a conclusion of their dissertation, they provide the reader with a series of existing examples of BIPV integration [Farkas *et al.* 2009].

Prototypes

Prototype construction is a common research method. Accordingly, several BIPV researchers have built BIPV façade prototypes to assess their research results. For example, the 2017 report from the IEA-PVPS shows a detailed, but a not exhaustive, state of the art of the BIPV prototypes where performance is measured and evaluated [Eder *et al.* 2017]. In addition, some of the above-mentioned BIPV façade researches have also constructed BIPV façade demonstrators in recent years [Farkas *et al.* 2013; Maturi 2013].

Hence, this section gathers a selection of façade prototypes which display BIPV as an integral part of the façade. The selection includes real-scale BIPV façade prototypes or main façade components where BIPV modules are integrated into the prototype design process as real construction materials. Ultimately, eight BIPV façade prototypes are selected and illustrated in Figure 3.20. They are presented in a precise order that refers to the degree of architectural concerns affecting the researches: from less to more architectural concerns.

The first BIPV prototype (A) shows the SFL BIPV test façade in Austria with different types of BIPV modules. It has been constructed by SFL Technologies GmbH in cooperation with AIT Austrian Institute of Technology, Energy Department. Its objective is to measure electrical and mechanical data regarding the thermal effects of a curtain wall on the different BIPV panels [Eder *et al.* 2017].

The second BIPV prototype (B) is the BIPV façade test facility of the Danish Technological Institute in Taastrup (Denmark). It is integrated into an office building and focuses on measuring different electrical and thermal impacts on BIPV systems. [Eder *et al.* 2017].

The third BIPV prototype (C) is the *FACT* test facility of the CEA INES (French National Institute for Solar Energy). This BIPV façade demonstrator is operational since 2016 and mainly measures electrical output, thermal behaviour, and indoor environment impact of different BIPV modules [Eder *et al.* 2017; PV sites 2018].

The fourth BIPV prototype (D) is the experimental *KUBIK* building at the Tecnalia research institute in Spain. *KUBIK* is dedicated to innovative products and systems testing, including BIPV, to optimise energy efficiency in buildings. Its objective is to take electrical and thermal impact measurements, as well as to evaluate the environmental influence on BIPV output [Vadillo 2016; Eder *et al.* 2017].

The fifth BIPV prototype (E) has been constructed by the French *Resources* research project and has a different objective than the above-presented ones. It measures the general thermal performance of the façade, as a building component. Therefore, the main objective of their research has a more architectural approach than the previous examples, which are focused on PV's technical performance. Within the Resources research project, different adaptive double-skin façade prototypes have been constructed and are called the *ETNA* façades. This research also addresses BIPV aesthetic issues, but focuses on BIPV products and not the overall composition of the façade [Gaillard *et al.* 2014; Loonen *et al.* 2015].

The sixth BIPV prototype (F) is called *BIPV-TEMP* and has been constructed between 2010 and 2012 in Lugano within the Swiss Federal Office of Energy's (SFOE) project conducted by the University of Applied Sciences and Arts of Southern Switzerland (SUPSI) in collaboration with the Institute for Applied Sustainability to the Built Environment (ISAAC). It approaches BIPV testing from an architectural technical perspective and aims at reproducing real working conditions of a BIPV element when used as a real component of a façade. It tests PV cell performance under architectural integration conditions. In addition, it aims at testing the different aesthetic potentials of BIPV by showcasing different module technologies with different façade features [Chatzipanagi *et al.* 2016].

The seventh BIPV prototype (G) is the mobile BIPV façade prototype constructed within the European research project *Construct PV*. The façade prototype has been designed in collaboration with architects and shows different BIPV products and design possibilities regarding façade morphology. This façade prototype and itinerant test-facility was presented for the first time in Bern in 2015 and is installed at the SUPSI-Campus in Lugano since 2017 [Construct PV 2018].

The eighth and last BIPV prototype (H) consists of a wooden BIPV façade component constructed for the IEA SHC task 41 to test different BIPV modules performance with a sun simulator. It is not a BIPV façade demonstrator itself, but it is a complete façade module which integrates BIPV, tests construction processes and material compatibility [Farkas *et al.* 2013].

In addition, the Solar Decathlon[11] projects shall also be mentioned in this section. Many of them integrate BIPV in their façades, and they demonstrate BIPV integration potential in the building context. Solar Decathlon projects are evaluated for their energy efficiency, but also their architectural quality. This usually implies a careful design of BIPV surfaces to integrate the building design concept [Solar Decathlon 2018]. However, these projects are singular small-sized pavilions with a façade design that cannot be directly exported to large scale façade design.

These façade prototypes are some of the main façade applied BIPV test centres and among the biggest BIPV façade demonstrators constructed lately [Eder *et al.* 2017]. All prototypes measure BIPV electrical output, but they differ on the measured parameters affecting their output. The first two prototypes – A and B – mainly monitor meteorological data and environmental influence on BIPV performance, taking electrical and thermal impact measurements on the active modules. Prototypes C and F include indoor environmental conditions in addition to electrical output and meteorological impact data. Prototype F integrates the *building construction element* condition of BIPV systems and measures the performance of BIPV panels under this condition. The façade prototype G is a showcase of different BIPV products and different potential integrations in a façade. Finally, the façade element H illustrates a complete façade module that could be directly part of a BIPV façade. The last three test facilities – F, G, and H - refer directly to technical architectural concerns in their research objectives: integration, morphology, and compatibility. F, G and H

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The Solar Decathlon is and architecture competition for students where solar energy systems and energy-efficient design strategies are incorporated into small pavillions [Solar Decathlon 2018].

prototypes measure the impact that a BIPV system has on the building and the impact the building has on the BIPV output, whereas the first ones – A, B, C, D and E – measure the impact of the external environment on the BIPV system. Ultimately, the Solar Decathlon projects integrate both energy and architectural concerns in a more or less successful way depending on each particular project. Solar Decathlon projects can be consulted on their website: solardecathlon.gov.

Recommendations

The outcome of the above-mentioned BIPV design researches has fostered the development of BIPV design and construction recommendations, which are available to all architects willing to incorporate BIPV into their design practices. Energy efficiency recommendations include a set of guidelines, which are the base to approve PV integration projects at a communal or regional level, especially in renovation buildings [Aguacil 2019]. In Switzerland, these guidelines promote adapting the PV system's design to the building's envelope regarding shape, inclination, limits, morphology, and colour. PV panels must not generate glare, and the connections details are recommended to be considered at an early design stage to avoid incompatibilities with other building elements such as chimneys or balconies [DAEC 2015].

The outputs of the ACTIVE INTERFACES project – finalised in 2018 – provide design recommendations regarding BIPV innovative technologies, integrated design, energy and environment, market adoption, and assessment and demonstration. This research project's results provide answers to common questions that may arise when considering the incorporation of BIPV into the architectural design process. Among the latter: novel BIPV technologies, fastening systems, reliability, energy performance, compatibilities with existing buildings and renovation examples. Further details can be found in activeinterfaces.ch [ACTIVE INTERFACES *et al.* 2019].

Ultimately, the above-mentioned researches and recommendations provide research methodology references, BIPV architectural assessment criteria, some general design guidelines and a selection of analysed BIPV façade's case studies. Existing researches also highlight the energy and design potential of BIPV façades, which contrasts with the limited number of examples that can be found in practice around the world. In that respect, Zomer *et al.* propose the integration of BIPV systems in large and iconic buildings to present BIPV virtues to broader audiences and inspire construction professionals to adopt BIPV practices [Zomer *et al.* 2013; SHC 2014].

3.2.2.5. Active façade design: architectural references

Some authors agree that architectural references are a suitable starting point for building design. They state that the availability of precedent knowledge has the potential of fostering design creativity, which is understood as *new combinations of known entities*. To be valuable, an architectural reference has to relate to contemporary architecture concerns, which in the context of this research are energy efficiency objectives [Taylor 1988; Finke 1990; Prost 1992; Goldschmidt 1998].

In search of existing active façade architectural references, completed BIPV façade projects have been searched worldwide, allowing us to acknowledge a state-of-the-art of BIPV practice. The project identification is performed through the study of Swiss Solar Prize awarded and submitted projects [Solar Agentur 2019], BIPV examples gathered by SUPSI in their website www.bipv.ch

[SUPSI 2019a] and BIPV examples gathered by the IEA PVPS Task 10 research project and presented in their website www.pvdatabase.org [IEA PVPS 2019]. Additionally, BIPV façade projects have been identified through web searching. Google is selected as a web search tool and the characters: *BIPV + façade* provide image results that have completed a study of the state-of-the-art of BIPV practice.

This process results in the identification of 208 BIPV façade projects that are analysed throughout this research's architectural approach (Chapter 4) and classified accordingly to the BIPV system's architectural features. Additional data such as location, year of completion and architect is provided on the lists, which can be consulted in Appendix A.4.2

The BIPV practice review has highlighted the small number of BIPV façades built in recent years. To illustrate this fact, the 2018's Swiss solar prize awarded the largest number of BIPV façade projects in the last ten years which was seven BIPV façade projects, representing 18% of the total awarded BIPV projects [Solar Agentur 2019].

A significant number of BIPV projects identified through the BIPV practice review has an unconvincing architectural expression. Many identified projects incorporate BIPV systems in a non-harmonious way with other building elements regarding format, colour or façade composition. Besides, the best-practice examples are rarely residential buildings, resulting in lack of BIPV architectural references to design and construct active residential façades. Some best-practice examples have been gathered and analysed through the study of the state of the art of the practice and can be consulted in Appendix A.4.3. The sample selection is based on the building's architectural quality – prizes and publications – and how the integration of the PV technology respects and enhances the general design concept of the project. This sample includes some projects in which the PV installation is enhanced and considered from the very beginning of the design phase instead of being hidden or camouflaged. It also provides an analysis of the different BIPV projects selected and identified as best-practice examples to better understand the design requirements of BIPV systems, which will be further developed in the present research project.

Despite the extent of BIPV research regarding BIPV products, performance and the above-mentioned BIPV design recommendations, the state-of-the-art references highlight the gap between BIPV research and practice. Taking that into consideration, it is assumed here that BIPV research, within an architectural approach, has the potential to generate efficient, affordable and harmonious architectural references, therefore fostering the integration of BIPV in current, contemporary architectural practices.

3.3. Synthesis

The research framework defines and delimits the field of research which is developed within the Swiss energy transition context. The themes covered by this thesis are manifold, including the building's energy efficiency requirements, the façade design potential to meet these requirements and the passive and active design strategies that can contribute to achieving this potential. Eventually, this research framework clarifies that the present doctoral thesis is focused on the façade design potential of collective residential buildings to contribute overcoming the gap between energy-efficient technologies and architecture, in the context of the energy transition.

To contribute to the energy transition of the building sector, façade design has to meet increasingly demanding energy efficiency requirements. In Switzerland, these requirements are established by the Swiss Energy Strategy 2050 and the 2000-Watt Society and integrated into Swiss energy standards: LEn, MoPEC and the norm SIA 2040:2017 [Volland *et al.* 2011; SFOE 2014; Suisse Energie 2015, 2018; SIA 2040 2017; AFCS 2018; EnDK 2018; OFEN 2018]. Ultimately, energy efficiency in buildings is promoted through subsidies and fiscal incentives, as well as best-practice and certification labels [OFEN 2017; Suisse Energie 2017; DGE 2018; Minergie 2019].

Existing research has highlighted that residential façades have a high potential to improve the building's energy efficiency by integrating passive and active energy strategies [Herzog *et al.* 2004; RIBA 2009; Boswell 2013; Ruggieri *et al.* 2013; Binz *et al.* 2014; Edenhofer *et al.* 2014; Zemella *et al.* 2014, 2014; Ihara *et al.* 2015].

Passive energy design strategies are constructional concepts that minimise the building's energy consumption, both operational and embodied [Zeng *et al.* 2017]. Within façade design, the former involves thermal losses and gains, air quality and daylight [Richarz *et al.* 2008]; and the latter involves the use of energy during the production and construction phase. Among passive operational energy design strategies, the improvement of thermal insulation has the greatest effect on the improvement of the building's energy efficiency [Ruggieri *et al.* 2013]. Passive embodied energy design strategies are based on low embodied impact façade design and construction. The most relevant low embodied impact construction principles involve lowering the energy consumption of the four phases of a building or a material life cycle: production, construction, operation and end-of-life.

Ultimately, among the passive energy design strategies, the following are highlighted due to their relevance in the energy-efficient façade design process:

- Improvement of the thermal insulation
- Use of natural and local construction materials
- Design for lightweight prefabrication
- Design for durability and flexible use
- Design for deconstruction, reuse and recycle.

Active energy design strategies are defined in the context of this research as façade designs that incorporate technical installations to generate on-site renewable energy. The study of state of the art highlights the potential of PV systems to provide buildings with on-site renewable energy [Jelle *et al.* 2012; Reijenga *et al.* 2012; Perlin 2013]. PV systems can be incorporated into buildings as *attached* elements (BAPV) or as *integrated* elements (BIPV). The latter generate electricity at the same time as they fulfil at least one architectural function of the building envelope.

Within the building envelope, façades have lower solar irradiation than roofs. Even though BIPV roofs generate a higher annual electrical output, BIPV façades have additional advantages regarding more homogeneous hourly and seasonal output and more available surface, especially in cities. Additionally, façade cladding materials are usually more expensive than roof cladding materials, which makes the replacement of expensive façade materials with BIPV more interesting from an economic point of view. Ultimately, as BIPV roof output is expected not to meet the increasing building energy efficiency targets, complementary BIPV façades are a potential solution to improve the building's energy performance towards the energy transition of the construction sector [Scognamiglio *et al.* 2014].

The study of the literature has also identified several BIPV integration barriers: the high cost of BIPV façades, the lack of knowledge and interest among architects, the lack of information adapted to designers and the poor aesthetics of BIPV solutions [Farkas *et al.* 2012b; Bonomo *et al.* 2015; Yang *et al.* 2015; Prieto *et al.* 2017]. Research is pushing forward to overcome these barriers resulting in drastic BIPV cost reductions [Biyik *et al.* 2017; SUPSI *et al.* 2017] and BIPV design guidelines [Munari Probst *et al.* 2007, 2012; 2019 Frontini *et al.* 2012; Reijenga *et al.* 2012]. In the context of this research, the most relevant BIPV façade design guidelines are:

- Incorporate the BIPV system as an integral part of the façade design and construction
- Incorporate the BIPV system in harmony with the rest of the building elements regarding colour, texture, and dimensional proportions
- Fit the BIPV system dimensions in the visual/structural grid of the façade composition
- Incorporate the BIPV system in harmony with the building's dimensions and morphology as well as with the building's urban context.

Existing research highlights the energy and design potential of BIPV façades, which contrasts with the limited number of examples that can be found in practice around the world. Indeed, the state of the art of BIPV practice has highlighted the small percentage of BIPV projects incorporating active façades and the unsufficient expressive quality of many of the existing ones.

Ultimately, this research framework brings to light the potential of façades to contribute to the building's energy efficiency by incorporating passive and active energy design strategies. Among these strategies, BIPV has a high unattained potential due to multiple barriers – poor aesthetics, high-cost perception and lack of knowledge – that define a gap between energy-efficient technologies and architecture.

Based on the study of the unattained energy-efficient façade potential, this doctoral thesis explores – through a research by design methodology – how the architectural design of collective residential façades can support the energy transition of the building sector. The core of this research aims at contributing to filling the gaps identified through the study of the state of the art of research and practice by fostering the evolution of current construction practices towards energy efficiency. To do so, the following chapters present the development of a new energy-efficient façade construction system, based on the study of existing architectural practices and incorporating energy efficiency systems and construction principles (Chapter 4). The energy and economic performance of this façade construction system are simulated to assess its potential to contribute to the energy transition (Chapter 5). Ultimately, the transfer potential towards professional practices is studied to evaluate if the research outcome can fill the gap regarding the integration of BIPV façades into architecture providing architecture professionals with assessed energy-efficient architectural references (Chapter 6). Each of the following steps of this current research work will contribute to bringing an answer to the research question.

4. Design approach

The research framework presented in Chapter 3 describes the prevailing energy optimisation requirements regarding building façades, within the energy transition context. This architectural demand can be fulfilled by integrating passive and active façade design strategies, which are low embodied impact construction principles and on-site energy generation systems, respectively. Among the latter, BIPV has been discussed to have a significant potential to provide buildings with renewable energy, but still not widely used within residential architectural practices.

Amid the different barriers preventing widespread use of BIPV technology, the unconvincing expression of existing solutions is identified as one of the principal, persisting obstacles (Chapter 3). An equilibrium must be achieved among different technical and aesthetic issues when integrating energy generation systems into the building envelope, especially into the façade for its public condition and exposure [Farkas *et al.* 2009]. This means that functional and structural façade features must be appropriately balanced with sustainable and aesthetic aspects without relegating any of these to the design background.

This chapter presents the first phase of the research methodology that takes an architectural design approach to tackle the expressive quality issue of BIPV façade application by incorporating BIPV technology into an energy-efficient façade design. To do so, the first step consists in analysing contemporary façade composition practices and construction requirements to determine what is the current architecture design context. Then, BIPV architectural features and construction requirements are analysed to determine how contemporary façade design practices can incorporate BIPV systems. These analyses determine the façade design potential to incorporate BIPV technology and set the base to develop a new façade construction system aiming at meeting energy efficiency targets from an architectural design perspective. Called Advanced Active Façade (AAF), this façade system provides a constructive solution along with a catalogue of building scenarios. This research output aims at generating a set of new architectural references to inspire energy-efficient façade design.

4.1. Workflow

The workflow of this research's phase: design approach, is structured in three steps: 1) the analysis step, 2) the design step, and 3) the implementation step. The outcome of these three steps is the AAF, also referred to as the design output, which serves as the base material for the quantitative assessment and can inspire energy-efficient architectural practices.

Step 1, the *Analysis* step (Section 4.2), consists of analysing contemporary collective residential façades and BIPV façades regarding design practices and construction requirements.

- The analysis of contemporary façade's designs practices aims at identifying façade design aspects that affect BIPV integration. This analysis is based on the identification of a representative sample of a contemporary collective residential building in the Swiss context and the analysis of the façade design. The latter highlights two façade design aspects: the façade composition and the façade morphology, which affect how and where BIPV is integrated into the façade.

- The analysis of contemporary façade's construction requirements aims at identifying construction principles that foster the building's energy efficiency along with the integration of BIPV systems. This analysis is based on the identification of passive energy strategies presented in Chapter 3 and develops on the construction principles that must be taken in energy-efficient façade design practices.

- The analysis of BIPV systems' design practices aims at identifying BIPV's design features that affect façade design. This analysis is based on the study of the state of the art of the practice. As a reminder, the latter is performed through the identification of a representative sample of BIPV façade projects within an international context and the analysis of several *Best-practice* examples, as introduced in Chapter 3 and presented in Appendix A.4.2 and A.4.3. This analysis identifies different BIPV system's visual and functional features, which affect its integration into collective residential building façades.

- The analysis of BIPV systems' construction requirements aims at identifying construction constraints that affect the façade construction and design. This analysis is based on the study of the BIPV system components, its maintenance and technical constraints resulting in several construction requirements that must be considered to optimise the BIPV façade's energy efficiency.

These four analyses provide the basis for developing the Advanced Active Façade (AAF), a new façade construction system with the potential of meeting the latest energy efficiency targets and fitting into contemporary architectural design currents.

Step 2: the *Design* step (Section 4.3) consists of defining a new façade construction system which combines passive and active energy design strategies integrating BIPV expressive and constructive issues towards meeting energy efficiency targets. This is the AAF, which intends to improve the building's energy efficiency through high insulation, low embodied impact construction and BIPV integration. The AAF aims at generating an energy efficiency façade constructive solution which is flexible enough to be incorporated into a large number of building design processes.

Step 3: the *Implementation* step (Section 4.4) consists of the integration of the AAF into an architectural design process in order to generate different building scenarios. To this end, a representative Swiss residential building design is identified and adapted to a plot located in a mid-dense area of the Swiss city of Lausanne. Different energy-efficient façades are designed based on the previously mentioned analysis output. This research process generates twelve AAF building scenarios, providing BIPV building architectural references.

Ultimately, the AAF construction system and the twelve building scenarios will serve as the base for the energy and economic efficiency assessment presented in Chapter 5 as well as its transfer potential assessment presented in Chapter 6.

4.2. Analysis

This section presents the different analysis of contemporary Swiss residential façades and BIPV façades regarding design practices and construction requirements. As a reminder, these analyses are performed to identify façade and BIPV design aspects that can affect BIPV integration into contemporary collective residential façades.

4.2.1 Contemporary collective residential façades

As highlighted within the Research framework (Chapter 3), façades are the building's largest component [Moussavi Nadoushani *et al.* 2017]. They are responsible for the appearance of buildings and their performances [Zemella *et al.* 2014]. Energy-efficient façade design can notably reduce buildings' operational and embodied energy and thereby their associated environmental impacts [RIBA 2009]. In that sense, we analyse here design practices and energy-efficient construction practices of contemporary collective façades.

4.2.1.1. Design practices

Façade design affects BIPV integration. For this reason, the state of the art of the contemporary residential façade design practice is analysed based on the identification of a representative sample of collective residential buildings, including 357 constructed projects.

This sample gathers buildings constructed since 2005, which defined a 10-year construction period at the beginning of this research (2015). This period has had an increasing number of constructed collective residential buildings every year, which represents 30% of the total building construction [OFS 2018].

To identify and analyse the building sample, the websites swiss-architects.ch and archdaily.com are taken as the primary source for data collection. Their search tool allows a pre-established criteria definition, which in this case limits the search to collective housing and apartment buildings constructed in Switzerland since 2005 [ArchDaily; DETAIL 2016; Swiss architects 2016].

This method allows the identification of 357 collective residential buildings constructed in Switzerland – enumerated and referred in Appendix A.4.1 – which are analysed to find façade design aspects that affect BIPV integration.

The contemporary façade design practice analysis identifies the façade composition and the façade morphology as two façade aspects that can affect BIPV façade integration. The façade composition promotes a façade classification based on its dimensional composition. The façade morphology promotes a façade classification based on its shape. These analyses aim at defining and classifying the contemporary façade composition practices where BIPV can be incorporated.

Façade composition

The analysis process highlights that residential façades have predominant and similar dimensions regarding their design composition. The coinciding dimensions usually relate to structural building elements or standardised façade accessories. These are the building's load-bearing structure, horizontal slabs, storeys height, balustrades, or standard-sized windows [Herzog *et al.*

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1.DWELLING IN MEILEN
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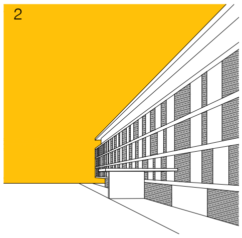

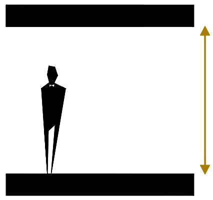

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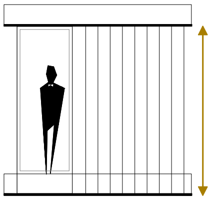
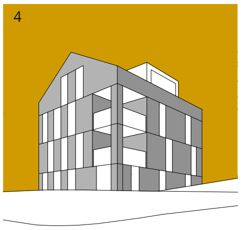

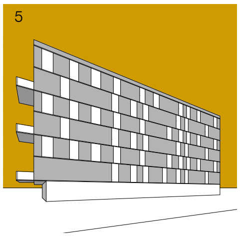

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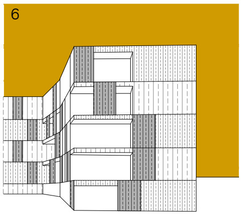

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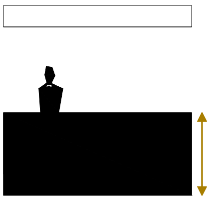
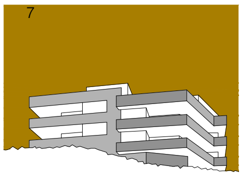

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8.DWELLING IN BASEL
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9.DWELLING IN MEGGEN
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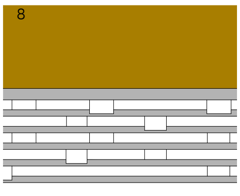

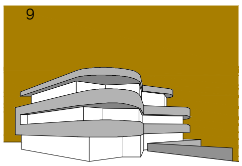

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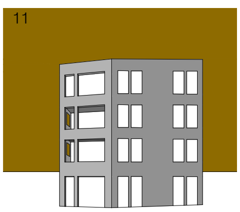

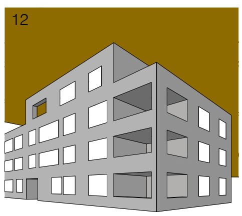

2004]. The coinciding element dimensions establish a classification regarding façade dimensional features that can be a basis to incorporate BIPV into façade design practices as a construction material.

The dimension of the different façade elements determines the subjacent rhythm of the façade composition. In 81% of the research sample buildings, the façade composition rhythm follows the pre-existing building structure rhythm: horizontal slabs, beams, pillars, and walls. In this case, the building construction can be directly comprehended from the façade composition. However, there is a notable percentage of façade projects (19% of the research sample) where façade composition establishes an independent rhythm from the building structure, hiding the structural loadbearing logic.

The contemporary façade composition analysis brings out four different composition practices based on the dimensional arrangement of the façade components. The identified façade composition practices are considered main categories, although this classification does not pretend to be exhaustive. They are represented in Figure 4.1 and described as follows:

Slab to Slab

This first composition practice refers to the predominant dimension of the façade, which corresponds to the clearance height between horizontal slabs. Within this group, horizontal lines defined by the slab thickness are the main façade design features. There are usually material and colour variations between horizontal profiles and façade cladding.

Although Swiss norms require a minimum of 240 cm clearance height inside residential apartments [*RLATC*, 1987, art. 27], current architectural common practices set an unofficial standard of a 250 cm free height between floor and ceiling for comfort reasons [Interview with I. Dahl Rocha, 2017].

Façades classified in this group can integrate a 250 cm high unique façade element or small format panels that fit into this dimension. This façade element can be defined by BIPV panels of 250 cm or smaller sizes fitting in this dimension.

The *Slab to Slab* composition practice is the most common among the contemporary residential façades of the Swiss building research sample. It is identified in 37% of the analysed buildings.

Total Storey

This second composition practice also involves horizontal slabs, but these latter are no longer fully expressed on the exterior façade. There is rather a reference to their positions in the form of thin profile, linear cleavage, or façade cladding modulation.

The predominant dimension of this composition includes the interior clearance height between floors plus the slab thickness, displaying the floor-to-floor dimension. According to Swiss common practice, this dimension is 285 cm. As indicated for the *Slab-to slab* group, BIPV façade elements can be adapted to the 285 cm dimension to be incorporated into this group of façades.

The *Total Storey* composition practice is less common than the other identified composition practices among the analysed façades of the

Figure 4.1
Classification of the contemporary residential façade composition strategies in Switzerland.

Complete references in Appendix A.4.1

Source: swiss-architects.ch and arch-daily.com

Swiss building research sample. It is identified in 11% of the analysed buildings.

Balustrade

This third identified composition practice gathers all the façade designs where the balustrades are displayed predominantly on the façade.

Balustrade height is regulated by Swiss norms to 100 cm [SIA 2010] and is measured from the upper layer of the terrace pavement. However, there are two main possibilities regarding the final balustrade dimension. In the case of a balustrade that does not cover the floor slab, it must have a minimum height of 100 cm. In the case of a balustrade dimension integrating the horizontal slab, the predominant dimension is 135 cm. These two dimensions can guide the production and integration of BIPV systems as façade balustrades.

The *Balustrade* strategy is identified in 33% of the case studies analysed in the Swiss buildings research sample.

Total Volume

This fourth composition practice involves the façades where the structured rhythm is entirely hidden by the building skin. In this case, the building is perceived as an object or as a volume where holes are designed to connect interior and exterior spaces. There is no determined predominant dimension within the façade composition. This suggests that different BIPV panel sizes can fit into this façade composition strategy, although, in most of the cases, personalised sizes might be required if BIPV is not incorporated into an early stage of the façade design process.

The *Total Volume* strategy is identified in 19% of the case studies analysed in the Swiss buildings research sample.

Even though four distinct façade composition practices are identified, building design can combine them. Indeed, some buildings of the research sample analysed here present a combination of the previously described façade composition practices. In these situations, the building is classified according to the predominant strategy.

This four-group classification referring to façade dimensional composition can certainly find its usefulness for BIPV producers. Indeed, this type of classification can guide the BIPV production sector to find BIPV standardisable measures, adapted to façade composition common practices. This does not mean that BIPV modules must have the exact above-mentioned dimensions, but that BIPV modules should be compatible with these measures.

BIPV panels are considered a construction material [EN 50583-1 2016]. Hence, they must comply with regular construction dimensional co-ordination requirements and standards of construction practices as established in *Dimensional co-ordination in the building: current trends and policies in ECE countries.* [United Nations 1974]: Buildings usually consist of a multitude of individual components, most of which are incorporated at different times and produced and erected by different companies. *We, therefore, need overriding geometrical rules to enable the construction of a flawless whole. Such a form of 'grammar' covers the overall building technology context of the (building-related)* *subsystems of loadbearing structure, façade, internal fitting-out and services, and is generally known as dimensional coordination* [Herzog *et al.* 2004].

This Swiss residential façade composition analysis results in a non-exhaustive façade classification based on dimensional composition practices. This original classification highlights the contemporary façade design potential to incorporate BIPV as part of the façade composition. It clarifies both the dimensions towards standardisable BIPV panel and the potential share of application into residential façades.

Façade morphology

A recurrent pattern of building shapes, which directly affects the façade morphology, is found throughout the analysis of the contemporary residential façade design practices. The identified façade morphologies relate to the design of the exterior spaces on the different building floors, that is to say, façades with no exterior spaces, with exterior spaces designed as balconies and with exterior spaces designed as loggias (Figure 4.2).

The analysis results in the identification and classification of three different façade morphologies. The latter is the basis to determine where BIPV can be integrated to avoid casted shadows of the façade's variable morphology.

At the same time, the building's façade morphology is directly related with the building's compactness, measured through the building's shape factor which is defined as the ratio of the building's envelope surface (A_{th}) to the building's Energy Reference Area (ERA). The building compactness can significantly affect the energy efficiency of a building at the design stage, because the larger the envelope surface is, the larger the energy losses through it are [Richarz *et al.* 2008].

Figure 4.2 represents the three façade morphologies identified through the contemporary façade design analysis. They are called and described as follows:

Clean volume

The first façade morphology is the one that has no protruding elements on the different storeys. It defines the building as a clean volume outlined by its thermal envelope. The study of the Swiss building sample highlights that this is the least common façade morphology among contemporary collective residential façade design practices. The *Clean volume* façade morphology represents 9% of the analysed buildings. This façade morphology is mostly found in urban renewal projects in high-dense urban contexts (Appendix A.4.1).

Regarding BIPV integration in buildings with a *Clean volume* façade morphology, panels can be integrated into any surface of the building envelope, as shown in Figure 4.2. This is possible because no elements are protruding from the façade and potentially casting shadows over active façade surfaces.

Balconies

The second façade morphology incorporates balconies protruding from the building's thermal envelope. Balconies do not affect the building's heat loss if the thermal bridges are avoided. However, balconies can lower heat gains and interior daylight intensity because they limit the façade surface irradiation. The *Balconies* façade

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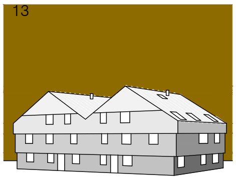

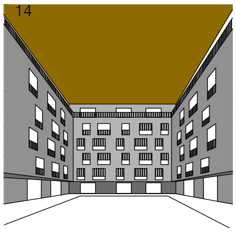

13.DWELLING IN LAUSANNE
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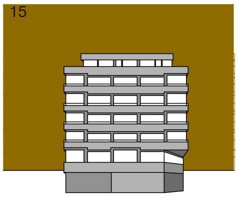
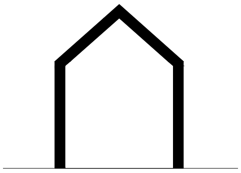
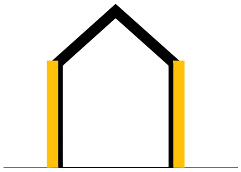
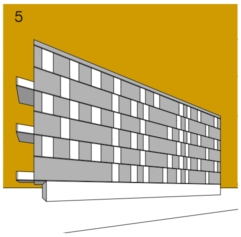
2013
15.DWELLING IN LUZERN
2011

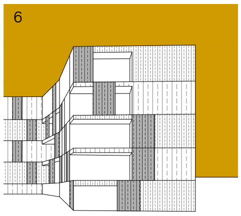






B A L C O N I E S





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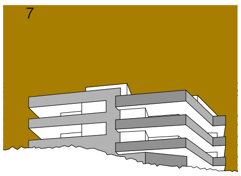
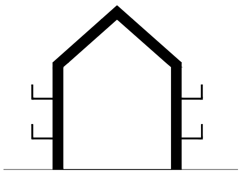
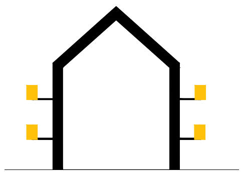
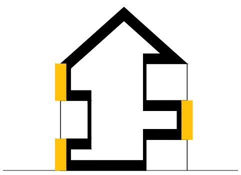
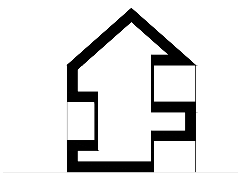




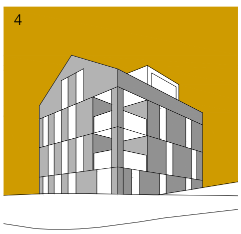


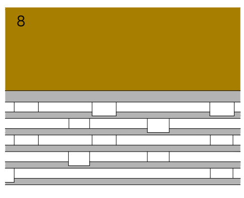
L O G G I A S





3.DWELLING IN ZURICH
2011
4.DWELLING IN MEGGEN
2012
8.DWELLING IN BASEL
2009





morphology is found to be the most abundant among the analysed Swiss residential building sample, representing 64% of the analysed collective residential building façades (Appendix A.4.1).

Regarding BIPV integration in buildings with a *Balconies* façade morphology, panels should be integrated into the outermost surface of the building envelope, which is mainly into the protruding elements to avoid casted shadows over active surfaces (Figure 4.2).

Loggias

The third façade morphology defines outdoor spaces by designing loggias on the different storeys. Loggias increase the thermal envelope's surface because they define an exterior space as a hollow in the building envelope. By consequence, this means that thermal losses may increase compared to the *Clean volume* and *Balconies* façade morphologies due to the lower building compactness. The *Loggias* façade morphology represents 28% of the analysed buildings (Appendix A.4.1).

Regarding BIPV integration in buildings with the *Loggias* façade morphology, panels must be integrated into the outermost surface of the building envelope. This means that the walls of the loggias must not integrate active surfaces because they are not fully irradiated and can have constant casted shadows (Figure 4.2).

The analysis of contemporary façade design practices regarding façade composition and façade morphology can define the integration potential of BIPV from a dimensional coordination and building shape perspective. However, façade construction requirements must be analysed to determine how BIPV integration potential can be formalised in a façade construction system.

4.2.1.2. Energy-efficient construction practice

The construction requirements of a façade include several considerations: mechanical resistance, stability, safety in case of fire, hygiene, health, safety, accessibility in use, protection against noise, energy economy, sustainable use of natural resources and energy efficiency. This section focuses specifically on the latter, as presented in Chapter 3 [EU 305/2011 2011], analysing energy-efficient façade construction principles. Among the latter embodied environmental impacts reduction is further developed in the following paragraphs, regarding residential building construction in Switzerland. In that regard, this analysis defines energy-efficient architectural recommendations, serving as a framework where BIPV systems can be incorporated.

The façade's embodied energy is a major aspect regarding energy efficiency and it is directly affected by the façade design and construction. Section 3.2.2.1 has introduced the main low embodied impact façade construction principles, which greatly vary depending on the available energy resources and local materials [Pomponi *et al.* 2018]. This section defines specific materials and construction strategies to lower the embodied energy of an energy-efficient façade among Swiss collective residential construction practices:

- The use of **natural and local** materials can significantly lower the embodied impact of a façade. For its availability in Switzerland and the sustainable forest exploitation practices, timber is considered as

Figure 4.2
Façade morphology schemes and corresponding BIPV integration.

Complete references in Appendix A.4.1

Source: swiss-architects.ch and arch-daily.com an adequate material for the construction of the façade substructure [Kuittinen *et al.* 2013; FOEN 2015].

Timber is a natural material with lower embodied carbon than other construction materials. It also has the benefit of carbon sequestration[1] during tree growth. This means that timber structures are providing physical storage of carbon that would otherwise be emitted back into the atmosphere [Cheung *et al.* 2015; Bull 2016].

Buildings in Switzerland must be highly insulated to comply with building energy norms and recommendations [SIA 180 2014; SIA 2040 2017]. The significant thickness of the façade's insulating layer involves a notable embodied impact that can vary depending on the insulating material. When comparing insulation's embodied energy values, the needed thickness of insulation to attain a determined thermal performance must be considered. Table 4.1 illustrates this and shows how the embodied energy of the insulators cannot be compared directly without acknowledging their particular thermal conductivity value.

The most common natural insulators in low-carbon building constructions are wood-fibre and cellulose. Other less common natural insulators include cork, sheep's wool, flax, and hemp. Wood-fibre insulators are made from wood chips compressed into boards using water or natural resins as a binder. They have a low embodied energy and can be used in breathing wall construction. Because of its good performance regarding non-renewable primary energy (NRPE), global warming potential (GWP), and thermal conductivity (λ), blown cellulose can be notably recommended to design an energy-efficient façade.

Cellulose insulators are recycled products made from newsprint and other cellulose fibres. They are available in a loose format, to be poured or sprayed, and in a board format. They usually include additives to provide fire resistance and to repel insects and fungi [Gray 2019].

There are three main disadvantages of natural insulation compared to synthetic insulation. The first one is the cost, as natural insulation materials are currently up to four times more expensive than conventional materials [Gray 2016]. The second one is the space requirements, which depends on the material's thermal conductivity.

1
It is the long-term storage of carbon in plants, soils, geologic formations, and the ocean. Carbon sequestration occurs both naturally and as a result of anthropogenic activities and typically refers to the storage of carbon that has the immediate potential to become carbon dioxide gas [Encyclopaedia Britannica].

MAIN INSULATION MATERIALS	NRPE kWh/kg	GWP kg CO2-eq/kg	λ W/mK
Extruded polystyrene	29,1	14,5	0,03
Polyurethane	30,2	7,52	0,025
Expanded polystyrene	29,8	7,64	0,04
Glass wool	7,75	1,13	0,036
Stone wool	4,33	1,13	0,038
Wood fiber	3,53	0,66	0,038
Blown cellulose	1,03	0,25	0,038

Table 4.1
Conductivity and pollutant loadings of the main insulation materials.

Source: Design-Builder data base and [KBOB 2016]

Natural insulation usually needs more thickness to reach the same thermal performance of the most common synthetic insulators: expanded or extruded polystyrene [Hegger *et al.* 2006]. The third one is the higher sensitivity to the moisture of natural insulators, which can accelerate the material's degradation [Korjenic *et al.* 2011].

- The use of **fewer** materials entails fewer embodied environmental impacts. When applied to façade design and construction, this principle promotes the study of façade physics to optimise the size of the different substructure elements. In line with this objective, the use of materials that can fulfil several façade requirements at the same time can reduce the amount and weight of construction materials. As an example, the use of OSB 3 panels with sealed joints can spare the incorporation of a windproof membrane or a vapour barrier.

- Similarly, the use of **lighter** construction materials requires smaller loadbearing elements. Regarding the use of timber and cellulose, the study of a **panel-based substructure** replacing a regular timber-frame substructure can entail the use of a smaller amount of substructure material.

- Following previous recommendations (Chapter 3), timber façades can be **prefabricated** in variable dimension modules that are assembled in the factory, transported and installed in the building site. The module dimensions depend on the building location and the specific façade design.

- To foster the **reuse of façade components**, the façade must be designed with a deconstruction plan. This involves maximising the use of mechanical and reversible connections rather than adhesive ones to separate façade construction materials with minimal material damage [Eco-innovation action plan 2011; Akinade *et al.* 2017; Eckelman *et al.* 2018]. In that order, it is recommended to use volts over silicon and welds to foster the reusability of the different façade components.

- The use of **recycled and recyclable** materials also play a role in low embodied impact façade. Natural materials such as wood are widespread recycled and cellulose is itself a recycled material. Regarding the recyclability of BIPV panels, after 30 years of the installation, the different layers of a BIPV module can be separated, and the middle layer of Silicon can be reinserted in the production line [Futura Sciences *et al.* 2017]. Ultimately, 96% of old BIPV panel materials can be reused to produce new BIPV panels; the remaining non-recyclable materials are mainly the cell encapsulants (EVA) [Sykorova *et al.* 2019] (Section 3.2.2.1).

Regarding operational passive energy strategies, energy-efficient construction practices in Switzerland require a specific minimum thermal transmittance value (U), which is related to the thermal conductivity (λ) of each material composing the façade. The insulation layer affects in a significant manner the façade's final thermal transmittance value due to the low thermal conductivity of insulation materials, as shown in Table 4.1. Swiss norms establish a minimum opaque façade's thermal transmittance value of 0.15 W/m^{2}K [SIA 380/1 2009]. To achieve energy-efficient façade, it appears appropriate to follow the most exigent Swiss best practice recommendation, label *Minergie P*, which requires a final façade transmittance value (U) for opaque façades of 0.10 W/m^{2}K [Minergie 2019].

The analysis of the above-described energy-efficient construction recommendations regarding energy efficiency highlights that BIPV systems should be integrated into prefabricated façade construction systems that use natural and local materials such as timber and cellulose and are designed to be disassembled and recycled minimising material use and waste.

To sum up this section, the contemporary façade analysis allows defining in a precise and contextualised manner the design framework and construction conditions where BIPV systems can be optimally integrated. However, it is worth noting that BIPV systems can fulfil different façade requirements depending on their specific architectural features, which all at once make its use more complex and richer. This aspect is analysed in the following section.

4.2.2 BIPV façades

Research is rapidly pushing forward the PV industry, which results in a growing number of different PV technologies and BIPV systems. PV technology performance has dramatically improved over the past five years and is expected to improve faster as science advances [Jelle *et al.* 2012; Jelle 2016].

The incorporation of BIPV systems can notably improve the building's energy efficiency [Edenhofer *et al.* 2014]. However, BIPV affects the façade design through its particular architectural features as well as its specific construction requirements. These elements are here analysed to identify what are the BIPV aspects that affect its incorporation in façades.

4.2.2.1. Architectural features

BIPV systems designed for façade application are mostly glass-glass modules (Section 3.2.2.1) and are generally classified according to their PV technology and performances. However, the façade being the protective envelope of the building, it needs to meet some requirements such as thermal insulation, weather protection, ventilation regulation, and sunlight control [Herzog *et al.* 2004]. BIPV systems can play an essential role by fulfilling one or more of these façade requirements [Roberts *et al.* 2009]. In line with this, some researches classify BIPV within an architectural approach.

The authors of the SUNRISE research project [Montoro *et al.* 2011] have classified BIPV systems *based on the function, the materials, and their mechanical characteristics*. In this case, BIPV systems are divided into five groups as follows: 1) standard in-roof systems, 2) semi-transparent systems, 3) cladding systems, 4) solar tiles and shingles, and 5) flexible laminates. In another study, Jelle et al. classified market-ready BIPV products according to PV element function into the following categories: 1) photovoltaic foils, 2) photovoltaic tiles, 3) photovoltaic modules, and 4) solar cell glazing [Jelle *et al.* 2012]. On his side, Attoye's research focuses exclusively on BIPV façades and classifies BIPV systems according to façade types, defining four groups: 1) curtain wall/ cladding systems, 2) solar glazing and windows, 3) external devices/ accessories, and 4) advanced / innovative envelope systems [Attoye *et al.* 2017]. These façade classifications are mostly based on the study of BIPV products and directly refer to particular building envelope's elements or specific BIPV products.

In an attempt to find a façade design-oriented BIPV system classification that maximises the façade design flexibility, this research has analysed 208 BIPV façade projects constructed worldwide. These projects are identified through the study of the state of the art of the BIPV practice introduced in Chapter 3 and presented in Appendix A.4.2 [IEA PVPS Task 10 2015; PV Upscale *et al.* 2015; SUPSI 2019].

The analysis of the BIPV design features of these projects results in the identification of two BIPV architectural features that affect how BIPV systems are incorporated into façades. These features are the BIPV's visual features (Figure 4.3) and the BIPV's functional features (Figure 4.4). Among the former, the BIPV systems light-permeability is highlighted as a feature affecting the way BIPV systems are integrated into a façade. Among the latter, the functional architectural features refer to the function that the BIPV system has as an integral part of the façade.

Based on BIPV systems' visual features, this research proposes BIPV system classification in three groups: a) Opaque BIPV systems, b) Translucent BIPV systems, and c) Transparent BIPV systems. This classification is directly related to the BIPV's façade architectural functions, which are: cladding functions, solar control functions, protection functions and glazing functions. These functional features can be fulfilled by the different opaque, translucent or transparent BIPV systems accordingly.

BIPV's visual architectural features

Opaque BIPV systems

They consist of opaque surfaces that are not light nor sight permeable. They include technologies such as Monocrystalline, Polycrystalline, Thin-Film, Perovskite, and Heterojunction with Intrinsic Thin layer(HIT) solar cells. Market-ready opaque BIPV systems can reach up to 24.4% efficiency [Green *et al.* 2018].

These BIPV systems can be installed as a regular façade cladding to protect the thermal insulation and building from the weather and general exterior agents such as noise or humidity. They can be part of a curtain wall façade design or a regular ventilated façade.

Opaque BIPV systems can also be integrated into façades as external devices or accessories, such as louvres, sunshades, parapets, spandrels or elements of visual and acoustic shielding [Attoye *et al.* 2017]. These elements can help the building to reduce its energy needs [Montoro *et al.* 2011].

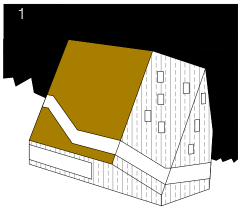
Opaque technology presents a high visual exposure when integrated into façades, impacting the building's architectural expression. For this reason, an additional effort is required when designing a façade with publicly exposed BIPV.

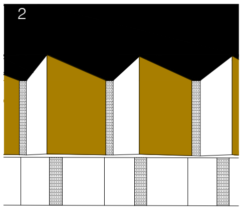
BIPV opaque modules are usually composed of two layers of tempered glass enclosing the PV cells between encapsulants and interlayers. This is what is called a glass-glass BIPV module. The back-layer can be made of another material such as aluminium. However, using different materials for constructing a BIPV module can generate problems due to the different coefficients of expansion of both materials when the module temperature increases.

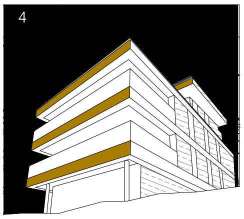
As previously discussed, recent transformative BIPV developments integrate different texture and colour filters into its composition,

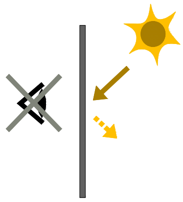
O P A Q U E

1. MONTEROSA HUT, ZERMATT
2009
2. NURSERY IN MARBURG
2013
3. MIXED BUILDING, MUNICH
2004
4. DWELLING IN WIL
2011

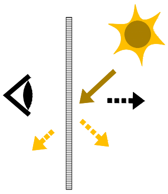


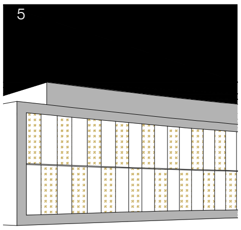


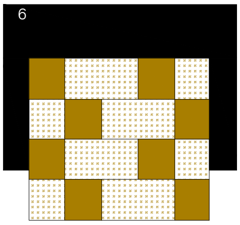




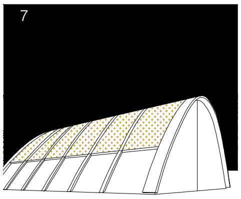
T R A N S L U C E N T

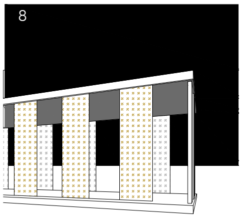






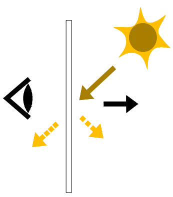
5. AGC CENTER, CHARLEROI
2014
6. CUSTOMER SERVICE CENTER,KONSTANZ
2011
7. FIRE DEPARTMENT, HOUTEN
2000
8. PV PAVILLION,POSTDAM
2011

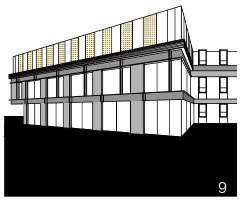


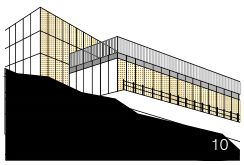


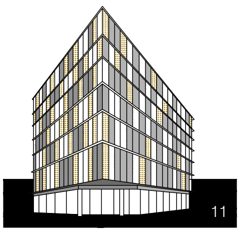
T R A N S P A R E N T

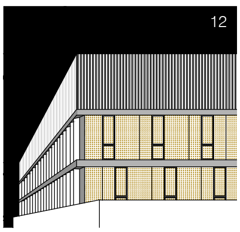
9. BIDWELL HOUSE, CAMBRIDGE
2018
10. AZURMENDI RESTAURANT, LARRABETZU
2014
11. ICSE, LAS PALMAS
2015
12. BRUNEL UNIVERSITY, LONDON
2016











providing architects with a broader spectrum of active façade possibilities [Söderström 2018].

Translucent BIPV systems

They are semi-opaque or translucent surfaces, which allow a filtered view through it and are permeable to light. They include Monocrystalline, Polycrystalline, Thin-Film, and Perovskite solar cells. The efficiency of these systems varies depending on the cell spacing or photovoltaic material density. As a general rule, the more transparent, the less performant [Interview with G. Cattaneo, 2018]. That said, the performance depends mainly on PV technology (Section 3.2.2.1). For instance, Monocrystalline translucent BIPV panels have an efficiency of around 12% for a 30% translucency. Thin-Film BIPV panel efficiency is around 5% for a 10% translucency [Jelle 2016].

Translucent BIPV panels are glass-glass based modules that can be used for solar control purposes and can be integrated into windows or glazing panels. They can also be part of a wind protection system in balconies or loggias. The cell spacing or pattern can be designed to match the particular requirements of the interior space. For example, the cells spacing can determine the interior space lighting, and the cells pattern can modify the interior space perception [Chamilothori *et al.* 2016].

Technically, the translucent quality can be achieved through cell spacing, cells thinning, or cells laser-grooving. Depending on these techniques, the translucent BIPV surface will have different appearances regarding homogeneity. While cells spacing can generate interesting patterns, cells thinning and regular cells laser-grooving can produce translucent and homogeneous active surfaces.

Transparent BIPV systems

They are glass-glass PV panel with transparent PV cells that are light-permeable and sight-permeable. They include technologies such as Thin-Film or Dye-Sensitized Solar Cells (DSSC). The first market available BIPV transparent technology was Thin-Film. Today, the average efficiency of these systems is 2.8%, depending on the degree of transparency [Onyx Solar 2019]. This technology is expected to achieve a 5% efficiency in five years, according to BIPV producers [Interview with P.O. Couche, 2016].

Transparent BIPV systems comply with window requirements and other required see-through surfaces. The high level of transparency is achieved by an intense laser-grooving of traditional PV technologies such as Thin-Film [Interview with P.O. Couche, 2016].

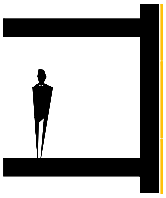
Transparent BIPV research is advancing at a fast pace due to the potential of BIPV being integrated into glazed façades [Husain *et al.* 2018]. At the moment, 80% of the transparent PV solutions are still at a research or pre-commercialization stage. The degree of transparency goes against maximising sunlight absorption by the PV material. For this reason, the development of transparent BIPV systems is driven by the balance between performance and transparency. The most performing transparency achieved for transparent BIPV panels is close to 80% [Skandalos *et al.* 2015; Husain *et al.* 2018].

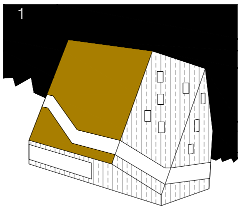
Figure 4.3
Classification of existing BIPV systems, regarding its architectural visual features and corresponding existing building examples.

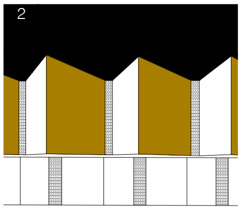
Complete references in Appendix A.4.2

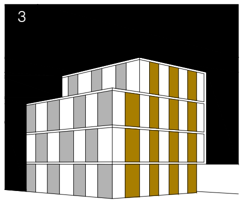
Souce: pvdatabase, bipv.ch, Onyx solar

FAÇADE CLADDING



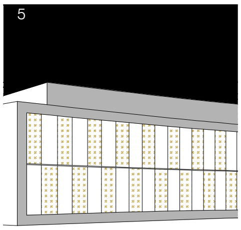


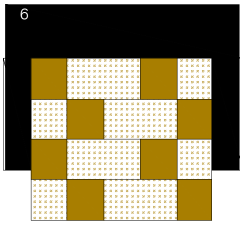


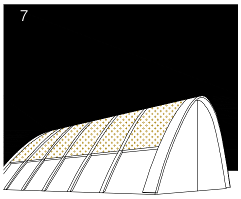


1. MONTEROSA HUT, ZERMATT
2009
2. NURSERY IN MARBURG
2013
3. MIXED BUILDING, MUNICH
2004

SOLAR CONTROL







5.AGC CENTER, CHARLEROI
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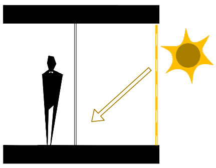
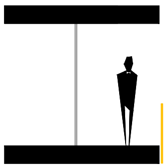
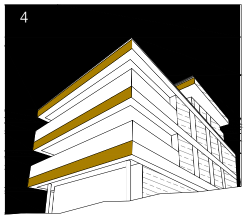
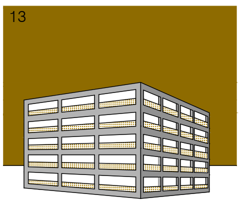
6.CUSTOMER SERVICE
CENTER,KONSTANZ
2011
7.FIRE DEPARTMENT, HOUTEN
2000

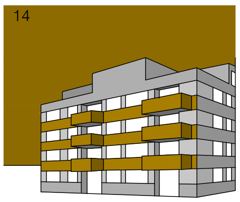


FAÇADE SECURITY

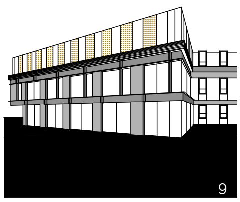




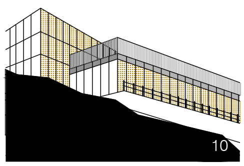


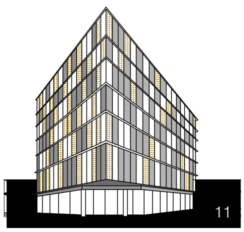


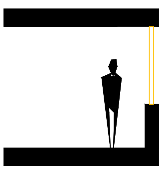
4. DWELLING IN WIL
2011
13. STI MICROELECTRONICS,
GRENOBLE
2001
14. DWELLING IN EINSIEDELN
2012



FAÇADE GLAZING







9. BIDWELL HOUSE, CAMBRIDGE
2018
10. AZURMENDI RESTAURANT,
LARRABETZU
2014
11. ICSE, LAS PALMAS
2015

BIPV's functional architectural features

Light-permeability features determine the architectural function of the BIPV element of the façade. Based on existing BIPV classifications [Montoro *et al.* 2011; Attoye *et al.* 2017] and the above-presented newly developed BIPV classification according to visual features, BIPV systems can be integrated according to the following functional features: façade cladding, solar control, façade security and façade glazing. These façade functions affect how BIPV systems can be integrated into residential building façades (Figure 4.4):

Façade cladding

The façade cladding notably affects the functional and aesthetic façade features. The façade cladding is a filter, a physical limit that defines how the building interacts with its context and protects the façade substructure and the interior of the building. The most relevant function of the façade cladding is to create an effective water barrier and to generate the air space needed to improve the façade's thermal performance [de Sousa Camposinhos 2014]. Furthermore, the façade cladding has a strong impact on the image of the general building perception [Attoye *et al.* 2017].

Opaque BIPV elements can fulfil façade cladding functions protecting the façade substructure and the façade insulation layer from exterior agents, as well as generating a ventilated air cavity required for the rear-ventilation of BIPV panels and for improving the thermal performance of the façade substructure.

Solar control

An optimal daylight level is achieved through proper façade design [Zemella *et al.* 2014]. Façades have the function of controlling indoor solar radiation by minimising glare and undesired energy loads in interior spaces [Konis *et al.* 2017].

Translucent BIPV panels can fulfil the function of interior daylight-regulation and solar control functions if they are integrated into the building envelope as additional façade components. Translucent solar control devices may partially obstruct the views but have the potential of optimising the building's energy efficiency [Attoye *et al.* 2017].

Façade security

Façades integrate protective elements to prevent people from falling from the buildings. These are the railings or balustrades of balconies and loggias, which guarantee the security of the building occupants [SIA 358 2010].

Railings and balustrades have a security function that can be fulfilled by opaque, translucent or transparent BIPV systems. The different degree of light permeability of the balustrade affects the privacy of the balconies or loggias as well as the total amount of daylight in the interior spaces adjacent to the balcony or loggia.

Façade glazing

Façade glazing is, in general, integrated into windows to provide the interior spaces with daylight and views. Façade glazing is generally

Figure 4.4
Classification of existing BIPV systems, regarding its architectural functional features.

Complete references in Appendix A.4.2

Souce: pvdatabase, bipv.ch, Onyx solar

integrated into the form of insulating transparent glazing to minimise energy losses [Herzog *et al.* 2004]. BIPV transparent glazing can replace regular one, fulfilling the façade glazing function and providing the building with the required daylight while generating renewable energy.

The analysis of the BIPV façade design practices regarding BIPV's visual and functional features allows classifying the different existing BIPV systems. This classification reveals that the visual features of BIPV systems directly affect the different functions they can fulfil as an integral part of the façade design and construction. In order to better define the constructive solution of a BIPV façade, its construction requirements are analysed and presented in the following section.

4.2.2.2. Construction requirements

By definition, BIPV elements are integrated as a construction product in the architectural design and the construction process. As every construction product, BIPV is regulated by European standards to ensure the compliance of minimum requirements (Section 3.2.2.1). At building façade scale, BIPV needs to satisfy a range of other architectural requirements and considerations for an optimal technical and aesthetic performance of the active façade.

Regulations

Published in 2016, the norm EN 50583-1: *Photovoltaics in buildings – Part 1: BIPV modules* defines BIPV elements as construction products *[EN 50583-1 2016]*. The document is addressed to manufacturers, planners, system designers, installers, testing institutes and building authorities. It regulates all construction issues regarding BIPV. First, it coordinates general requirements resulting from the Low voltage directive and the Construction Products Directive of the European Union. Second, it regulates the requirements resulting from the panel material itself, which is frequently a glass panel. Ultimately, the norm refers and deals with the requirements resulting from panel mounting location within the building.

As electrical components, BIPV products must comply with the Low Voltage Directive 2014/35/EU [EU 2014], whose main requirements are:

- Protection against hazards arising from the electrical equipment;
- Protection against hazards that may be caused by external influences of the electrical equipment.

As construction products, BIPV modules are regulated by the European Construction Product Regulation (CPR) [EU 305/2011 2011]. The latter stipulates seven essential requirements for construction products:

- Mechanical resistance and stability
- Safety in case of fire
- Hygiene, health and the environment
- Safety and accessibility in use
- Protection against noise

- Energy economy and heat retention
- Sustainable use of natural resources

Both the BIPV norm EN 5058-1 and the CPR are mainly focused on the production of BIPV panels and systems. They regulate their conformity with European construction standards *[EN 50583-1 2016]*. Table 4.2 gathers a summary of the general European requirements and construction product legislation that BIPV products must meet [EN 50583-1 2016].

Façade construction requirements

BIPV systems are composed of three main components: the BIPV panels, the Balance of System (BOS) and the façade fastening system [Yoo *et al.* 1998]. The design and arrangement of these components must be part of the early façade design process for an optimal result regarding technical and expressive issues [Munari Probst *et al.* 2012a].

The main components of BIPV systems are the BIPV panels. As mentioned above, they can fulfil different architectural façade functions as façade cladding, solar control, security or glazing. In addition, they affect particular aesthetic aspects when defining the façade's texture, colour and layout [Munari Probst *et al.* 2012a].

As explained in Section 3.2.2.1, BIPV panels can be composed of different material layers. However, façade BIPV systems usually integrate glass-glass modules as a construction product [Interview with G. Cattaneo, 2018]. Owing to their fragile nature, they have to be integrated into façade surfaces with a low risk of impact or vandalism [Munari Probst *et al.* 2012a].

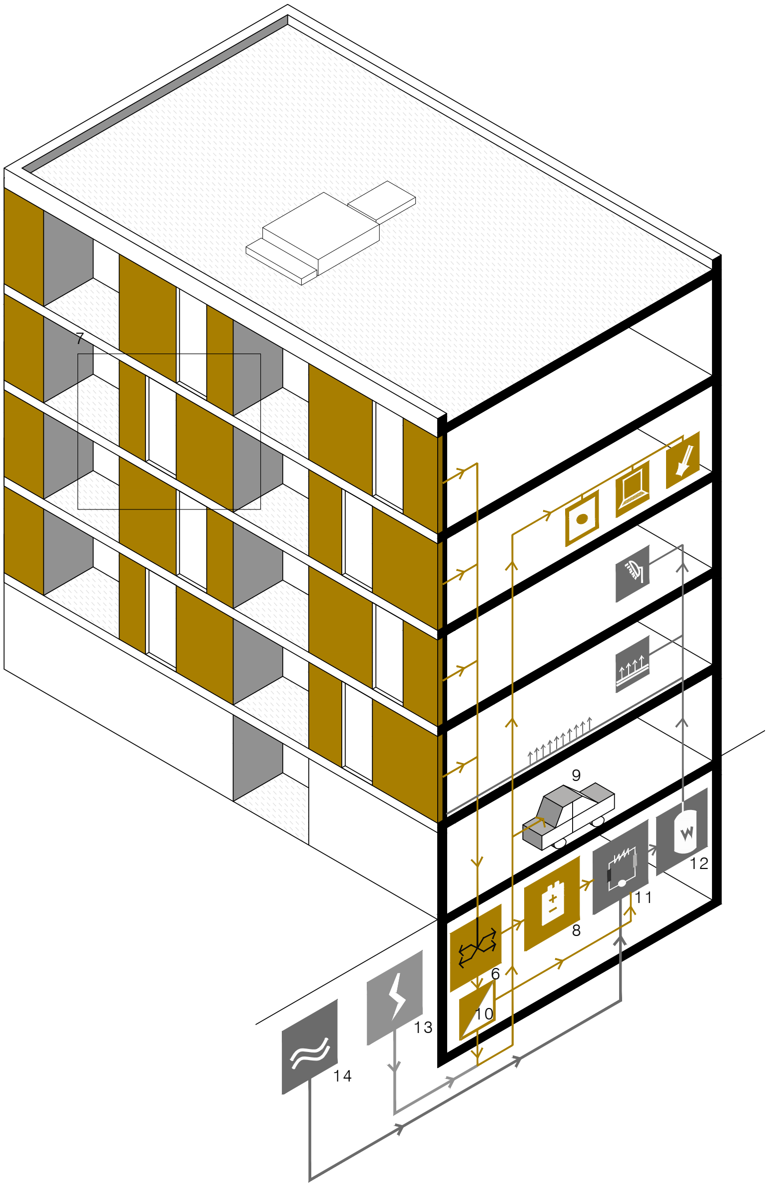
BIPV modules can rapidly increase in temperature when fully irradiated, which leads to a decrease in their electrical output [SUPSI 2019]. Optimal ventilation allows minimising the performance losses due to panel overheating, especially for crystalline-cell-based BIPV panels [Jelle 2016]. This requirement is met when BIPV is incorporated as balustrade, glazing or solar control elements and promotes a ventilated façade design when incorporating BIPV as façade cladding [SUPSI 2019].

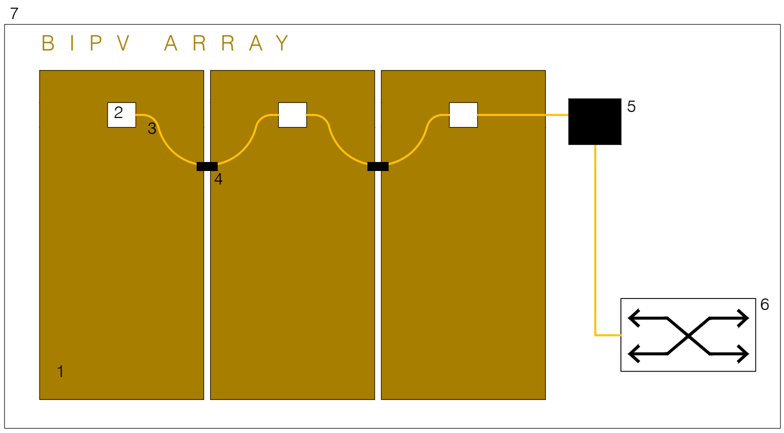
Table 4.2
BIPV General Requirements for all categories of BIPV modules containing glass panes integrated into façades.

Source: [EN 50583-1 2016]

BIPV FAÇADE GENERAL EUROPEAN REQUIREMENTS

CPR REQUIREMENT	STANDARDS, GUIDELINES	COMMENT
1. MECHANICAL RESISTANCE AND STABILITY	A.2	DEPENDING ON APPLICATION AND NATIONAL REQUIREMENTS
2. SAFETY IN CASE OF FIRE	EN 13501-1 EN 13501-2	STANDARD CLASSIFICATION MANUFACTURER TO DECLARE THE FIRE RATING
3. HYGIENE HEALTH AND ENVIRONMENT		AS PER DIRECTIVE 2011/35/EU: PV MODULES EXEMPTED FROM THE ROHS DIRECTIVE
4. SAFETY AND ACCESIBILITY IN USE	EN 13022-1 EN 12600 EN 13116 EN 12179	-ONLY APPLICABLE FOR BIPV MODULES OR PV INSULATING GLASS UNITS TO BE BONDED ADHESIVELY WHICH ARE SOLD SEPARATELY FROM THE FRAMEWORK AND INSTALLED UNDER THE RESPONSIBILITY OF THE DESIGNER AND ASSEMBLER. -FOR LAMINATED SAFETY GLASS ONLY
5. PROTECTION AGAINST NOISE	EN 127558	
6. ENERGY ECONOMY AND HEAT RETENTION	EN 410 and A.3. EN ISO 12631 EN 673 or EN 674 or EN 675	LIGHT AND SOLAR ENERGY CHARACTERISTICS THERMAL RESISTANCE AND TRANSMITTANCE THERMAL CHARACTERISTICS OF GLASS
7. SUSTAINABLE USE OF NATURAL RESOURCES	EN 15804 CEN/TR 15941 EN 15942 EN 15978	SEE ALSO FINAL REPORT OF IEA-PVPS TASK 12





B I P V S Y S T E M C O M P O N E N T S

1. FAÇADE BIPV PANELS
2. JUNCTION-BOX
3. CABLING
4. CONNECTIONS
5.INVERTER
6. BUILDING'S ENERGY MANAGEMENT
7. BIPV ARRAY
8. BATTERY
9. ELECTRIC CAR SHARING
10. INVERTER
11. HEAT PUMP
12. WATER TANK
13. ELECTRIC GRID
14. SEWER

Figure 4.5
BIPV system components and electrical system scheme.

Source: Hegger Hegger Schleiff

The second main component of a BIPV system is the BOS, which is the electrical system that connects the BIPV panels with each other, with the building's distribution panel and with the public electrical network. Avoiding electrical connection issues in the early stage of the façade design can optimise the electrical output of the BIPV system. BIPV's electrical system is composed of junction-boxes (JB), cables, connections, and inverters (Figure 4.5) [Messenger *et al.* 2016].

Every BIPV module has a JB that covers the soldering points between the ribbons of the panel and the cables. It is usually placed at the rear side of the panel, although it can be placed on the side of the module for aesthetic reasons when BIPV panels are transparent or bifacial. Two connection cables with plug connectors come out of the JB. These cables must be UV resistant, insulated, and protected against moisture.

Cabling can be routed behind the panels through the façade ventilated cavity or the fastening system profiles, depending on the BIPV panel fastening system and the type of BIPV panel (opaque, translucent or transparent). BIPV panels can be connected in series or in parallel[2] to form an array. BIPV systems are subdivided in arrays with similar environmental influences and solar irradiation; it is usual to have a BIPV array per floor and per orientation [Odersun 2011].

When designing translucent and transparent BIPV systems, some design problems can arise as a consequence of the visibility of the above-described BIPV electrical system components (JB, cables, connections and inverters). These elements are part of a BIPV system and must be integrated into the BIPV façade design. When BIPV systems are transparent, more complex architectural designs must be implemented in order to integrate the fixation and electrical system into the design.

BIPV modules generate direct current (DC) electricity, which cannot be used in domestic appliances. For this reason, every array is connected to an inverter that converts DC electricity into alternating current (AC) electricity before entering the building's distribution panel [Interview with G. Cattaneo, 2018].

The third component of a BIPV system is the panel fastening system. The latter is connected to a mounting system which transmits BIPV panel loads (weight and wind) to the building's loadbearing structure or the façade's self-supporting substructure. As mentioned before, BIPV modules are usually composed of glass panels. Table 4.3. illustrates different fastening systems that can be used when integrating BIPV as façade cladding.

When BIPV is integrated as façade cladding, its fastening system involves the design of a ventilated façade. This provides the required ventilation of BIPV panels to control overheating and minimises panel performance loses. According to some authors, a minimum ventilated air cavity between 8 and 10 cm is needed to guarantee air circulation and lower the temperature of BIPV panels [Brinkworth *et al.* 2005; Maturi *et al.* 2015]. Hence, the regular ventilated façade fastening system needs to be adapted to respect this 8 to 10 cm air cavity requirement. However, it is prudent to design a wider air cavity according to the construction constraints, especially for large-format BIPV panels. When integrating BIPV in balustrades or solar control devices, rear ventilation should also be guaranteed [SUPSI 2019].

2

When BIPV modules are connected in series, the same current flows through all the series-connected modules. This implies that when a BIPV module is not working (for shading reasons or other dysfunction), the current cannot flow correctly and the electrical output is reduced.

When BIPV modules are connected in parallel, electrical current flows independently through the modules, which avoids the previous problem but ads complexity to the cabling connexion [Odersun 2011].

4.2.3 Analysis step outline

Through this analysis step of the contemporary residential façades design practices and BIPV architectural features and functions, two façade design aspects that affect BIPV integration are identified, as well as two BIPV design aspects that affect how it is integrated into a façade.

Regarding contemporary residential façade design practices, the façade composition and the façade morphology are identified to potentially affect BIPV integration. The former highlights that there are predominant dimensions in collective residential building façades where BIPV panels must fit, these are the floor-to-ceiling dimension, which is frequently 250 cm, the floor-to-floor dimension, which is frequently 285 cm, and the balustrade dimension, which is around 100 and 135 cm. These dimensions are based on Swiss regulations and the study of common Swiss practices [*RLATC*, 1987, art. 7; SIA 358 2010]. The façade composition analysis has also identified a façade composition strategy which has no particular predominant dimension, were customised and small-format BIPV panels have the highest potential to fit the façade design.

The façade morphology analysis identifies three different morphologies that affect the façade surface where BIPV must be integrated to specifically avoid casted shadows from other façade elements. The analysis results show that BIPV must be integrated into the outermost surface of the building envelope. That is to say, as façade cladding if there are no balconies, as balustrade if there are balconies, and as façade cladding or balustrade if the façade design integrates loggias. In this case, the walls of the loggia cannot incorporate active surfaces as façade cladding because it is a shadowed area during long periods of the day.

BIPV FASTENING SYSTEMS

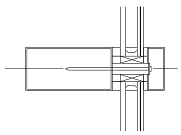
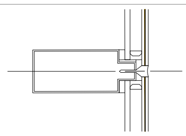
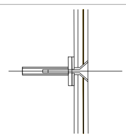
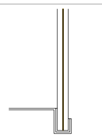
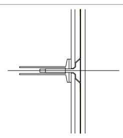
MULLION-TRANSOM FAÇADE LINEAR MOUNTING SYSTEM	- PANEL FRAMING IS VISIBLE - SNOW CUMMULATION MIGHT PARTIALLY SHADE BIPV PANELS - EXPRESSION OF THE FAÇADE GRID	
STRUCTURAL SEALANT GLAZIING LINEAR MOUNTING SYSTEM	- PANEL FRAMING IS INVISIBLE - NO EXTERNAL PROTRUDING ELEMENTS - HOMOGENEOUS AND SMOOTH APPEARANCE	
DRILLED SPOT FITTING POINT-FIXING SYSTEM	- DRILL HOLES MUST MAINTAIN A MINIMUM OFFSET FROM THE EDGE OF THE PANE - DRILL PANES CAN BE USED INDEPENTLY OF THE CELL PRODUCTION	
CLAMP FIXINGS POINT-FIXING SYSTEM	- FIT AROUND THE EDGE OF THE GLASS PANES - FIXINGS MUST OVERLAP THE GLASS BY AT LEAST 25 mm - CLAMPED AREA MUST BE GREATER THAN 1000 mm²	
UNDERCUT ANCHOR FIXING SYSTEM POINT-FIXING SYSTEM	- MECHANICAL POINT-FIXINGS THAT REMAIN INVISIBLE - GLASS IS NOT DRILLED RIGHT THROUGH - EFFICIENT USE OF THE PV SURFACE AREA	

Table 4.3
BIPV façade glass-glass fastening systems.

Source: [Odersun 2011]

Regarding BIPV design practices, the *Analysis* step also identifies two BIPV design aspects that affect its integration into façades. These are the BIPV system's visual and functional features. The visual features refer to the light-permeability of the different existing BIPV systems: opaque, translucent and transparent. BIPV's visual features directly affect its energy performance and its façade function. Opaque BIPV systems can be integrated as façade cladding or façade security elements and have the highest performances; translucent BIPV systems can be integrated as façade solar control systems or façade security elements; transparent BIPV systems can be integrated as façade glazing elements or façade security elements and have the lowest performance.

Both façade and BIPV design practice analysis results define the potential of BIPV systems to be incorporated into contemporary collective residential façades by defining dimensions, positions, visual expression and façade function.

However, contemporary façades and BIPV systems have several construction requirements and expectations to be met at the same time. Regarding contemporary façades, energy-efficient construction practices are highlighted, in line with the initial findings and energy regulations presented in Chapters 2 and 3. Contemporary façades are required to minimise the building's operational and embodied energy. The former is commonly achieved through the increase of insulation, and the latter can be achieved through the incorporation of low embodied impact construction principles in the façade design and construction processes.

Regarding BIPV façades, BIPV systems are considered as construction materials and hence required to comply with the European CPR [EU 305/2011 2011]. Additionally, this analysis highlights several specific requirements, which mostly refer to the fragile nature of BIPV panels, their orientation and their ventilation. The latter can minimise overheating and maximise its energy output.

Ultimately, the *Analysis* step provides the basis to develop a new façade construction system which meets the latest energy and construction requirements, integrates active surfaces in a way that fits the contemporary façade design currents, and incorporates BIPV fulfilling different façade architectural functions. As above mentioned, both contemporary and BIPV façades analysis determine the design potential of integrating BIPV into façades addressing its expressive architectural issues and meeting contemporary façade requirements. This design potential is addressed in the following section to attain building energy efficiency targets from an architectural design approach.

4.3. Integrated Design

The architectural design process usually starts with the formulation of a problem or a need [Prost 1992]. In the context of this research, this formulation is materialised by the identification of the façade's energy performance requirement. From this starting point, the designer analyses the specific temporal, cultural and physical context of the project, which in this case, relates to the analysis of contemporary façade and BIPV practices. Then, the designer searches his or her memory for meaningful images to ultimately produce an architectural solution for the previously formulated problem [Prost 1992, Rey 2018]. As discussed in Section 3.2.2.5, the meaningful images stored in the architect's memory are called architectural references that inspire the creative process. Architectural references are a collection of images – buildings, construction details or material images – which establish a suitable starting point for the architectural design process [Goldschmidt 1998]. According to several authors, *visual displayed material can play an instrumental role in creative problem solving, invention and design* [Finke 1990, Goldschmidt 1998].

From an architectural design approach, this chapter aims at producing a new architectural reference to inspire, motivate, and guide architects to design active energy-efficient façades.

4.3.1 The Advanced Active Façade (AAF) construction system

The Advanced Active Façade (AAF) is developed as an appropriate response to the objective of producing this new architectural reference for active and energy-efficient façade design practices. It is designed to meet the highest standards of performance regarding energy efficiency while being based on the contemporary façade design context.

To achieve this objective, this energy-efficient façade combines passive and active energy design strategies by incorporating BIPV into highly-insulated and low embodied impact façade designs. In that regard, the AAF construction system defines an architectural reference at the façade construction level.

Regarding solar elements, this façade concept integrates BIPV as a visible architectural component, showcased as an integral part of the façade design and construction, which provides the building with locally-sourced renewable energy. The AAF is expected to provide architects with a final product that guarantees the compliance of energy and construction Swiss norms and can be adapted to different design and urban contexts. The façade construction system is designed based on the previous analysis of the contemporary residential and BIPV façades, and the energy-efficient construction practices and requirements presented in Section 4.2.1.2 and Section 4.2.2.2.

The AAF construction system defines a low embodied environmental impact façade substructure with a highly insulated façade core where BIPV can be incorporated in four variations as an active façade cladding, active window glazing, active security elements or active solar control façade accessories. BIPV thus becomes a visible architectural component, showcased as an integral part of the façade design and construction, which provides the building with locally-sourced renewable energy. The AAF is composed of low embodied impact materials and designed as a non-loadbearing[3] façade, which guarantees

3
As defined by the European Norm EN13501-2: A non-loadbearing wall is designed not to be subjected to any load other its self-weight [AFNOR 2016].

more flexibility in the façade composition compared to other loadbearing options. The dissociation of the façade from the load-bearing structure can also extend the building life-cycle because it provides flexibility to modify the façade according to the building use and requirements. Extended life-cycles are essential for the sustainable use of buildings [SIA 2017].

The methodology adopted to develop the AAF construction system is based on the following phases: 1) specify the low embodied impact construction principles to be followed among the contemporary façade construction practices presented in Section 4.2.1.2; 2) design the construction detail of the AAF system; 3) verify and adapt the material quantity, material nature and element thickness to comply with Swiss energy efficiency requirements, fire security and other construction regulations; 4) define the final version of the AAF construction system in detail.

Design process

The AAF construction system design process has benefited from the collaboration of several interdisciplinary experts: experienced architects, façade specialists, low embodied impact design professionals and BIPV producers [Interview with D. Bolomey, 2017; S. Mercier, 2017; S. Piguet, 2018; G. Cattaneo, 2018]. This process has also relied on the expert advice of construction product developers, who were consulted when their products were considered to integrate the AAF [Interview with A. Chaffard, 2018; Interview with J. Rojon, 2018].

At a façade construction level, the main design principles adopted to lower the AAF construction system embodied environmental impacts are:

- Use of natural or low embodied carbon materials: lower the global embodied impact.
- Adjust material quantity: use fewer materials and define a lighter façade.
- Design for prefabrication: minimise waste.
- Design for disassembling: reuse façade elements or recycle.

Throughout the design process, two specific choices are key to determine the final configuration of the AAF construction system. The first is the choice of timber as the main material of the façade substructure as it is recommended in Section 4.2.1.2. Timber has the lowest carbon impact among the most commonly used structural construction materials in Switzerland. In addition, the Swiss land can locally provide wood, minimising transport-related embodied energy [FOEN 2015].

The second choice is the decision to use blown cellulose[4] as the main insulator for its lower environmental impact compared to other insulation materials, as shown in Table 4.1 and also recommended in Section 4.2.1.2 [KBOB 2016]. Blown cellulose has the best thermal performance when compared to other cellulose formats such as cellulose panels, which have a higher density and lower thermal performance. Blown cellulose has a thermal conductivity (λ) of 0,038 W/mK, which is similar to other insulating materials commonly used in Switzerland such as stone wool (Table 4.1).

These low embodied impact construction principles directly affect the AAF's design process and outcome. To illustrate this, the decision to use blown cellulose as the main insulator affects the construction design details, due to its

4
Cellulose is a recycled insulating product made mainly from newsprint and other cellulose fibre. The material is available in a loose format, which can be poured or sprayed, and in a board format. This material usually includes additives to provide fire resistance and to repel insects and fungi.

powdery nature. Cellulose powder cannot be mechanically fixed or glued. It is usually used on roofs where it lies over the horizontal roof structure. However, using blown cellulose is technically more complicated on vertical façades for gravity reasons. Blown cellulose must be contained in a case so that it maintains its volume, density, and dryness. Upon these requirements, the solution is to design a panel-based construction system where wood-panels form the substructure of the façade and define a water and wind-sealed case for the blown cellulose.

This solution also favours minimising the façade carbon footprint because wood-panel structures use less material and are lighter than solid timber structures. The substructure is composed of thin large-format panels – the frontal panels – and self-supporting timber ribs. The frontal panels (numbers 3 and six on Figure 4.6) are 1.5 cm thick and define the exterior and interior sides of the case. The timber ribs (number 5 on Figure 4.6) are installed between the frontal panels, perpendicular to the façade, and define the thickness of the façade substructure. The latter is 4 cm thick, for the adequate arrangement of the self-tapping screws [SIA 265 2012]. This timber case is supported by the steel L-profiles fixed to the horizontal slab (number 10 on Figure 4.6), which transmit the façade load and efforts to the main loadbearing structure of the building.

In accordance with low-carbon design principles, the façade system is designed for prefabrication. This optimises the process of filling the cases with blown cellulose and generates less waste. The façade is designed to be produced in modules (number 11 on Figure 4.6) of variable dimensions depending on the particularities of each façade and the means of transport from the façade prefabrication factory to the construction site. The wood-panel substructure guarantees the lightness of the façade prefabricated modules, which facilitates its transportation. Light prefabricated façade modules can be transported and installed on-site, using less machine force than for heavy façade construction systems.

To minimise thermal bridges on the façade, due to the vertical timber ribs (number 5 on Figure 4.6), the total insulation thickness is divided into two insulating layers with similar thermal conductivity. The main layer (35 cm) is composed of the blown cellulose contained in the wood-panel cases. The secondary layer (5 cm) is composed of a layer of wood-fibre panels placed on the interior side of the façade structure. Both insulations are placed with a non-coinciding vertical substructure minimising the thermal bridges generated by the vertical timber ribs.

In addition, dividing the insulation layer allows wall slots and notches to be made into the wood-fibre part without adding a supplementary air chamber for embed plumbing and routing electrical connections. This optimises the total façade thickness. In a like manner, the cellulose case is not affected by building services routing and is kept water and airtight. The possibility of doing and modifying wall slots and notches enables flexible use and distribution of the residential interior spaces. Indeed, it would not be possible to embed and modify wiring and secondary pipes in the cellulose hermetic cases.

As a reminder, AAF presents four different variations. It integrates BIPV as 1) façade cladding, 2) façade glazing, 3) façade security elements and 4) solar control systems. In all cases, the active surface's environmental impact and economic cost are integrated and calculated as an integral component of the AAF.

When the BIPV system is integrated as **façade cladding** elements, the AAF defines a frameless façade panel system (Figure 4.6). BIPV façade cladding has the risk of experiencing overheating, which drastically lowers its performance. For this reason, the cladding joints must allow optimal ventilation of the rear air cavity.

The frameless BIPV panel fastening system is initially designed as an invisible point-fixing system to minimise the material quantity of the fastening system, which is the *Undercut anchor fixing system* represented in Table 4.3. This fastening system entails a high panel production complexity, which results in a higher cost of the BIPV system.

After discussions with CSEM's BIPV producers [Interview with G. Cattaneo, 2018], a frameless linear fastening system is designed to simplify and reduce the cost of the BIPV panel production. Among the existing frameless linear fastening systems, a fire-resistant Structural Sealant Glazing (SSG) solution is selected [EOTA 2012]. The designed fastening system incorporates a horizontal profile adhered to the rear face of the BIPV panel (number 15 on Figure 4.8) that transfers the panel loads to another horizontal profile which receives the loads and transmits them to the façade substructure (number 16 on Figure 4.8).

In an iterative design and assessment process, this frameless linear fastening system is optimised by adding a vertical rail (number 14 on Figure 4.8) to be adhered to the rear face of the BIPV panel with an SSG solution, instead of adhering a horizontal rail (Figure 4.8). This optimisation prevents the accumulation of water on the structural sealant product, which could lead to faster deterioration of the product shortening the BIPV system lifespan. This BIPV fastening system is developed by the Swiss façade substructure company Wagner System AG for the German BIPV production company Avancis [Wagner System AG 2019].

The proposed fastening system design meets the BIPV panel rear-ventilation architectural requirement mentioned in Section 4.2.2.2. As a reminder, a minimum air gap of 8 cm must be guaranteed to avoid panel overheating. This is achieved with the dimensioning of the metallic wall brackets (number 18 in Figure 4.8) and the vertical profile (number 17 in Figure 4.8). Electrical cabling, adequately insulated, is routed through this air gap. The ventilated air cavity provides sufficient space to install junction boxes and handle electrical connections.

With active or non-active façade cladding, special attention must be paid when fixing the façade cladding's fastening system to the façade's substructure with screws perforating the fibrocement board (number 3 on Figure 4.6). The wall brackets (number 18 on Figure 4.8) must coincide with the vertical timber ribs (number 5 on Figure 4.6) so that BIPV panels efforts are directly transmitted to a loadbearing element. The direct fixation to the ribs also guarantees the tightness of the cellulose case, avoiding potential leaks or hygrometric changes, which would modify its thermal performance.

When the BIPV system is integrated as **façade glazing,** the active glass is integrated into a window frame, as shown in Figure 4.9. The window frame can be fixed or openable and must integrate part of the BOS: junction box and cabling, as illustrated in Figure 4.10 (number 17).

Heat gains due to solar irradiation on windows can lead to interior space overheating, especially during summer. The most effective way to avoid this problem is to block solar irradiation on the glazed surface with exterior solar control elements. In Switzerland, installing exterior slatted blinds is the most common solution today. Consequently, if sun irradiation is blocked in front of a BIPV window glazing, there is no energy generation on the active surface at the time of higher irradiation. For this reason, the design of active windows in residential façades must be carefully studied regarding its compatibility with external solar control devices.

When integrated as **façade security** elements, the BIPV surface is integrated as a balustrade, as shown in Figure 4.11. In this case, the junction box and the electrical cabling (numbers 13 and 14 in Figure 4.12) are protected by the top metal railing (number 12 in Figure 4.12) of the balustrade as illustrated in Figure 4.12.

Active balustrades have the potential to incorporate bifacial BIPV systems (Section 3.2.2.1) because they are usually free-standing elements that receive direct radiation on one side and indirect radiation on the other side. As a reminder, the bifacial function of a BIPV system can increase up to 30% its energy output [Hansen *et al.* 2017].

When integrated as **façade solar control** elements, the BIPV are usually part of a panel sliding system, as shown in Figure 4.13. The fact that the BIPV panels are mobile adds design complexity regarding the routing of the electrical connections. Figure 4.14 shows a design solution which incorporates a spiral cable flexible enough to cover a determined sliding distance for each panel.

Solar control elements as the ones illustrated in Figure 4.13 can also harvest solar radiation in both the front and rear face. Hence, bifacial performance can increase the BIPV system's output.

The sliding movement of the different solar control elements must be limited to avoid overlapping of two BIPV surfaces, which would minimise the electrical output of the one that remains behind.

The non-active AAF façade claddings are defined with wood, aluminium, or fibrocement-board façade claddings. Nevertheless, the construction detail does not vary significantly: the exterior façade cladding changes its nature, and the air cavity is reduced from 8 cm to 4 cm.

Regulation compliance

In Switzerland, the most demanding construction recommendation regarding thermal insulation is *Minergie P* [Minergie 2019], which requires a final façade transmittance value (U) of 0.1 W/m^{2}K. A total of 38 cm of thermal insulation (λ= 0,038 W/mK) is needed to achieve this value according to the calculations performed through this iterative design process. Calculations are performed with the building simulation software: Design-Builder (DB), considering the potential thermal bridges generated by the timber ribs.

Eventually, the AAF has the potential to integrate the load-bearing building structure – timber pillars – interleaved with the cellulose cases. The two layers of insulation enable complying with *Minergie*'s thermal requirements and minimise the thermal bridges without modifying the general design of the system. Wood-fibre panels next to the building structure – where the cellulose thickness is reduced – are replaced with a super-performant thermal insulator to meet the required thermal performance of the façade. These products are synthetic polyisocyanurate or polyurethane foams (Jackodur, Eurothane or similar) with lower thermal conductivity values (λ=0.024-0.022 W/m^{2}K) but higher environmental impact: around 40 times more GWP than cellulose [KBOB 2016; Jackodur 2018; Eurothane 2019].

Initially, the cellulose case was designed with Oriented Strand Board (OSB) panels on both interior and exterior faces. Specifically, OSB 3 panels were taken for its qualified use in humid conditions, guaranteeing the vapour barrier and wind-stopper functions of the surface [EN 2006]. However, this AAF construction system configuration is modified because *protection against fire* Swiss norms establish that a ventilated façade with low fire-resistance insulation materials – RF2 or RF3[5] –such as cellulose, must exclusively have fire-resistant materials – RF1 – defining the ventilated air cavity [AEAI 2015]. In the case of the AAF, the natural insulation – cellulose – has an RF2 fire classification [Isofloc 2015] and OSB panels have an RF3 fire qualification [KRONO 2018]. This means that the exterior panel of the insulation case cannot be an OSB panel. A fireproof fibrocement board with RF1 fire qualification is thus chosen to define the exterior face of the case [Fermacell 2014]. In addition, this material is water- and windproof when sealed with adhesive tape and can guarantee façade's impermeability without adding a wind barrier, according to Preface façade experts [Interview with S. Mercier, 2017].

Due to the system's lack of mass, the acoustic insulation is achieved by concatenating layers with different acoustic absorption coefficients. The series of successive and different insulating panels and materials improve the acoustic insulation properties of the system [Herzog *et al.* 2004], which help meet the SIA 181:2006 standard [SIA 181 2006]. In addition, BIPV façade cladding provides a sound dumping up to 25 dB according to the results published by SUNRISE project [Montoro *et al.* 2011]. The standard SIA 181:2006 [SIA 181 2006] requires a maximum of 27dB from outside air noise to be measured inside a home. The acoustic performance insulation depends on the building context sound conditions. For this reason, the façade acoustic insulation properties should be tested and adapted to each specific project. As a solution to potential acoustic issues, the interior finish of the wall, which consists of a panel of plasterboard, can be doubled or replaced with high performant acoustic insulation panels [Knauf 2018].

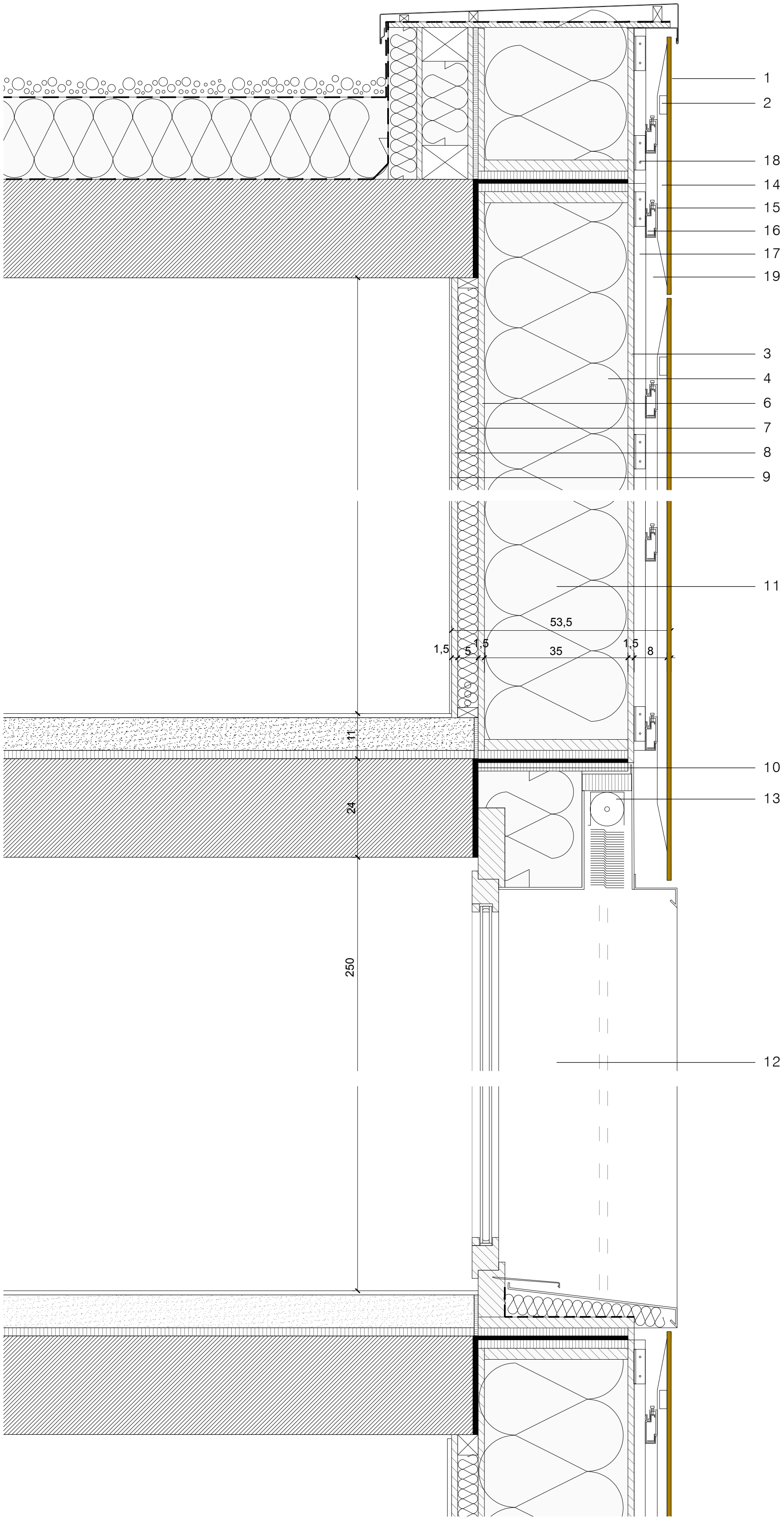
Regarding the physical requirements of the BIPV system, the panels integrated into the AAF construction system are glass-glass BIPV panels. Specific thickness must be calculated for each specific panel dimension, project location and fastening system following the norm SIA 260: 2013. This norm establishes limits to the BIPV panel deformation which is smaller when it has adhered fastening systems compared to other mechanical fixings such as clamped mounting solutions [SIA 260 2013; Palm *et al.* 2018].

Ultimately, the study and verification of the AAF preliminary design result have evolved to comply with the Swiss norms and experts' recommendations. Most of the research work regarding regulation compliance is carried out to find a fire-resistant panel with a low-embodied carbon, resulting in the identification of fibrocement panels which have a good fire and acoustic performance although its embodied environmental impact is higher than other non-fire-resistant options.

Design outcome

This design process results in the AAF construction system illustrated in the following pages (Figure 4.7 to Figure 4.14). The different AAF construction details illustrate the integration of BIPV systems as façade cladding, façade glazing, façade security and façade solar control elements.

5
Being Swiss and European protection against fire codes different, RF1 corresponds to A1 and A2-s1, d0 in the European code SN EN 13501-1:2009; RF2 corresponds the categories between: A2-s1,d1 and C-s3,d2; and RF3 corresponds to the categories between: D-s1, d0 and E-d2 [AEAI 2017].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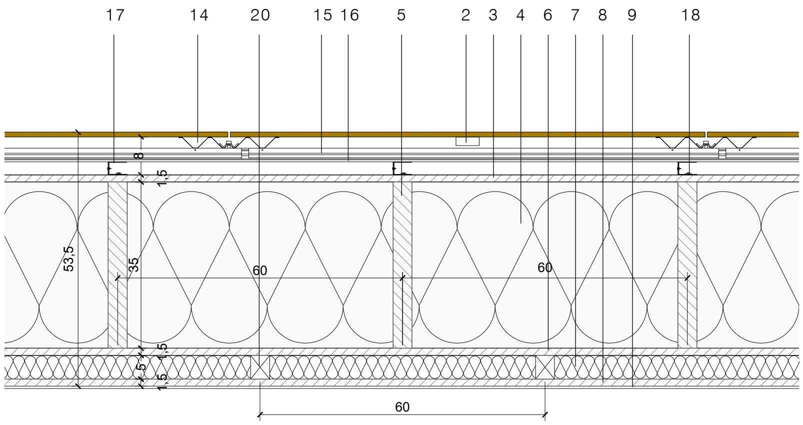


1. BIPV PANELS
2. JUNCTION BOX
3. FIBROCEMENT PANELS WITH SEALED JOINTS: 1.5 cm
4. BLOWN CELLULOSE INSULATION: 35 cm
5. WOOD FAÇADE SUBSTRUCTURE: SOLID WOOD RIBS
6. OSB PANELS WITH SEALED JOINTS: 1.5 cm
7. WOOD FIBRE INSULATION: 5 cm
8. PLASTER BOARD: 1.25 cm
9. INTERIOR COATING: PAINT
10. STEEL L-SECTION FOR FAÇADE LOAD RECEPTION
11. PREFABRICATED AAF FAÇADE MODULE
12. WINDOW FAÇADE MODULE
13. EXTERIOR SLATTED BLINDS
14. BACK VERTICAL RAIL ADHERED TO BIPV PANEL
15. HORIZONTAL AGRAFFE SUPPORTING PROFILE. LOAD TRANSMISSION
16. HORIZONTAL AGRAFFE SUPPORTING PROFILE. LOAD RECEPTION
17. VERTICAL PROFILE
18. WALL BRACKETS
19. VENTILATED AIR CAVITY 8 cm
20. INTERIOR COATING SUBSTRUCTURE

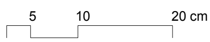
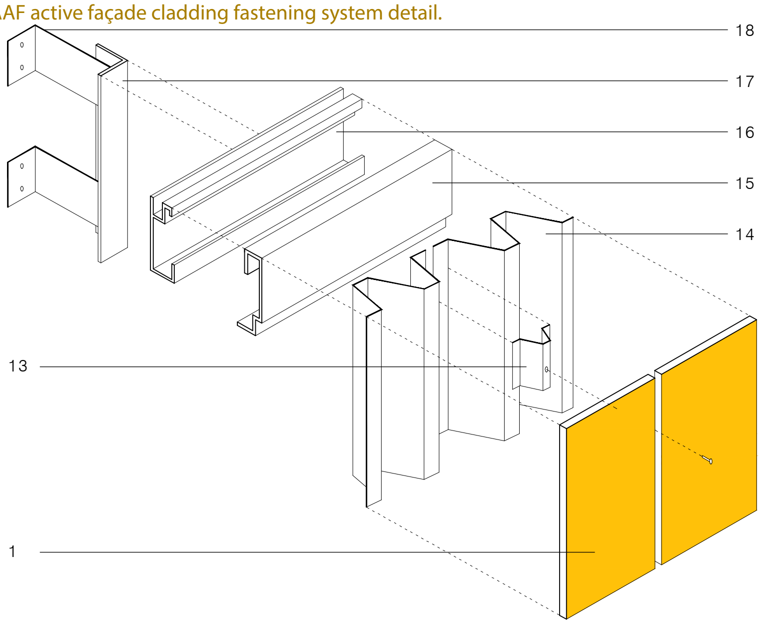


Figure 4.6

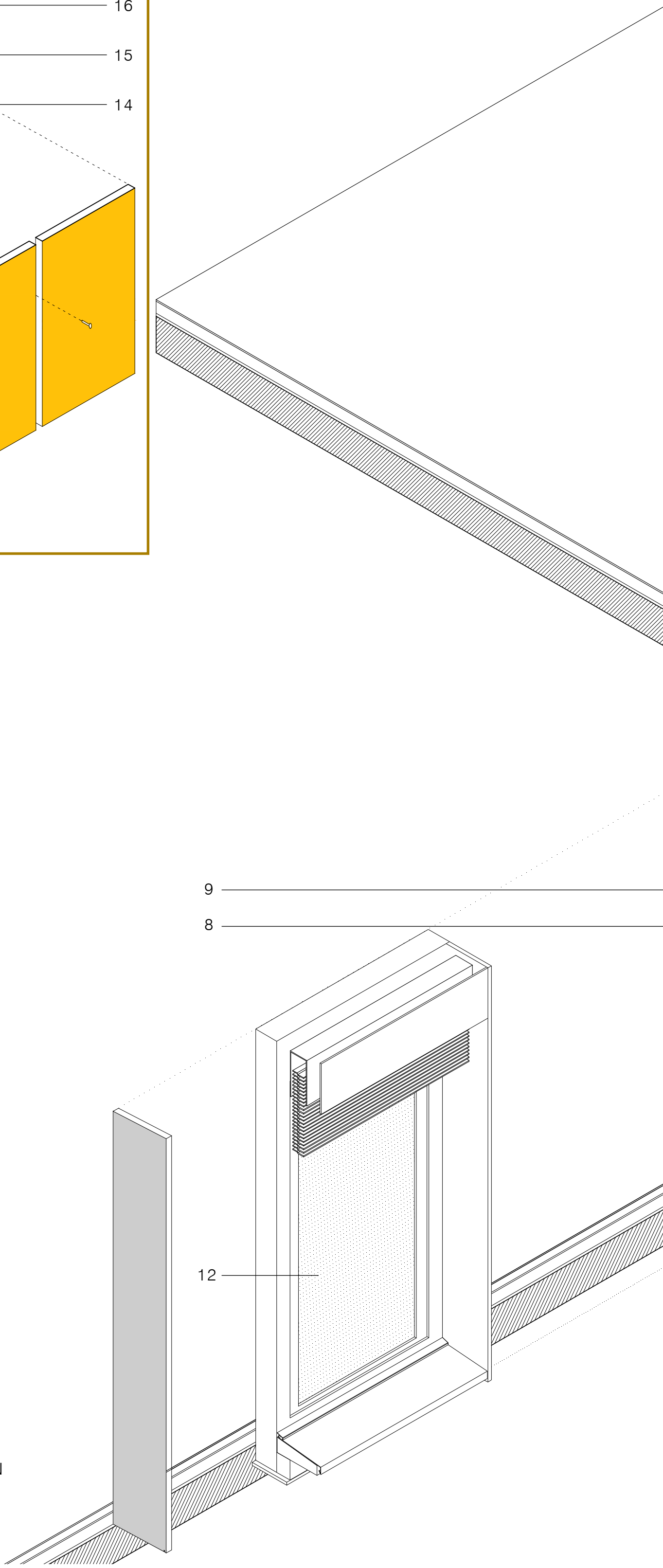
AAF construction system: plan and section detail.

Figure 4.8

AAF active façade cladding fastening system detail.



DETAIL A



1. BIPV PANELS
2. BIPV PANEL FASTENING SYSTEM_DETAIL A
3. FIBROCEMENT PANELS WITH SEALED JOINTS
4. BLOWN CELLULOSE INSULATION
5. WOOD FAÇADE SUBSTRUCTURE: SOLID WOOD RIBS
6. OSB PANELS WITH SEALED JOINTS
7. WOOD FIBRE INSULATION
8. PLASTER BOARD
9. INTERIOR COATING: PAINT
10. STEEL L-SECTION FOR FAÇADE LOAD RECEPTION
11. PREFABRICATED AAF FAÇADE MODULE
12. WINDOW FAÇADE MODULE

13.SECURE MOUNTING CLAMPS
14. BACK VERTICAL RAIL ADHERED TO BIPV PANEL
15.HORIZONTAL AGRAFFE SUPPORTING PROFILE. LOAD TRANSMISSION
16. HORIZONTAL AGRAFFE SUPPORTING PROFILE. LOAD RECEPTION
17. VERTICAL PROFILE
18. WALL BRAKETS

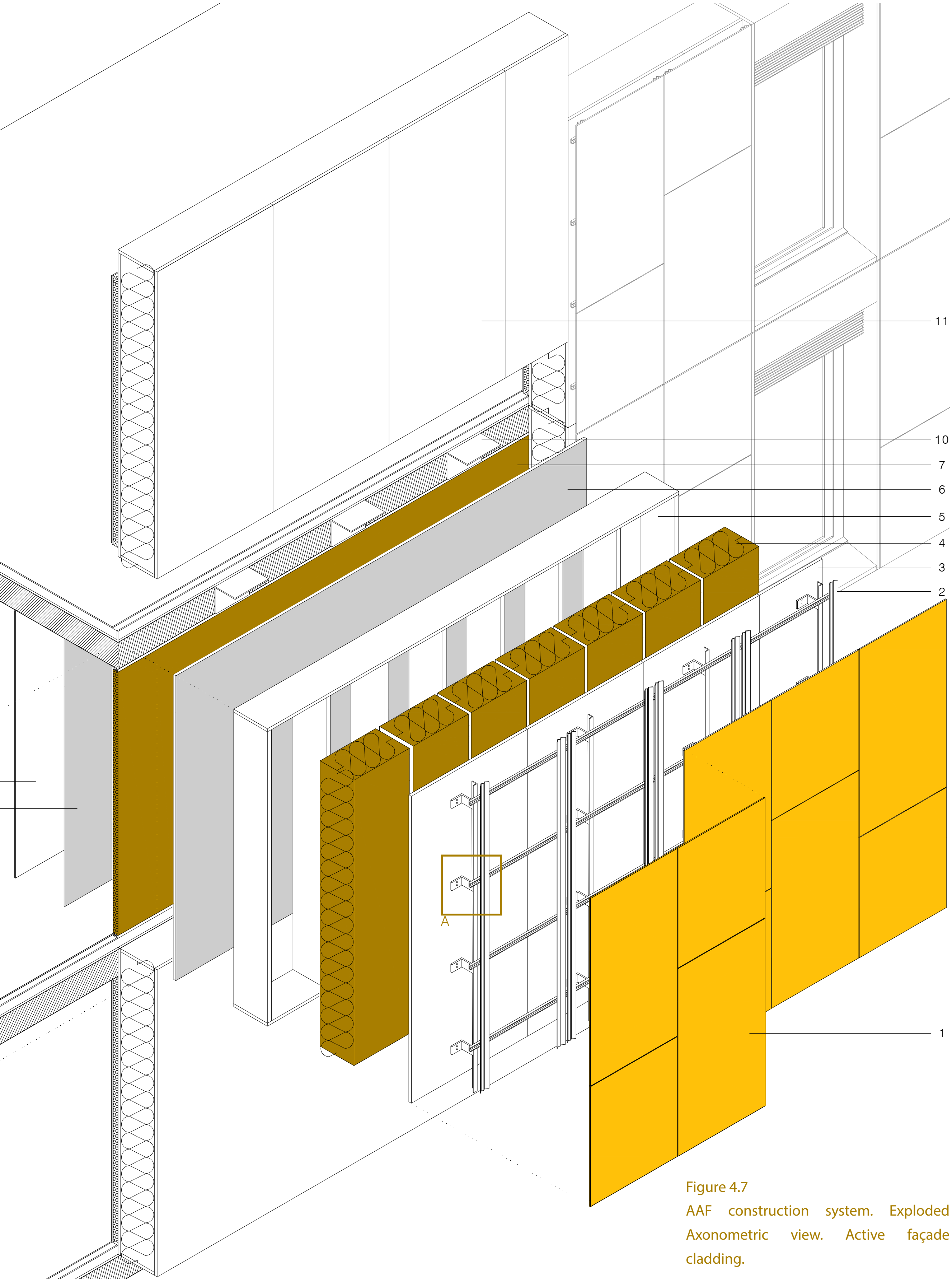
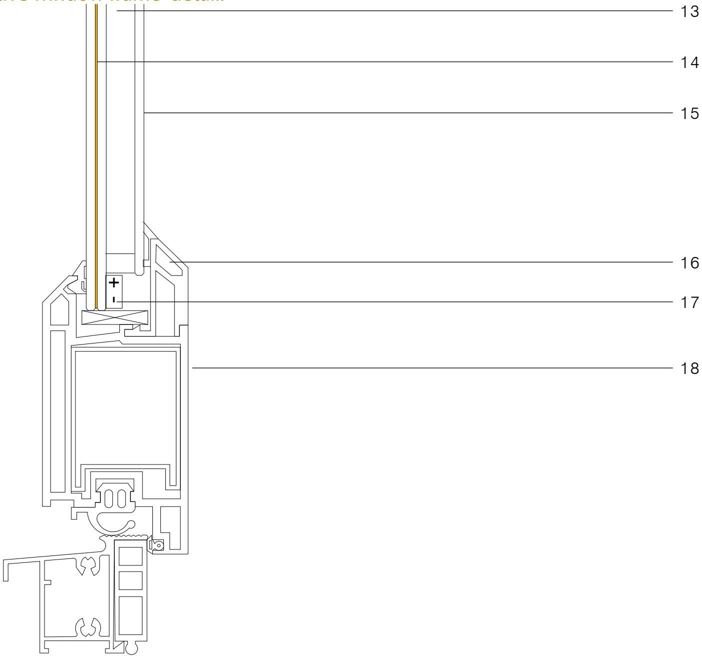
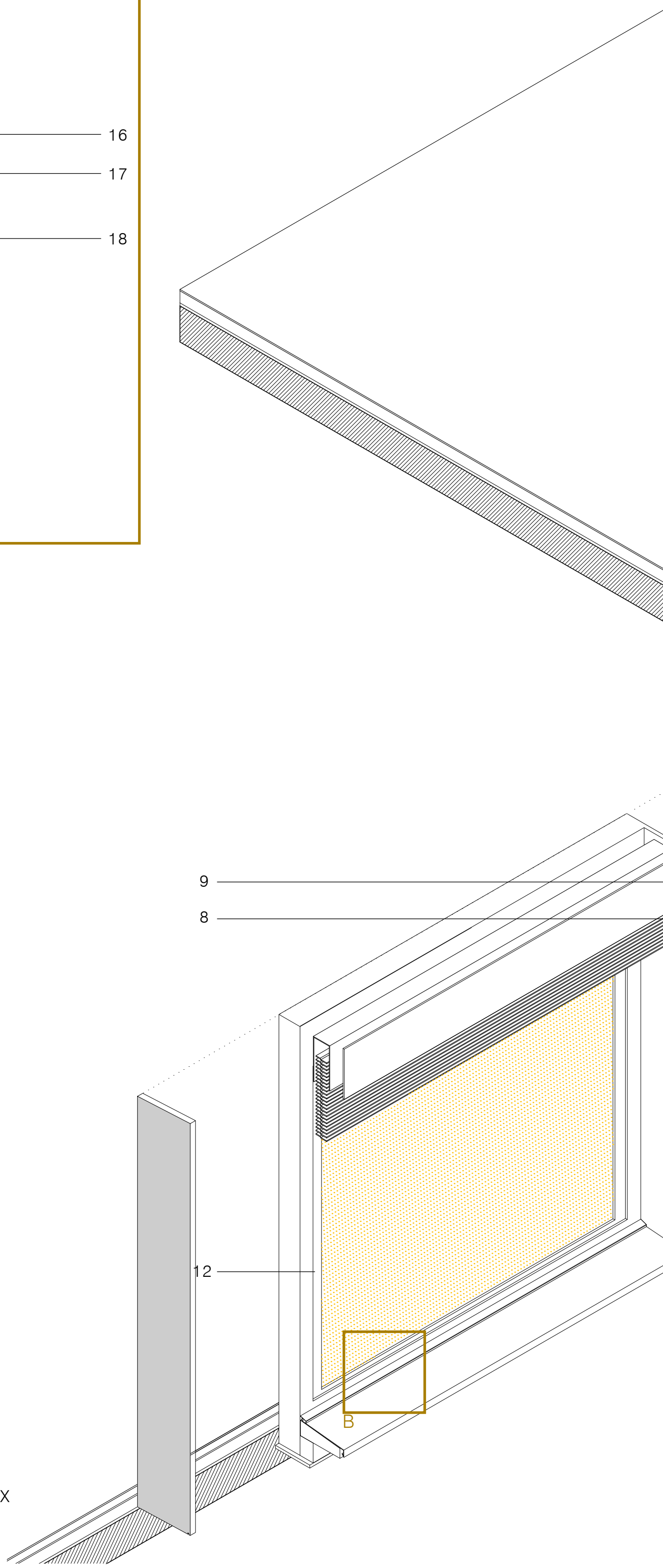


Figure 4.7
AAF construction system. Exploded Axonometric view. Active façade cladding.

Figure 4.10
AAF active window frame detail.



DETAIL B



1. FAÇADE CLADDING
2. FAÇADE CLADDING FASTENING SYSTEM
3. FIBROCEMENT PANELS WITH SEALED JOINTS
4. BLOWN CELLULOSE INSULATION
5. WOOD FAÇADE SUBSTRUCTURE: SOLID WOOD RIBS
6. OSB PANELS WITH SEALED JOINTS
7. WOOD FIBRE INSULATION
8. PLASTER BOARD
9. INTERIOR COATING: PAINT
10. STEEL L-SECTION FOR FAÇADE LOAD RECEPTION
11. PREFABRICATED AAF FAÇADE MODULE
12. BIPV WINDOW FAÇADE MODULE_DETAIL B

13. INSULATING BIPV GLAZING
14. LAMINATED BIPV PANEL
15. REGULAR GLASS PANEL
16. INTERNALLY POSITIONED GLAZING BEAD. ACCESS TO JUNCTION BOX
17. JUNCTION BOX AND ELECTRICAL CABLING
18. WINDOW FRAME

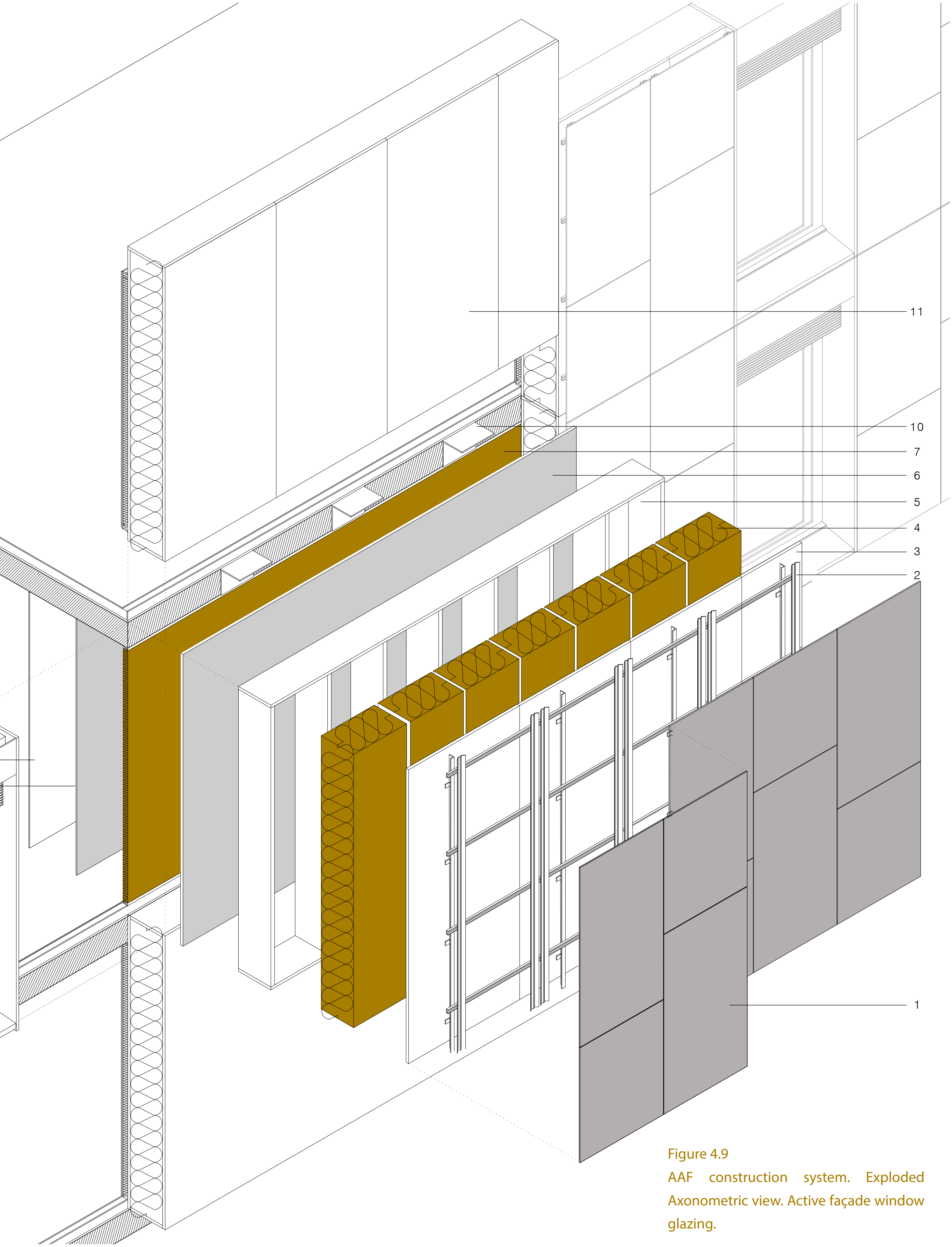
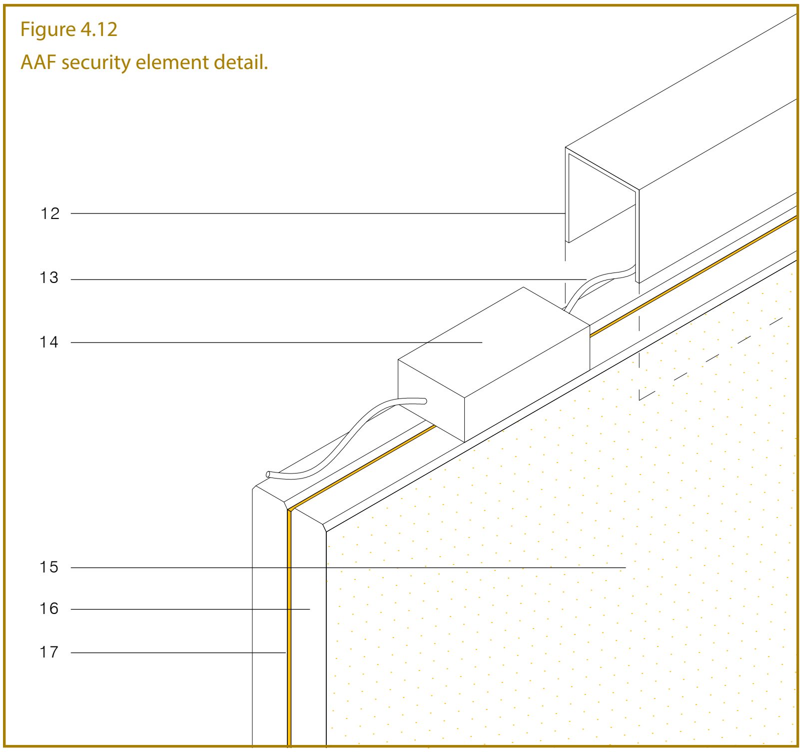


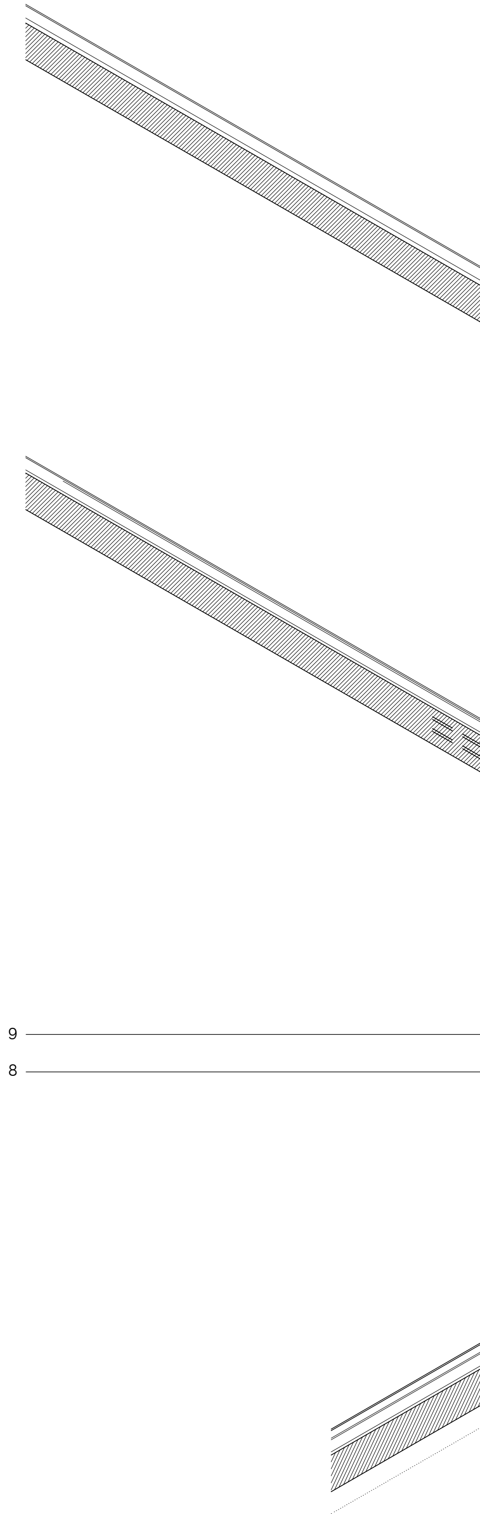
Figure 4.9

AAF construction system. Exploded Axonometric view. Active façade window glazing.

Figure 4.12
AAF security element detail.



DETAIL C



1. FAÇADE CLADDING
2. FAÇADE CLADDING FASTENING SYSTEM
3. FIBROCEMENT PANELS WITH SEALED JOINTS
4. BLOWN CELLULOSE INSULATION
5. WOOD FAÇADE SUBSTRUCTURE: SOLID WOOD RIBS
6. OSB PANELS WITH SEALED JOINTS
7. WOOD FIBRE INSULATION
8. PLASTER BOARD
9. INTERIOR COATING: PAINT
10. BIPV BALUSTRADE_DETAIL C
11. FAÇADE LOGGIA

12. BALUSTRADE TOP RAILING
13. CABLING
14. JUNCTION BOX
15. BIPV SECURITY FAÇADE ELEMENT: BALUSTRADE
16. SECURITY GLASS
17. PV CELLS

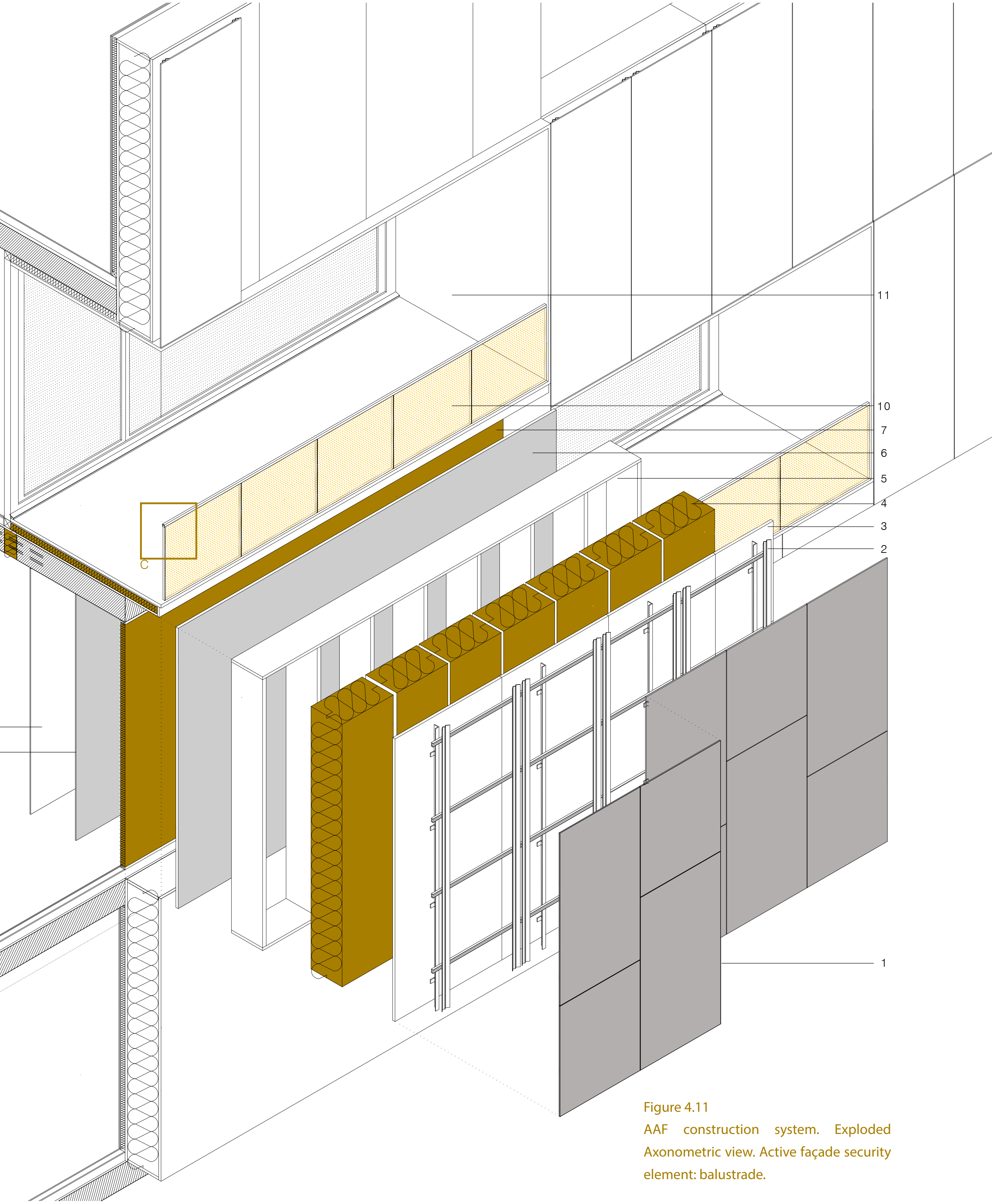
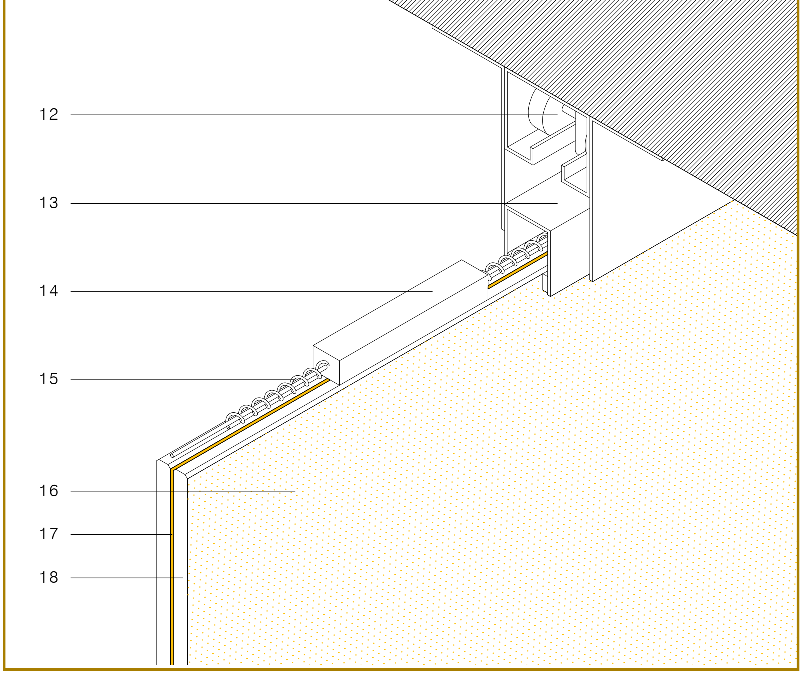
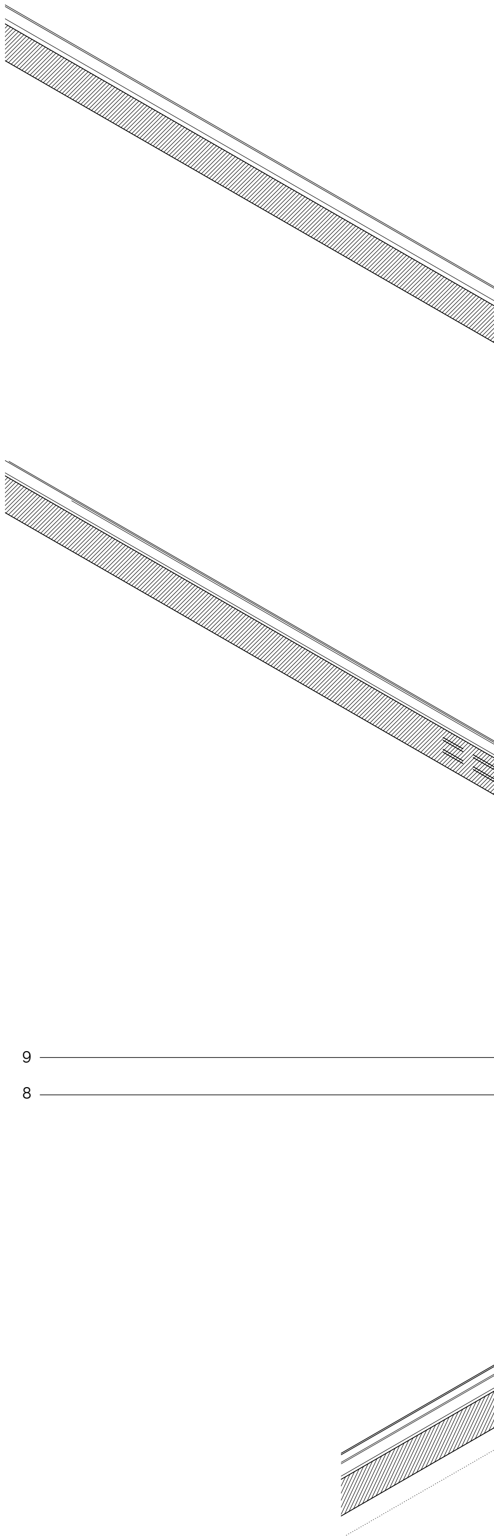


Figure 4.11
AAF construction system. Exploded Axonometric view. Active façade security element: balustrade.

Figure 4.14
AAF solar control element detail.



DETAIL D



1. FAÇADE CLADDING
2. FAÇADE CLADDING FASTENING SYSTEM
3. FIBROCEMENT PANELS WITH SEALED JOINTS
4. BLOWN CELLULOSE INSULATION
5. WOOD FAÇADE SUBSTRUCTURE: SOLID WOOD RIBS
6. OSB PANELS WITH SEALED JOINTS
7. WOOD FIBRE INSULATION
8. PLASTER BOARD
9. INTERIOR COATING: PAINT
10. BIPV SOLAR CONTROL FAÇADE ELEMENT_DETAIL D
11. FAÇADE LOGGIA

12. SLIDING SYSTEM
13. TOP RAILING
14. JUNCTION BOX
15. CABLE ROUTING IN SLIDING PANEL
16. BIPV SOLAR CONTROL ELEMENT
17. PV CELLS
18. SECURITY GLAZING

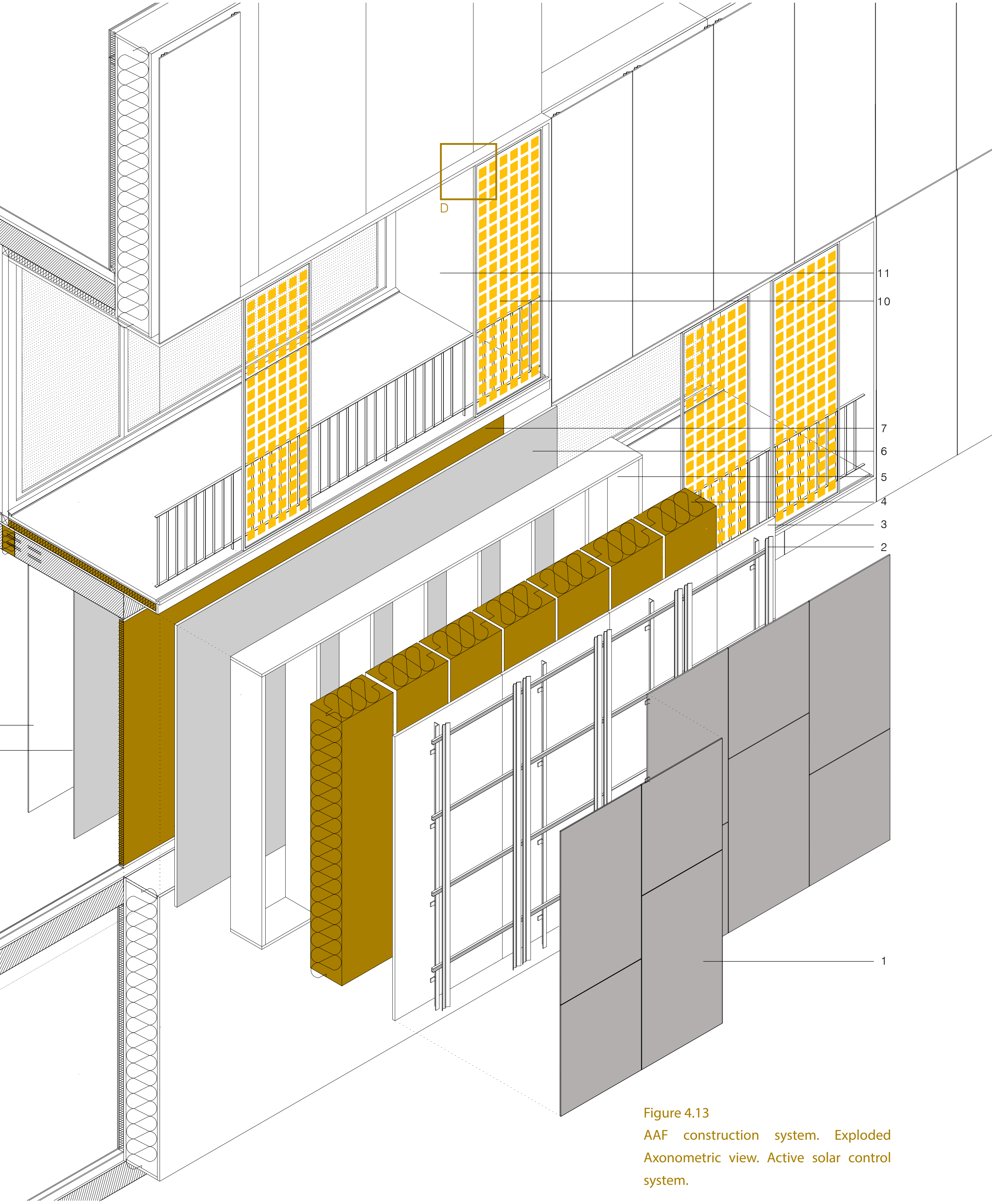


Figure 4.13

AAF construction system. Exploded Axonometric view. Active solar control system.

4.3.2 Design step outline

The outcome of this research step is the Advanced Active Façade (AAF), which aims at becoming an architectural reference of energy-efficient façade construction in the collective residential building context. To this end, the design process is based on the *Analysis* step, which identifies different façade and BIPV design aspects that affect its integration in collective residential buildings.

The AAF combines passive and active energy design strategies: it is highly insulated, follows low embodied impact construction principles and incorporates BIPV as an integral part of the façade. Relying on multidisciplinary professional advice, the AAF construction design process outlines a prefabricated, non-loadbearing, wood-panel façade substructure which incorporates blown cellulose as the primary insulator and active surfaces to generate renewable energy. The AAF contemplates the integration of active surfaces as BIPV façade cladding, BIPV façade glazing, BIPV façade security elements (e.g. balustrade) and BIPV façade solar control elements.

Depending on each of these BIPV façade functions, specific fastening systems are designed to adapt the incorporation of a non-active façade element to the incorporation of a BIPV façade element. These details are provided in Figure 4.6 to Figure 4.14 and highlight the following:

- The incorporation of façade cladding must design a minimum size air cavity of 8 cm to maximise the rear face ventilation of the BIPV panel and minimise its energy performance losses due to overheating.
- The window frame of a BIPV glazing must incorporate the junction box and electrical cabling in a way that it can be accessed without demounting the whole window.
- Active balustrades incorporating transparent or translucent BIPV panels can have the junction boxes placed in the edge of the panel to avoid their visual perception. This junction box is protected under the top-railing where the electrical cabling is routed.
- The incorporation of BIPV panels as solar control systems has an additional complexity if the panels are mobile. The sliding movement must be limited to avoid panel overlapping. The cable routing can be solved with an elastic spiral electrical connection, as shown in Figure 4.14.

At the end of the AAF design process, the resulting energy-efficient façade design is confronted with building energy performance recommendations [Minergie 2019], *protection against fire* norm [AEAI 2015], acoustic standards [SIA 181 2006] and physical resistance standards [SIA 260 2013] to determine the final dimension and nature of each element composing the AAF construction system.

Ultimately, the AAF aims at becoming an architectural reference of energy-efficient façade design, which provides a flexible façade design solution to multiple residential building scenarios and complies with all construction regulations and latest requirements.

4.4. Implementation

The outcome of the *Design* step, the AAF, aims at providing architects with an architectural reference which can be implemented in various façade design scenarios to meet the latest energy efficiency building requirements. To illustrate and demonstrate this design flexibility, the designed energy-efficient façade is implemented into the building design architectural process, generating the AAF building scenarios. The definition and the development of these building scenarios are presented here, followed by an outline of the implementation process.

4.4.1 The Advanced Active Façade (AAF) building scenarios

The AAF building scenarios are an assortment of façade designs which directly relate to concerns that are on the contemporary Swiss architecture agenda: energy efficiency, cost, urban context integration, and harmonious architectural expression [SIA 112 2017].

The methodology followed to develop the AAF building scenarios is structured as follows: 1) definition of a representative urban context, 2) definition of a representative residential building as a base for the façade design, and 3) development of different AAF building scenarios within an *innovative* architectural approach (Section 3.2.2.1).

Representative urban context

The so-called *Swiss-plateau* (Figure 4.15) covers around 30% of the Swiss surface area and hosts two-thirds of the total population. This region has similar climate and geographic conditions throughout its territory that can be considered as representative for a majority of building contexts [Confédération Suisse 2017]. Within the Swiss-plateau, the City of Lausanne, medium-sized and representative of the average Swiss city, is chosen for developing and contextualising the building scenarios.

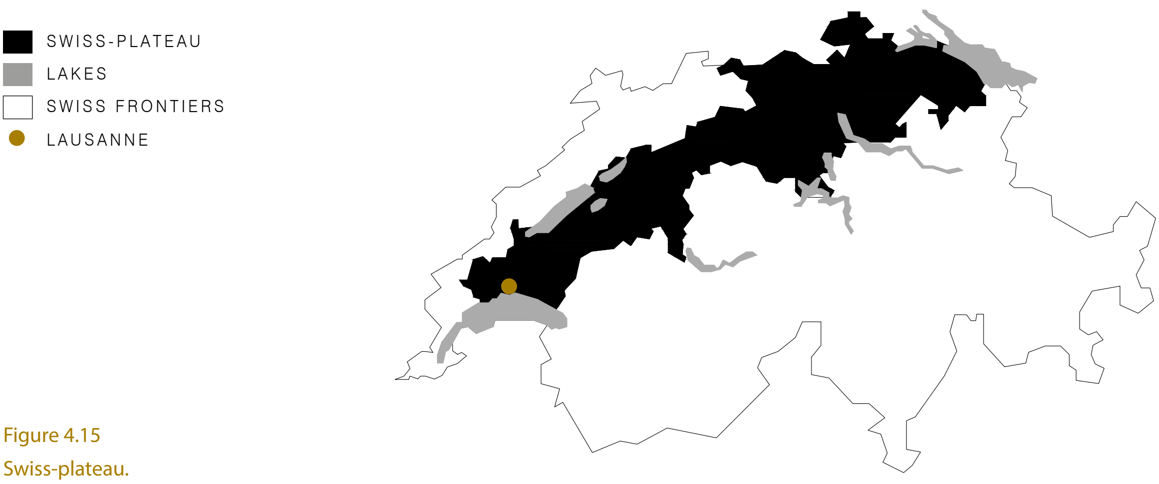


Figure 4.15
Swiss-plateau.

Figure 4.16
Location plan of the plot chosen for contextualizing the building scenarios.

In recent years, the drawbacks of urban sprawl – inefficient land use, increasing pressure on the landscape, and increase of mobility impacts – are highlighting the need for favouring urban densification processes for sustainable urban development [Rey 2011]. In sight of this, a plot of land in Lausanne that could be subjected to an urban densification project is identified.

In this phase, data are collected through the review of the digital cartographic information provided by the Canton de Vaud on www.map.lausanne.ch and www.geo.vd.ch. These online platforms display information about the different on-going and planned urban renewal projects in the region. In addition, extended information about plans, projects and ownership of each plot can be consulted.

Plot number 4778 in Chemin de Primerose is identified by analysing the urban renewal projects in the Lausanne-city area. Its optimal orientation for BIPV integration and its urban densification potential make it ideal for contextualising the building scenarios.

The selected site measures 2399 m^2 in a mid-dense urban area at the southwest of Lausanne's train-station (Figure 4.16). The terrain has an average slope of 14% towards the southwest with views on Lake Geneva and the French Alps. The neighbourhood is a residential area, and the street that connects the plot to the city traffic network is a dead end. Therefore, traffic around the building is almost inexistent.

Figure 4.17
Partial zoning plan: PPA 676.

Source: Commune de Lausanne

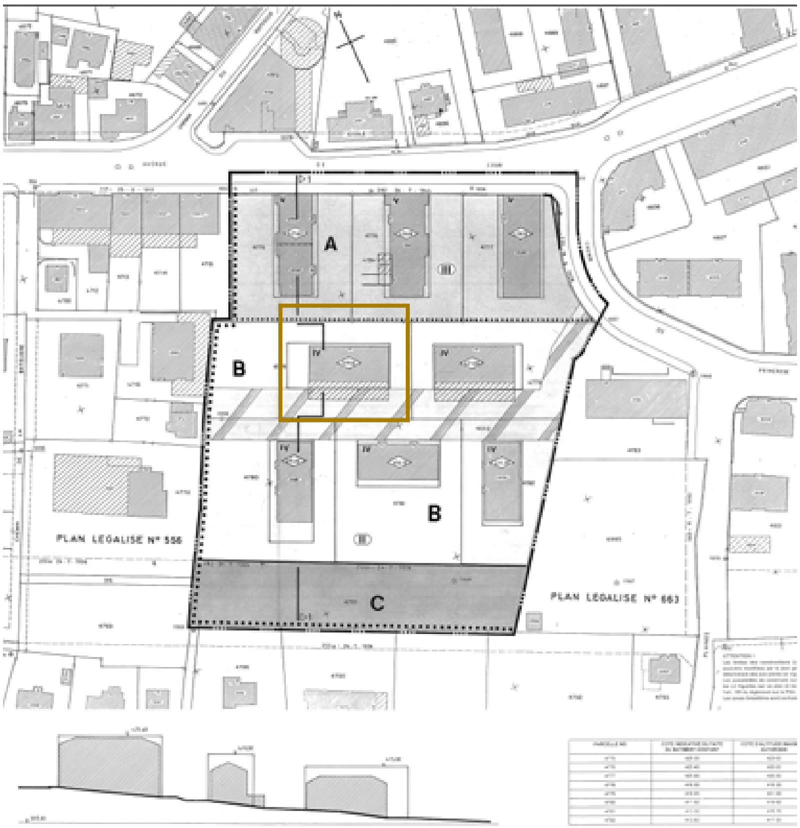


Figure 4.18
Existing building in plot 4778.

A partial zoning plan (PPA for Plan Partiel d'Affectation) is projected for the small area indicated in Figure 4.17, which includes the selected plot 4778. This PPA 676 allows increasing both the urban density and the building footprint of the existing construction (Figure 4.18).

Representative Swiss collective residential building

The identification of a representative collective residential building within the Swiss context sets a common base for the design of the different building scenarios, which can be comparable regarding energy efficiency.

The *representative* building (Figure 4.19) is designed based on the Swiss statistics for buildings constructed between 2006 and 2015 [OFS 2018] and on the study of Swiss collective residential buildings of recent construction presented in Section 4.2.1.1 This *representative* building consists of a five-storey block with two staircases and four double-oriented apartments per floor. This common base for all the building scenarios allows to compare the building's energy and economy performance and to evaluate the results which will be presented in Chapter 5.

The urban context of the PPA 676 is studied as well as the plot's building capacity and its construction limits. Based on this information, the *representative* building's scheme (Figure 4.19) is adapted to the requirements and limitations of the chosen plot in Chemin de Primerose, as illustrated in Figure 4.20. The final project resulted in a five-storey building with two staircases and six apartments per floor.

Façade design

As specified in the research framework, the current BIPV façade design is developed within an *innovative* approach. As a reminder, the *innovative*

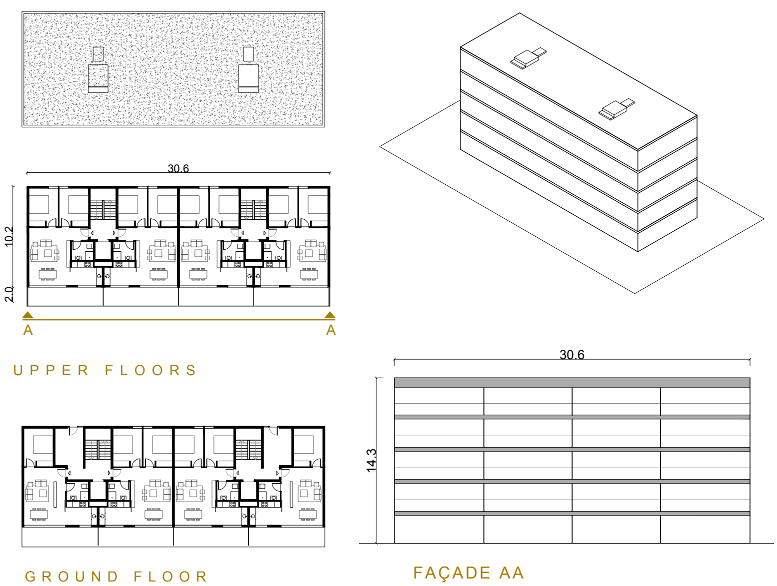


Figure 4.19
Representative collective residential building in Switzerland

approach maximises the integration of active surfaces in accordance with the façade design project and the type of BIPV integration chosen. This approach involves the incorporation of active surfaces in all four façades to increase the total annual energy output of the BIPV installation.

The starting point of the façade design process is the analysis results presented in Section 4.2. The contemporary façade analysis results in the identification of façade and BIPV design features that affect BIPV integration into contemporary façade design. These are the façade's composition, the façade's morphology, the BIPV's visual features, and the BIPV's functional features. The combination of these aspects is the basis for the generation of AAF building scenarios, as illustrated in Figure 4.21.

In order to reasonably limit the number of scenarios developed within this research process, the combinations have been performed as follows: the four façade composition strategies are combined with the three BIPV's visual features identified in Section 4.2.2.1. More precisely, this results in twelve scenarios that combine the *Slab to slab, Total storey, Balustrades* and *Total volume* façade composition strategies with *Opaque, Translucent* and *Transparent* BIPV systems. The remaining design aspects, that is to say, the different façade morphologies and the different BIPV façade functions, are incorporated into the design process to generate design variants of the main AAF building scenarios.

The set of AAF building scenarios implement the AAF into architectural design practices and show how BIPV can be integrated into the façade design process. The objective of this façade design phase is to illustrate, from an architectural approach, how façade cladding, external shading devices, glazing and other façade applications can be designed as active surfaces on a BIPV façade. These façade applications can incorporate opaque, translucent or transparent BIPV systems, respectively and depend on the façade's specific architectural

Figure 4.20
Chemin de Primerose's collective residential building project: Site plan.

requirements. In that sense, it displays a variety of possibilities where the AAF construction system can be implemented.

Ultimately, the AAF implementation process produces a set of architecture plans and three-dimensional visualisations to publicly communicate the building scenario design outcome following an architectural language. With a building scale, the AAF building scenarios are the basis for the quantitative assessment of the AAF, enabling building energy and economic simulations (Chapter 5) which can be compared with common practices.

The following pages present the AAF building scenarios, which are labelled according to the composition strategy classified by number (1: *Slab to slab*; 2: *Total storey;* 3: *Balustrade; 4: Total volume*) and according to the type of BIPV system classified by letter (A: *Opaque BIPV;* B: *Translucent BIPV*; and C: *Transparent BIPV*).

Each AAF building scenario is presented with a graphic description of the project including architectural visualisation and architectural drawings (plans and elevations) and with a written description of the façade design aspects (façade composition, façade morphology, BIPV visual features and BIPV functional features).

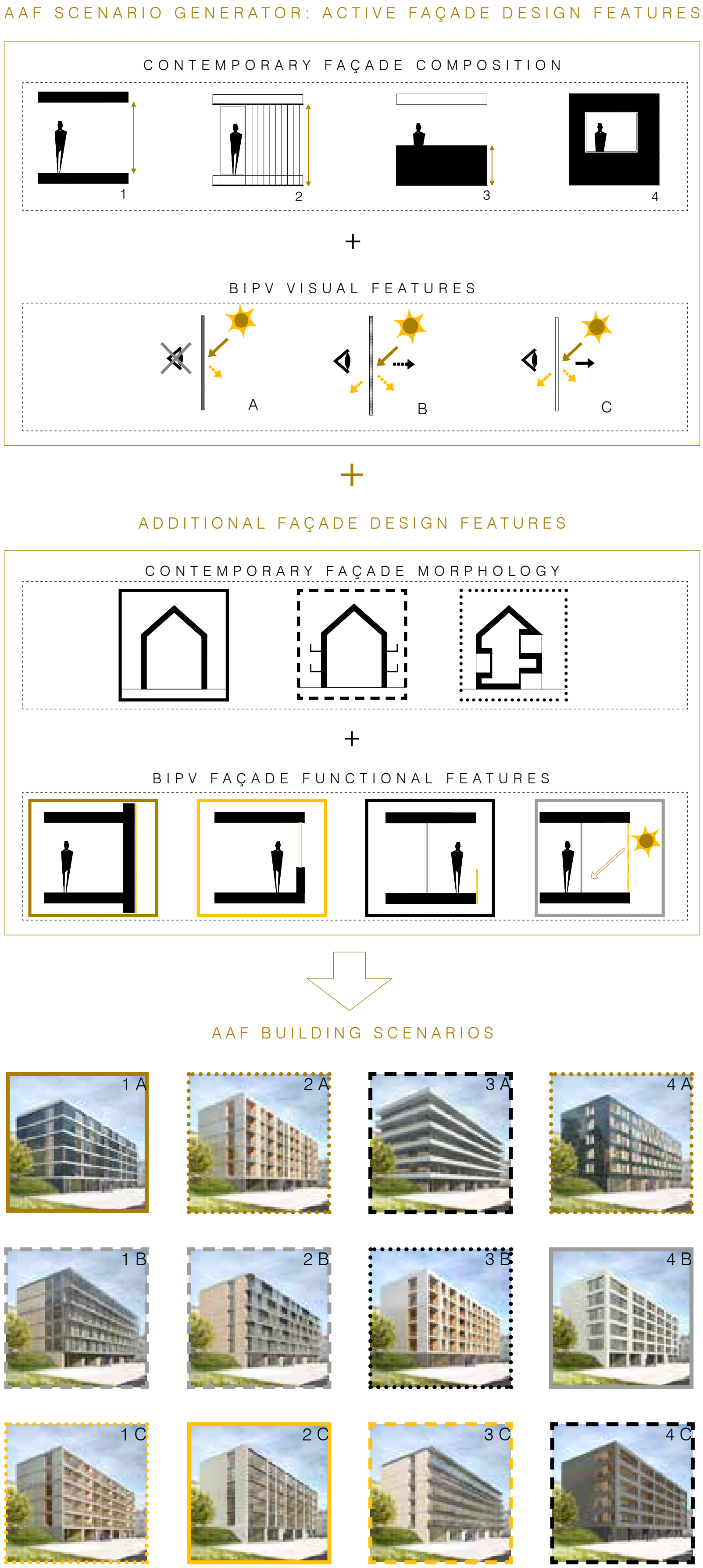


Figure 4.21
AAF implementation methodology

AAF BUILDING SCENARIO 1A

Figure 4.22
Architectural visualization of the AAF building scenario 1A.

BUILDING SCENARIO DATA

TOTAL ACTIVE SURFACE ON FAÇADE:

825 m²

south façade: 213 m²
east façade: 161 m²
west façade: 161 m²
north façade: 290 m²

BIPV SYSTEM:

visual feature: opaque
functional feature: façade cladding

FAÇADE DESIGN:

façade composition: slab to slab
façade morphology: clean volume

MARKET READY PV TECH:
Monocrystalline

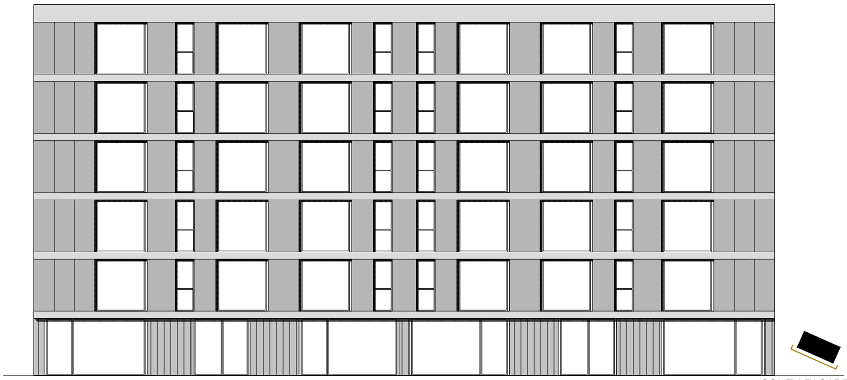
HIGH-PERFORMANCE PV TECH:
Tandem-Perovskite

BUILDING

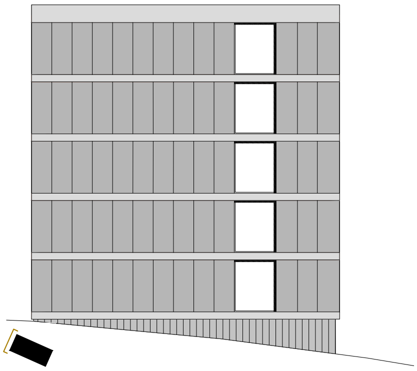
ERA: 2843 m²

A_{th}: 2806 m²

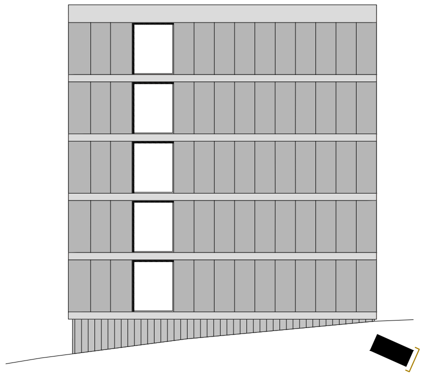
Shape factor (compactness): 1



SOUTH FAÇADE

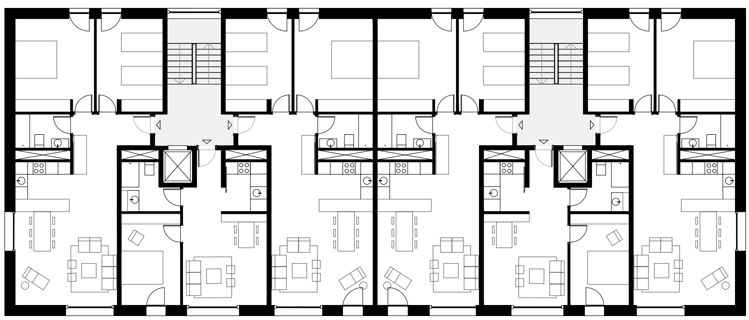


WEST FAÇADE



EAST FAÇADE

NORTH FAÇADE



LEVEL 1
404.60 m

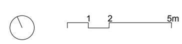


Figure 4.23
Façades elevations and building plans for the AAF building scenario 1A.

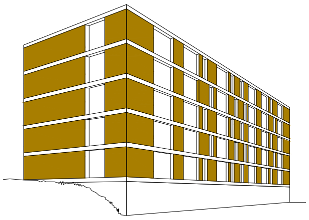


Figure 4.24
Schematic façade BIPV integration. AAF building scenario 1A.

The 1A AAF building scenario combines a *Slab to slab* façade composition with an opaque BIPV façade cladding.

Façade composition

The *Slab to slab* façade composition displays the horizontal slab of each floor by a horizontal metal profile along the entire façade. The metal profiles define the façade surface in between slabs, where BIPV is integrated as a uniform façade cladding in the entire façade (Figure 4.24).

The area defined for BIPV integration has a 250 cm height, which is covered with three BIPV panels of 83 cm height and variable width. This variant is represented in the building image (Figure 4.22). However, the BIPV panels can also be designed with total height BIPV panels of 250 cm and 100 cm length. This variant is represented in the architectural drawings (Figure 4.23).

Façade morphology

The definition of a Clean volume characterises the 1A's façade morphology. The absence of elements protruding from the façade allows a total active façade to be designed.

The absence of loggias improves the thermal performance of the building, thanks to its compactness [Richarz *et al.* 2008]. Consequently, this project has the potential to be highly energy-efficient.

The building's shape factor is calculated based on the total surface of the thermal envelope (A_{th}) divided by the energy reference area (ERA) [Marsault 2018]. In this case, (Figure 4.2), the shape factor is 1.00.

BIPV visual features

This building scenario incorporates a BIPV system that consists of frameless glass-glass opaque BIPV panels. The façade displays dark PV technology, which can be Monocrystalline silicon, Thin-Film or Tandem-Perovskite.

BIPV functional features

The BIPV system is integrated as a façade cladding with an invisible ventilated façade substructure, as illustrated in Figure 4.6. The invisible fastening system of the BIPV panels is adhered to the backside of the modules with SSG, according to detail in Figure 4.8.

Design remarks

The horizontal metal profiles that divide the façade composition into horizontal sectors must be kept coplanar to the active surface. A protrusion of this element would cast a permanent shadow on BIPV cells, which can notably affect the final energy output of the BIPV system.

The total BIPV façade design needs to be adapted to the building environment as well as to the potential dysfunction of some elements. In this case, dummy[6] panels should be installed in lower west façade to prevent the nearby vegetation from casting a shadow on active surfaces.

Large BIPV installations, such as the one integrated into building scenario 1A, risk to over-generate electricity exceeding the building's energy demand. This issue will be discussed in Chapter 5, where an energy simulation of all AAF building scenarios is assessed, and storage integration is evaluated.

6
A Dummy panel is a non-active panel that has the same aspect as active BIPV panels.

AAF BUILDING SCENARIO 1B

Figure 4.25
Architectural visualization of the AAF building scenario1B.

BUILDING SCENARIO DATA

TOTAL ACTIVE SURFACE ON FAÇADE:

377 m^2

*south façade: **148 m^2***
*east façade: **36 m^2***
*west façade: **36 m^2***
*north façade: **157 m^2***

BIPV SYSTEM:

*visual feature: **translucent***
*functional feature: **solar control***

FAÇADE DESIGN:

*façade composition: **slab to slab***
*façade morphology: **balconies***

MARKET READY PV TECH:
Monocrystalline

HIGH-PERFORMANCE PV TECH:
Tandem-Perovskite

BUILDING

*ERA: **2843 m^2***

*A_{th}: **2806 m^2***

*Shape factor (compactness): **1***

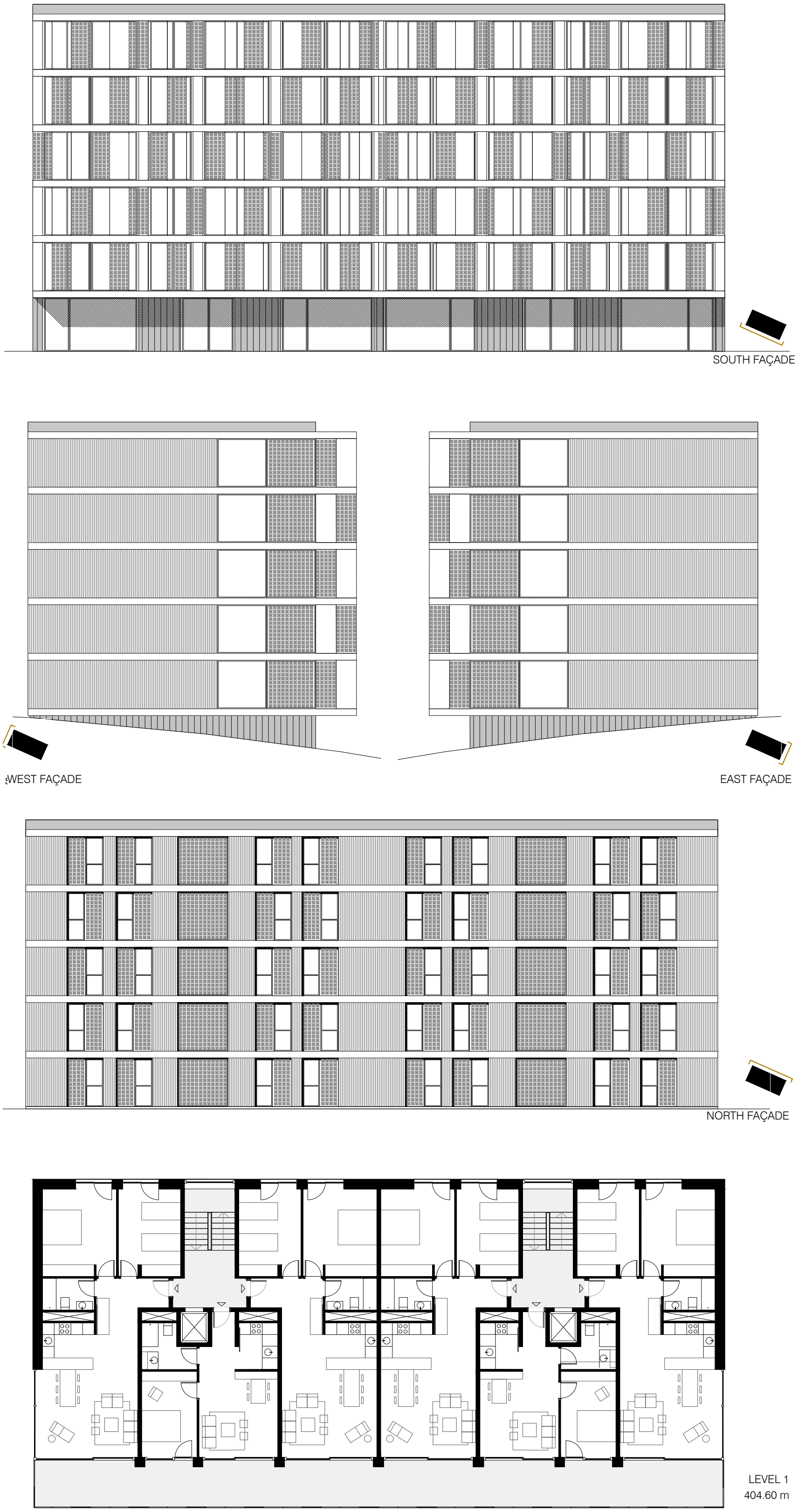


Figure 4.26
Façades elevations and building plans for the AAF building scenario 1B.

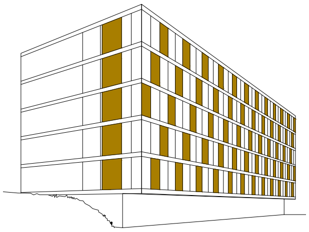


Figure 4.27
Schematic façade BIPV integration. AAF building scenario 1B.

The 1B AAF building scenario combines the *Slab to slab* façade composition strategy with translucent BIPV solar control elements.

Façade composition

The *Slab to slab* façade composition displays the horizontal slab of each floor by a horizontal metal profile along the entire façade. The metal profiles define the façade surface in between slabs where BIPV is integrated as translucent glazed solar control elements (Figure 4.26).

The area defined for BIPV integration has a 250 cm height which is covered with a single floor-to-ceiling BIPV panel. Panels of 100 cm width are designed for dimensional coordination purposes [United Nations 1974].

Façade morphology

The 1B's façade morphology corresponds to the previously-identified *Balconies* morphology. Most of the translucent BIPV system is incorporated into the south façade, which is designed with long glazed terraces to form a winter-garden. The glass-glass translucent active panels are integrated and regularly interleaved in the glass façade surface (Figure 4.27). In this case, the transparent glass panes can be opened entirely and slid behind the BIPV panels, which are always fixed and kept under direct solar irradiation.

The façade morphology does not affect the building's shape factor because the thermal envelope does not include the winter-garden. Building scenario 1B's shape factor is 1.00.

BIPV visual features

This building scenario incorporates a BIPV system that consists of framed glass-glass translucent modules, which integrate wafer-based silicon cells (Monocrystalline, Polycrystalline or Tandem-Perovskite). Panel translucency is achieved through cell spacing: 65% of the BIPV panel is covered with PV cells, and the other 35% is left completely transparent.

BIPV functional features

The BIPV system is integrated as a façade solar control system, as presented in Figure 4.13. The fastening system of the BIPV panels is located at the top and the bottom of the BIPV panel and the panel is mechanically fixed to a metal frame, as shown in Figure 4.13.

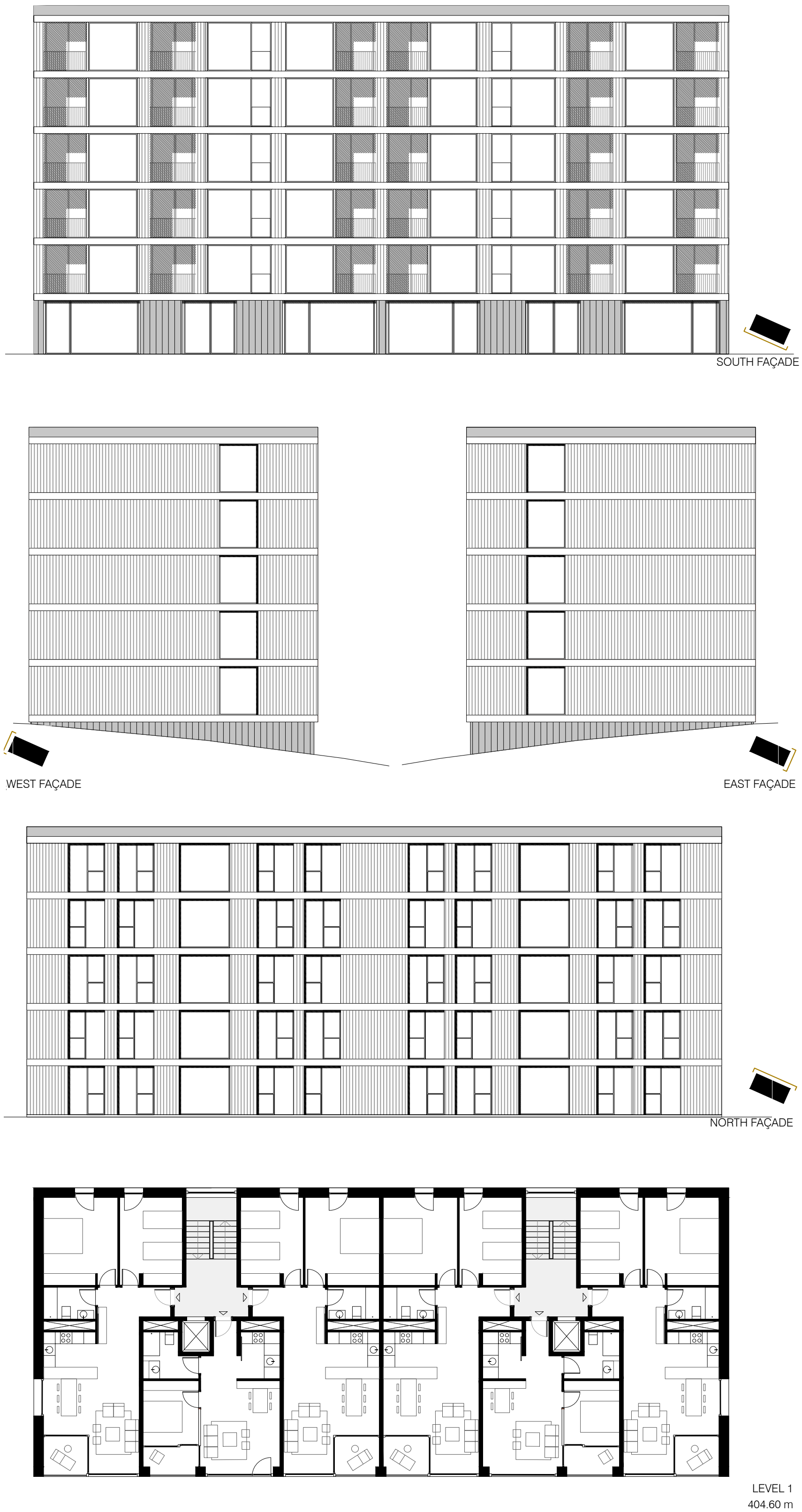
Design remarks

Elements protruding from the active surface must be avoided. This means that horizontal slab profiles must be kept coplanar with the BIPV modules and that all sort of railing or balcony protection must be installed behind the BIPV system. For the same reason, all winter-garden openings must slide behind the BIPV panels or be opened towards the interior.

East, west and north façades also integrate translucent BIPV glazing in room and staircase windows (Figure 4.27). Translucent BIPV is not integrated into windows where exterior views are required. Instead, it is limited to complementary glazed surfaces where light is required, and views are provided through other windows.

AAF BUILDING SCENARIO 1C

Figure 4.28
Architectural visualization of the AAF building scenario 1C.



BUILDING SCENARIO DATA

TOTAL ACTIVE SURFACE ON FAÇADE:

272 m²

south façade: 167 m²
east façade: 24 m²
west façade: 24 m²
north façade: 157 m²

BIPV SYSTEM:

visual feature: transparent
functional feature: façade glazing

FAÇADE DESIGN:

façade composition: slab to slab
façade morphology: loggias

MARKET READY PV TECH:
Thin-Film

HIGH-PERFORMANCE PV TECH:
Thin-Film

BUILDING

ERA: 2617 m²

A_{th}: 2931 m²

Shape factor (compactness): 1.1

Figure 4.29
Façades elevations and building plans for the AAF building scenario 1C.

Figure 4.30
Schematic façade BIPV integration. AAF building scenario 1C.

The 1C AAF building scenario combines the *Slab to slab* façade composition strategy with transparent BIPV glazing.

Façade composition

The *Slab to slab* façade composition displays the horizontal slab of each floor by a horizontal metal profile along the entire façade. The metal profiles define the façade surface in between slabs, where BIPV is integrated as transparent façade windows (Figure 4.30).

The area defined for BIPV integration has a 250 cm height, which is covered with floor-to-ceiling BIPV windows of variable dimensions varying from 100cm to 300cm (Figure 4.28 and Figure 4.29).

Façade morphology

The 1C's façade morphology incorporates *Loggias* to define the apartments exterior spaces. This increases the thermal envelope surface while reducing the building's ERA and increasing the building's shape factor to 1.12. A higher shape factor means that the building is less compact, which, at this preliminary design stage, is an indicator of higher energy demand.

BIPV visual features

This building scenario integrates BIPV panels which consist of transparent Thin-Film photovoltaic technology in a glass-glass BIPV module. The transparency of the BIPV panels is achieved by perforating the Thin-Film layer with laser-based techniques. Panels of different transparencies can be fabricated with this method. The BIPV system displayed in 1C offers a 30% visible light transmittance.

BIPV functional features

The BIPV system is integrated as façade glazing, as presented in Figure 4.28. The BIPV surface is integrated into a regular window frame of specifically 250 cm height to be integrated into 1C's façade composition.

Design remarks

This AAF building scenario has brought out a major issue when developing BIPV glazing. Heat gains due to solar irradiation on windows can lead to interior space overheating, especially in summer. The most effective way to avoid this is to block solar irradiation on the glazed surface with exterior solar control elements. At the moment, in Switzerland, the installation of exterior slatted blinds is the most popular solution. Consequently, if solar irradiation is blocked before reaching BIPV glazing, there will be no energy generation on the active surface at the time of direct irradiation of the active surface.

This strategy illustrates a problem that can be solved by changing the glazed surface orientation or applying this façade design on buildings located in colder climates where passive energy gains are welcomed in every season. Another solution would be to develop BIPV technologies with high albedo performance, which would have a good energy performance when not directly irradiated.

AAF BUILDING SCENARIO 2A

Figure 4.31
Architectural visualization of the AAF building scenario 2A.

BUILDING SCENARIO DATA

TOTAL ACTIVE SURFACE ON FAÇADE:

843 m²

south façade: 167 m²
east façade: 179 m²
west façade: 179 m²
north façade: 318 m²

BIPV SYSTEM:

visual feature: opaque
functional feature: façade cladding

FAÇADE DESIGN:

façade composition: total storey
façade morphology: loggias

MARKET READY PV TECH:
Filtered Monocrystalline

HIGH-PERFORMANCE PV TECH:
Filtered Tandem-Perovskite

BUILDING

ERA: 2617 m²

A_{th}: 2931 m²

Shape factor (compactness): 1.1

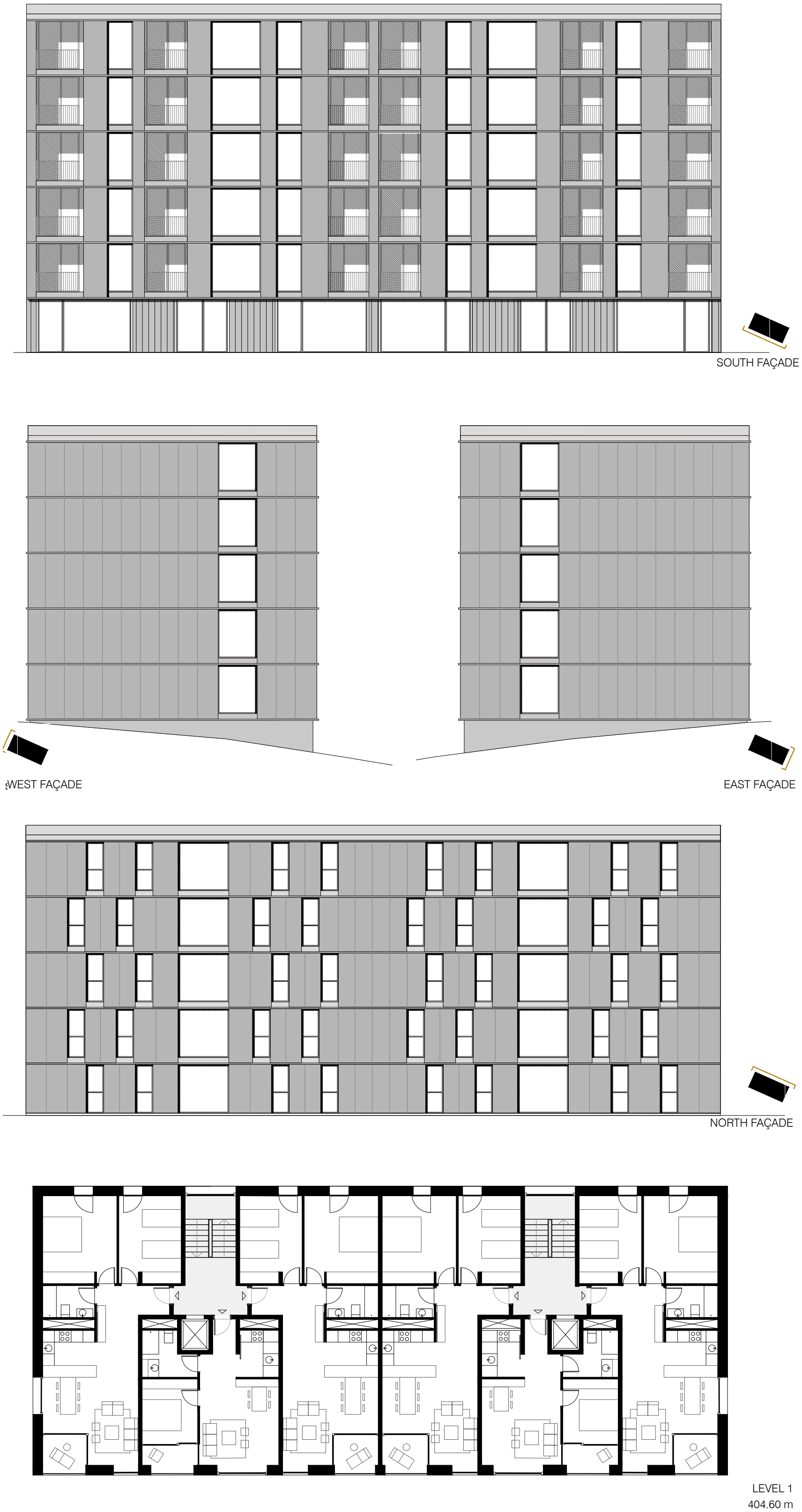


Figure 4.32
Façades elevations and building plans for the AAF building scenario 2A.

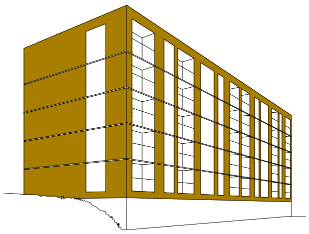


Figure 4.33
Schematic façade BIPV integration. AAF building scenario 2A.

The 2A AAF building scenario combines the *Total storey* façade composition strategy with an opaque BIPV façade cladding.

Façade composition

The *Total storey* façade composition displays each storey dimension with a small horizontal profile or a specific façade layout. In the case of 2A, a thin aluminium profile is selected to integrate the façade design and emphasise the storey dimension of 285 cm, according to Swiss common practices.

The surface in between profiles integrates BIPV opaque façade cladding (Figure 4.33), which can be of small format as represented on the architectural visualisation of the building (Figure 4.31) or total height format as represented on the architectural drawings on Figure 4.32.

Façade morphology

The 2A's façade morphology incorporates *Loggias* to define the apartments exterior spaces. This increases the thermal envelope surface while reducing the building's ERA and increasing the building's shape factor to 1.12. A higher shape factor means that the building is less compact, which is an indicator at the preliminary design stage of higher energy demand.

BIPV visual features

This building scenario incorporates a BIPV system that consists of frameless glass-glass opaque BIPV panels. The façade displays filtered BIPV panels with the modified visual expression of the active surface. The filter is a light-permeable grey metallic mesh that alters the colour and texture of regular BIPV panels enhancing its aesthetic potential. However, a 35% panel energy performance loss is associated with the incorporation of the filter, compared to a regular Monocrystalline or Tandem-Perovskite BIPV panel [Söderström 2018] (Section 3.2.2.1).

BIPV functional features

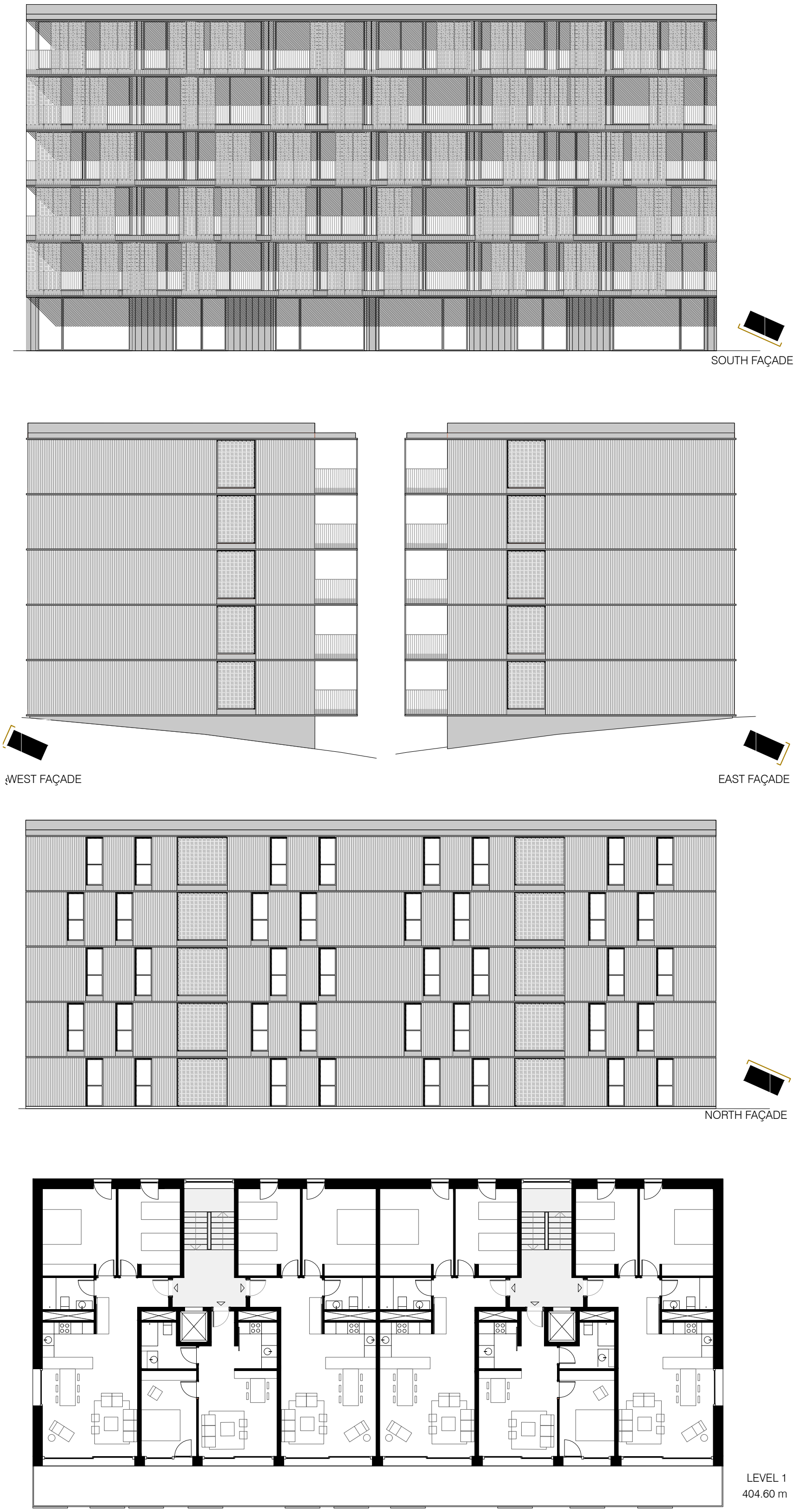
The BIPV system is integrated as a façade cladding with an invisible ventilated façade substructure, as illustrated in Figure 4.6. The invisible fastening system of the BIPV panels is adhered to the backside of the modules with structural sealant glazing (SSG), according to detail in Figure 4.8.

Design remarks

This type of façade design integrates a metal profile to define the floor height. As in previous façade designs, this profile should be kept coplanar to the active surface. However, for aesthetic reasons, this façade design searches the shadow line on purpose to enhance horizontality. For this reason, BIPV panel construction must take this into account and foresee a space at the top of every panel where no PV cells are placed.

AAF BUILDING SCENARIO 2B

Figure 4.34
Architectural visualization of the AAF building scenario 2B.



BUILDING SCENARIO DATA

TOTAL ACTIVE SURFACE ON FAÇADE:

356 m^2

south façade: 250 m^2
east façade: 23 m^2
west façade: 23 m^2
north façade: 60 m^2

BIPV SYSTEM:

visual feature: translucent
functional feature: solar control

FAÇADE DESIGN:

façade composition: total storey
façade morphology: balconies

MARKET READY PV TECH:
Polycrystalline

HIGH-PERFORMANCE PV TECH:
Tandem-Perovskite

BUILDING

ERA: 2843 m^2

A_{th}: 2806 m^2

Shape factor (compactness): 1

Figure 4.35
Façades elevations and building plans for the AAF building scenario 2B.

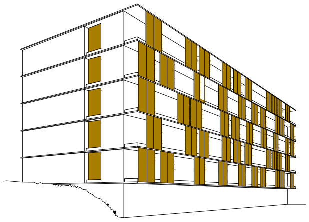


Figure 4.36
Schematic façade BIPV integration. AAF building scenario 2B.

The 2B AAF building scenario combines the *Total storey* façade composition strategy with translucent BIPV solar control panels.

Façade composition

The *Total storey* façade composition displays a small metal profile that goes around the thermal envelope and the balconies at the level of the horizontal slab, unifying the whole building's architectural expression and defining each storey dimension at 285 cm.

This space is defined for BIPV integration, which is covered by total height BIPV panels of 180 cm width, combining two 90 cm BIPV panels framed together (Figure 4.34 and Figure 4.35).

Façade morphology

The 2B's façade morphology corresponds to the *Balconies* group. Most of the translucent BIPV system is incorporated into the south façade which is designed with long balconies along the whole façade.

This façade morphology does not affect the building's shape factor, which is 1.00.

BIPV visual features

This building scenario incorporates a BIPV system that consists of framed glass-glass translucent modules, which integrate wafer-based silicon cells (Monocrystalline, Polycrystalline or Tandem-Perovskite). Panel translucency is achieved through cell spacing: 65% of the BIPV panel is covered with PV cells, and the other 35% is left entirely transparent.

BIPV functional features

BIPV panels are integrated as sliding elements for solar control purposes, as shown in Figure 4.13. The sliding guide of the panels must limit BIPV movement so that there is no BIPV overlapping, which would lead to panel shading and minimise the energy output.

Design remarks

Elements protruding from the active surface must be avoided. This means that the horizontal profiles must be kept coplanar with the BIPV modules and that all sort of railing or balcony protection must be installed behind the BIPV system to avoid panel shading.

In the 2B building scenario, the sliding BIPV elements must be on the same rail so that there is never a superposition of two or more BIPV panels.

In addition, translucent BIPV modules are integrated into some windows of the east and west façades as well as in the north façade. In the same way that is done for the AAF building scenario 1B, translucent BIPV integration in windows is limited to those where exterior views are not required. These windows are located on the building staircase or in the dining area of some apartments, where other windows provide views to the exterior space.

This façade design raises the issue of the BIPV system's manoeuvrability. Sliding BIPV panels involve an extra complexity at the time of the design of the electrical connections. Although this type of BIPV sliding systems already exists on the market, it is going to require higher maintenance than a fixed translucent BIPV system.

AAF BUILDING SCENARIO 2C

Figure 4.37
Architectural visualization of the AAF building scenario 2C.

BUILDING SCENARIO DATA

TOTAL ACTIVE SURFACE ON FAÇADE:

258 m^2

south façade: 48 m^2
east façade: 25 m^2
west façade: 25 m^2
north façade: 160 m^2

BIPV SYSTEM:

visual feature: transparent
functional feature: façade glazing

FAÇADE DESIGN:

façade composition: total storey
façade morphology: clean volume

MARKET READY PV TECH:
Thin-Film

HIGH-PERFORMANCE PV TECH:
Thin-Film

BUILDING

ERA: 2843 m^2

A_{th}: 2806 m^2

Shape factor (compactness): 1

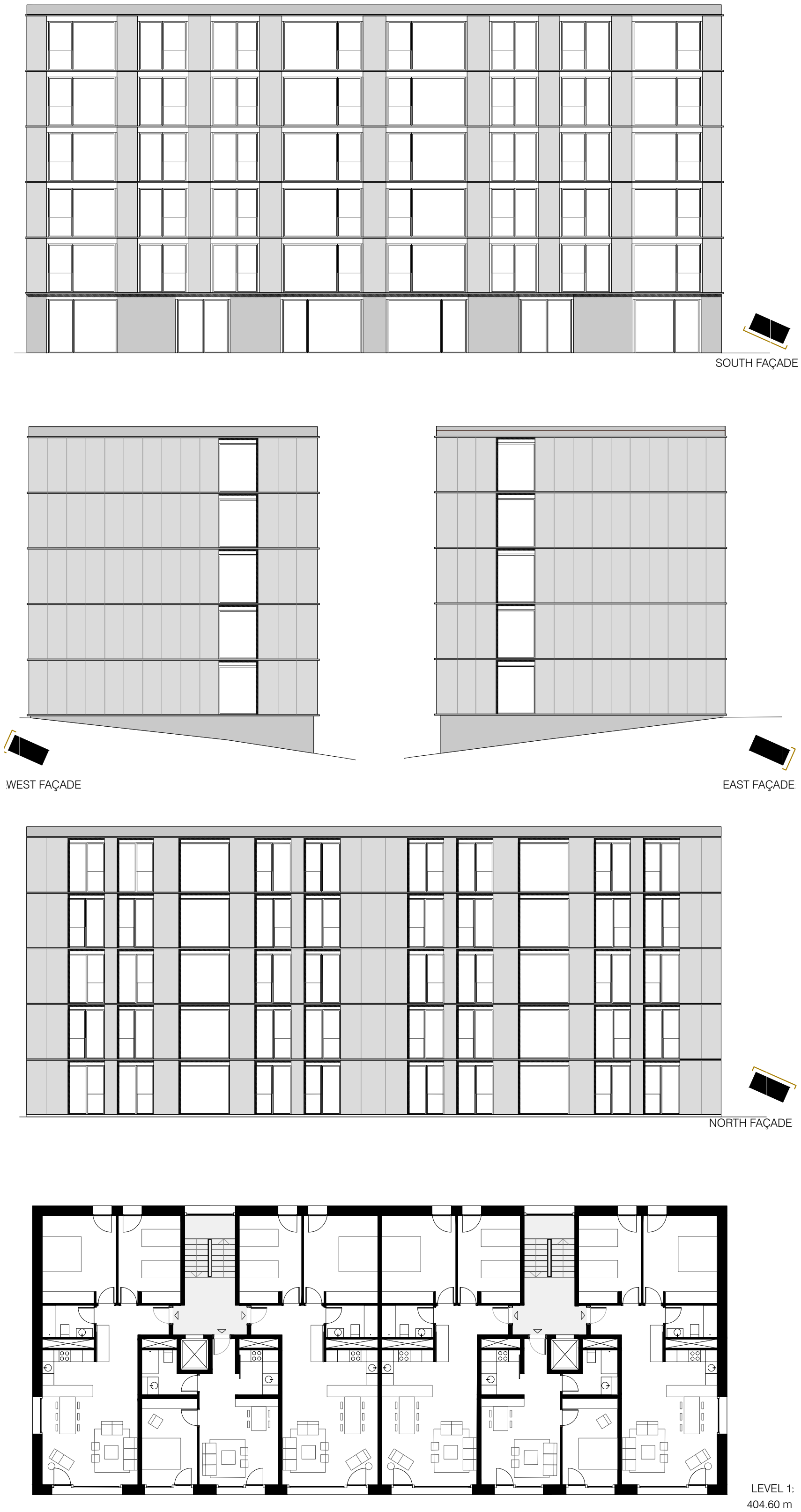


Figure 4.38
Façades elevations and building plans for the AAF building scenario 2C.

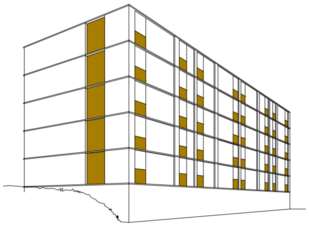


Figure 4.39
Schematic façade BIPV integration.
AAF building scenario 2C.

The 2C AAF building scenario combines the *Total storey* façade composition strategy with transparent BIPV glazing.

Façade composition

The *Total storey* façade composition includes thin profiles around the entire façade, which evoke a reference to the horizontal structure of the building and display the storey dimension at 285 cm. In this case, the profile is made of prefabricated concrete pieces like the rest of the façade cladding.

Façade morphology

The 2C's façade morphology is characterised by the definition of a *Clean volume*. The absence of elements protruding from the façade provides design liberty to incorporate active surfaces into any façade element – in this case, into windows (Figure 4.37).

The façade morphology corresponds to the one classified as a *Clean volume* (Figure 4.2), which has a shape factor of 1.00.

BIPV visual features

This building scenario integrates BIPV panels consisting of transparent Thin-Film photovoltaic technology in a glass-glass BIPV module. The transparency of the BIPV panels is achieved by perforating the Thin-Film layer with laser-based techniques. Panels of different transparencies can be fabricated with this method. The BIPV system displayed on 2C offers a 30% visible light transmittance.

BIPV functional features

The BIPV system is integrated as façade glazing as presented in Figure 4.9. The BIPV surface is integrated into a regular window frame of specifically 250 cm height to be integrated into 2C's façade composition (Figure 4.38).

Design remarks

The horizontal metal profiles that divide the façade composition into horizontal sectors must be kept coplanar to the active surface. A protrusion of this element would cast a permanent shadow on BIPV cells, which can notably affect the final energy output of the BIPV system.

BIPV glazing is adapted to window fabrication and its dimensional coordination. Even if the predominant dimension of the façade is 285 cm, windows are limited to a maximum height of 250 cm to avoid thermal bridges.

This building scenario was initially designed with full active window glazing on the south orientation. However, a critical review of all designs brought out the incompatibility between highly-irradiated active window glazing and window shading systems, which are required in south-oriented glazed façades. The 1C building scenario maintains the initial design to illustrate this remark, but 2C is modified to illustrate the optimisation process of the architectural approach better.

AAF BUILDING SCENARIO 3A

Figure 4.40
Architectural visualization of the AAF building scenario 3A.

BUILDING SCENARIO DATA

TOTAL ACTIVE SURFACE ON FAÇADE:

558 m²

south façade: 192 m²
east façade: 87 m²
west façade: 87 m²
north façade: 192 m²

BIPV SYSTEM:

visual feature: opaque
functional feature: façade security

FAÇADE DESIGN:

façade composition: balustrade
façade morphology: balconies

MARKET READY PV TECH:
Filtered Monocrystalline

HIGH-PERFORMANCE PV TECH:
Filtered Tandem-Perovskite

BUILDING

ERA: 2843 m²

A_{th}: 2806 m²

Shape factor (compactness): 1

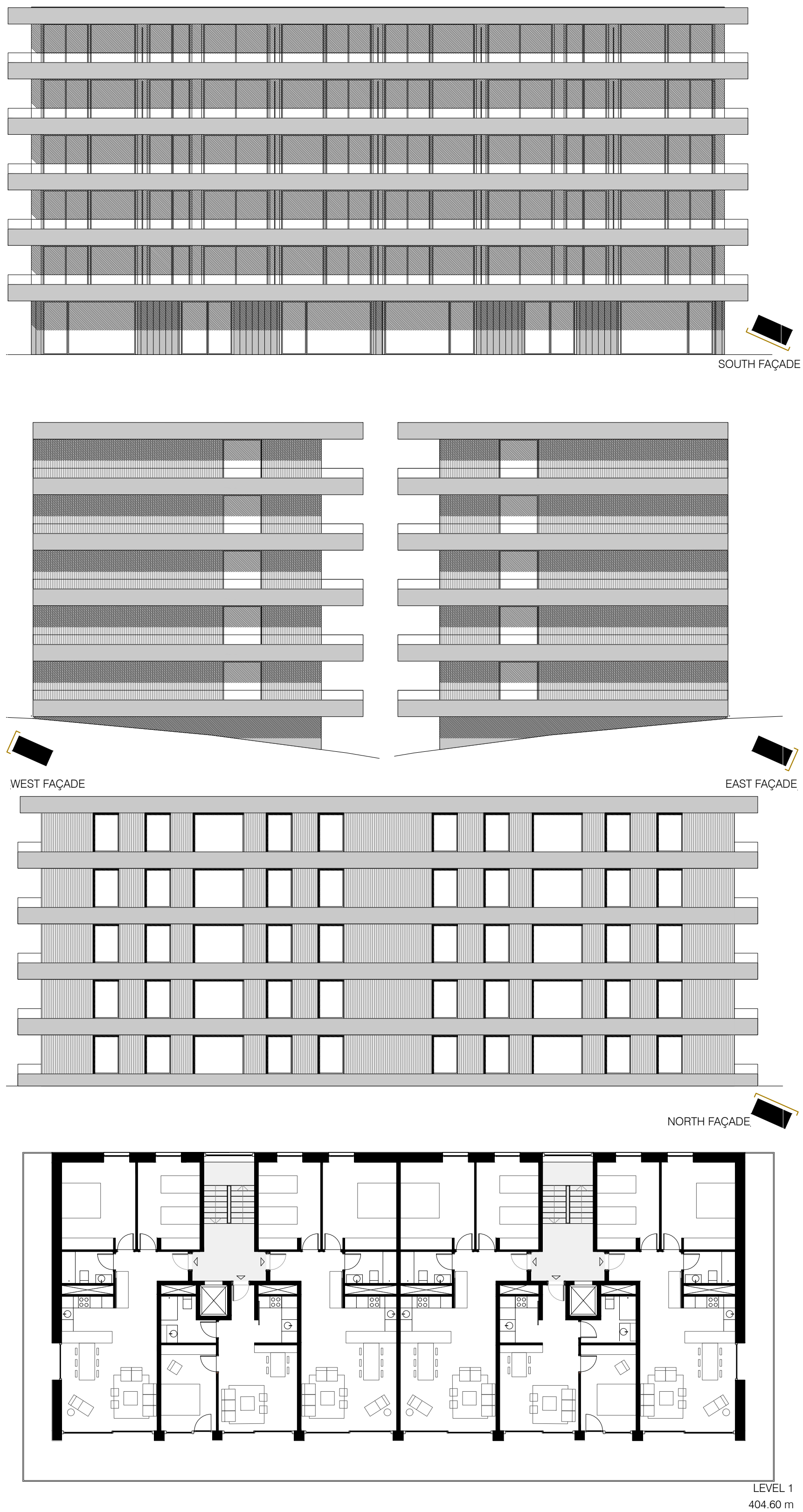


Figure 4.41
Façades elevations and building plans for the AAF building scenario 3A.

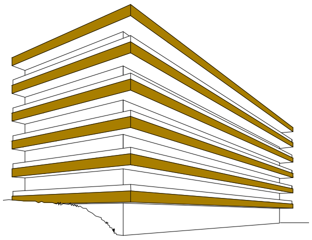


Figure 4.42
Schematic façade BIPV integration.
AAF building scenario 3A.

The 3A AAF building scenario combines the *Balustrade* façade composition strategy with an opaque BIPV balustrade railing.

Façade composition

The *Balustrade* façade composition includes façade designs where the balcony or loggia's balustrade dimension predominates. This dimension is usually around one-meter-high but can vary depending on the façade's design.

In this case, the balustrade is composed of a 100 cm high opaque parapet and a glazed 35 cm railing.

Façade morphology

This building scenario has a façade morphology that integrates balconies on the south, east and west façades without altering the original thermal envelope of the building, as shown in Figure 4.40. This results in a shape factor of 1.00.

BIPV visual features

This building scenario incorporates a BIPV system that consists of frameless glass-glass opaque BIPV panels (Figure 4.42). The façade displays filtered BIPV panels with the modified visual expression of the active surface. The filter is a light-permeable grey metallic mesh that alters the colour and texture of the regular BIPV panels enhancing its aesthetic potential. However, an 35% panel energy performance loss is associated with the incorporation of the filter, compared to a regular Crystalline or Tandem-Perovskite BIPV panel [Söderström 2018] (Section 3.2.2.1).

BIPV functional features

The BIPV system is integrated as balustrade railing. It is composed of glazed elements that comply with balcony security requirements [SIA 358 2010]. These elements are installed to complete the regulatory height of one meter from the top of the terrace floor covering to the balcony railing (and Figure 4.41). The BIPV system substructure is a regular metal system fastened to the timber parapet of the balcony as displayed in the construction detail in Figure 4.11.

Design remarks

Balconies are usually the façade elements that protrude the most from the thermal envelope line. Consequently, there are no other façade elements that can cast a shadow on the balcony's vertical active surface. This guarantees complete solar irradiation throughout the day, considering a stand-alone building with no surrounding shadow casting. For this reason, BIPV integration in balconies is usually an effective and simple integration regarding façade design.

Balustrade BIPV integration presents other advantages such as normalised parapet dimensions by Swiss and European norms (SIA 358, 2010), which involves a BIPV standardisation potential to lower BIPV production costs. In addition, these formats are often around 1-meter-high, which define a panel size that is light to transport and easy to install. Ultimately, this type of BIPV integration has easy maintenance with no need to install scaffolding on the façade if BIPV panel replacement or cleaning is needed.

AAF BUILDING SCENARIO 3B

Figure 4.43
Architectural visualization of the AAF building scenario 3B.

BUILDING SCENARIO DATA

TOTAL ACTIVE SURFACE ON FAÇADE:

208 m^2

south façade: 118 m^2
east façade: 10 m^2
west façade: 10 m^2
north façade: 70 m^2

BIPV SYSTEM:

visual feature: translucent
functional feature: façade security

FAÇADE DESIGN:

façade composition: balustrade
façade morphology: balconies

MARKET READY PV TECH:
DSSC

HIGH-PERFORMANCE PV TECH:
Thin-Film

BUILDING

ERA: 2617 m^2

A_{th}: 2931 m^2

Shape factor (compactness): 1.1

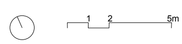


Figure 4.44
Façades elevations and building plans for the AAF building scenario 3B.

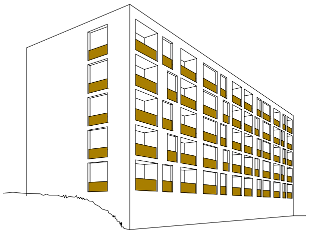


Figure 4.45
Schematic façade BIPV integration. AAF building scenario 3B.

The 3B AAF building scenario combines the *Balustrade* façade composition strategy with a translucent BIPV balustrade railing.

Façade composition

The *Balustrade* façade composition includes façade designs where the balcony or loggia's balustrade dimension predominates. This dimension is usually around one-meter-high but can vary depending on the façade's design. In this case, the balustrade is composed of a 100 cm high translucent railing.

Façade morphology

The 3B's façade morphology incorporates *Loggias* to define the apartments exterior spaces. This increases the thermal envelope surface while reducing the building's ERA and increasing the building's shape factor to 1.12. A higher shape factor means that the building is less compact, which is an indicator at the preliminary design stage of higher energy demand.

BIPV visual features

This building scenario incorporates translucent BIPV panels. These panels can integrate coloured PV technologies as DSSC, which is displayed in Figure 4.43, or translucent coloured Thin-Film BIPV panels.

BIPV functional features

Figure 4.45 illustrates how the building is designed with loggias and fully openable windows. Both façade elements require a balustrade for security reasons, on all four façades. BIPV balustrade glazing needs to comply with security requirements. Two horizontal metal profiles at the top and bottom of the BIPV panels form the BIPV fastening system. This allows keeping the translucent nature of the system by minimising the visibility of the fastening system. The fixing profiles are also designed to hide the metal connectors and the junction boxes of the BIPV panels, which are placed on the upper side of the modules, as shown in Figure 4.11.

Design remarks

Integrating DSSC BIPV technology involves integrating colour into the façade. Dye-Sensitized BIPV systems are produced on red, green, and orange colours, which are the ones that better harvest sunlight, according to H. Glass BIPV producers [Interview with I. Pola, 2017]. This characteristic opens a wide range of possibilities when integrating BIPV in façades.

The AAF building scenario 3B integrates active glass balustrades into loggias, which are coplanar with the façade cladding. In this type of scenario, a careful design must guarantee that no façade elements or accessories are casting a shadow over the BIPV panels. However, the particular technology integrated into this example is not as sensible as crystalline PV technologies to cell shading. It can generate energy with indirect light and in interior spaces [Interview with I. Pola, 2017].

AAF BUILDING SCENARIO 3C

Figure 4.46
Architectural visualization of the AAF building scenario 3C.

BUILDING SCENARIO DATA

TOTAL ACTIVE SURFACE ON FAÇADE:

335 m²

*south façade: **223 m²***
*east façade: **26 m²***
*west façade: **26 m²***
*north façade: **60 m²***

BIPV SYSTEM:

*visual feature: **transparent***
*functional feature: **façade security***

FAÇADE DESIGN:

*ffaçade composition: **balustrade***
*façade morphology: **balconies***

MARKET READY PV TECH:
Thin-Film,

HIGH-PERFORMANCE PV TECH:
Thin-Film

BUILDING

ERA: 2843 m²

A_{th}: 2806 m²

Shape factor (compactness): 1

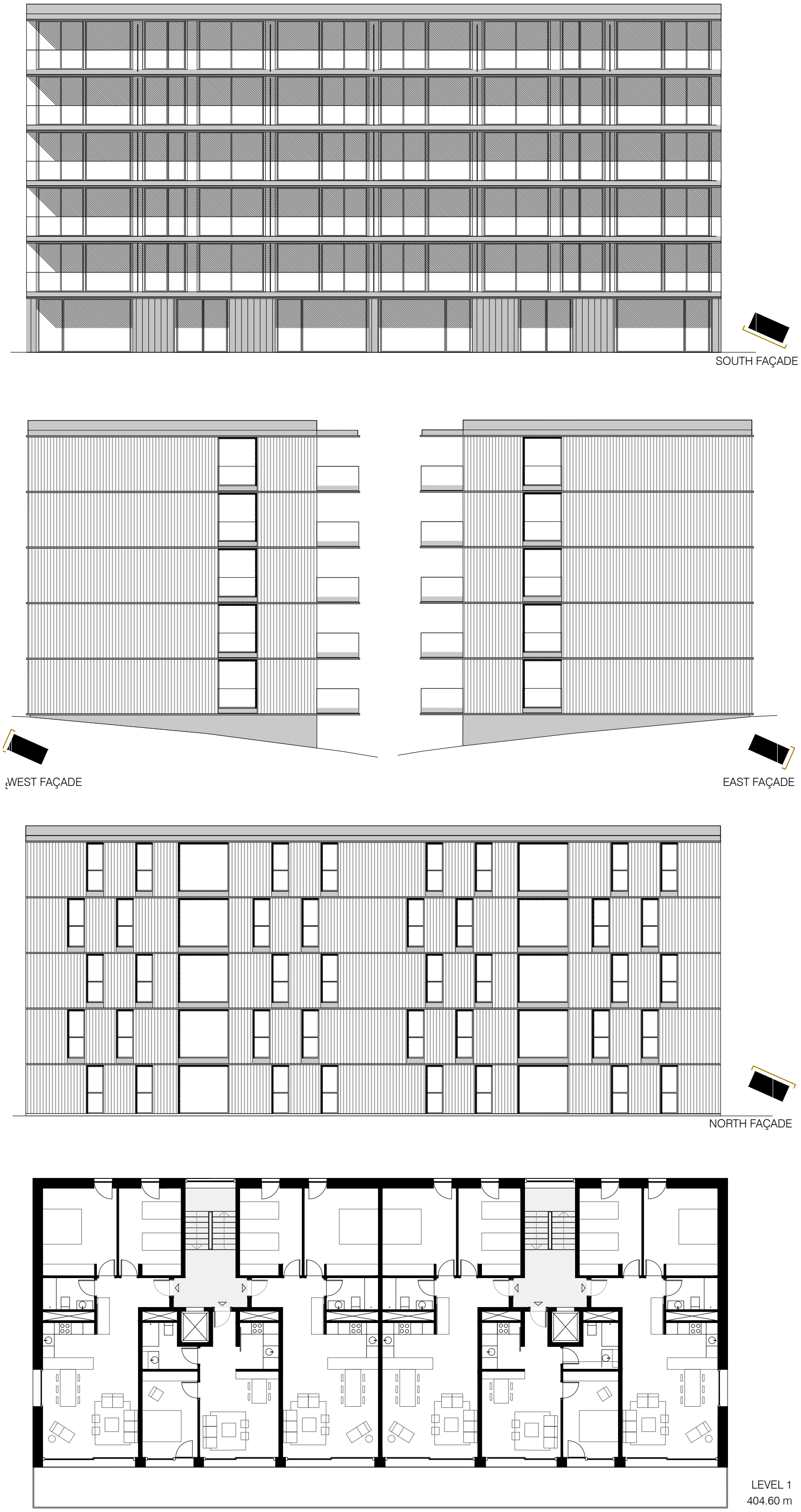


Figure 4.47
Façades elevations and building plans for the AAF building scenario 3C.

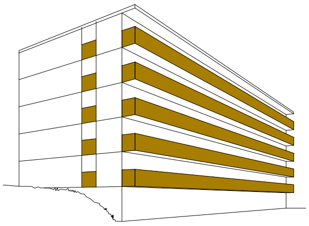


Figure 4.48
Schematic façade BIPV integration. AAF building scenario 3C.

The 3C AAF building scenario combines the *Balustrade* façade composition strategy with a transparent BIPV balustrade railing.

Façade composition

The *Balustrade* façade composition includes façade designs where the balcony or loggia's balustrade dimension predominates. This dimension is usually around 1 meter high but can vary depending on the façade's design.

In this case, the active glass surface that forms the balustrade (Figure 4.47) is placed in front of the slab edge, which measures 35 cm. This involves a minimum height of the balustrade's BIPV modules of 135 cm, for security reasons. The width of the panels is designed to have 100 cm for dimensional coordination purposes [United Nations 1974].

Façade morphology

This building scenario has a façade morphology which integrates balconies on the south façade without altering the original thermal envelope of the building, as shown in Figure 4.40. This results in a shape factor of 1.00.

BIPV visual features

This building scenario integrates BIPV panels consisting of transparent Thin-Film photovoltaic technology in a glass-glass BIPV module. The transparency of the BIPV panels is achieved by perforating the Thin-Film layer with laser-based techniques. Panels of different transparencies can be fabricated with this method. The BIPV system displayed on 3C offers a 30% visible light transmittance.

BIPV functional features

The building represented on Figure 4.46 integrates an active glass balustrade along with the balconies on its south façade and the east and west façade windows, highlighting horizontality on the façade's architectural expression (Figure 4.48).

The BIPV system is fastened as a regular glazed balustrade with a metal substructure that includes two metal railings on the top and the bottom of the panels and vertical profiles every 3 metres (Figure 4.11).

Design remarks

Transparent BIPV balustrades are fully ventilated surfaces with negligible shaded areas. They can replace regular glazed balustrades with little modifications of its construction system. Junction boxes and cabling need to be placed and routed within the substructure metal railings.

In the particular example of BIPV glazed balustrades, Thin-Film modules can work as BIPV bifacial modules when produced to do so. This is possible because balustrade surfaces are irradiated with direct and indirect light on both sides of the panel and the amorphous silicon is capable of generating energy from both front and rear faces, resulting in a higher energy output [Polysolar 2015; Guerrero-Lemus *et al.* 2016].

Due to the optimal performance of Thin-Film technologies under indirect light, the whole staircase windows integrate active glazing, as well as the fixed lower part of bedrooms' windows.

AAF BUILDING SCENARIO 4A

Figure 4.49
Architectural visualization of the AAF building scenario 4A.

BUILDING SCENARIO DATA

TOTAL ACTIVE SURFACE ON FAÇADE:

1011 m²

south façade: 273 m²
east façade: 205 m²
west façade: 205 m²
north façade: 328 m²

BIPV SYSTEM:

visual feature: opaque
functional feature: façade cladding

FAÇADE DESIGN:

façade composition: Total volume
façade morphology: Loggias

MARKET READY PV TECH:
Monocrystalline

HIGH-PERFORMANCE PV TECH:
Tandem-Perovskite

BUILDING

ERA: 2617 m²

A_{th}: 2931 m²

Shape factor (compactness): 1.1

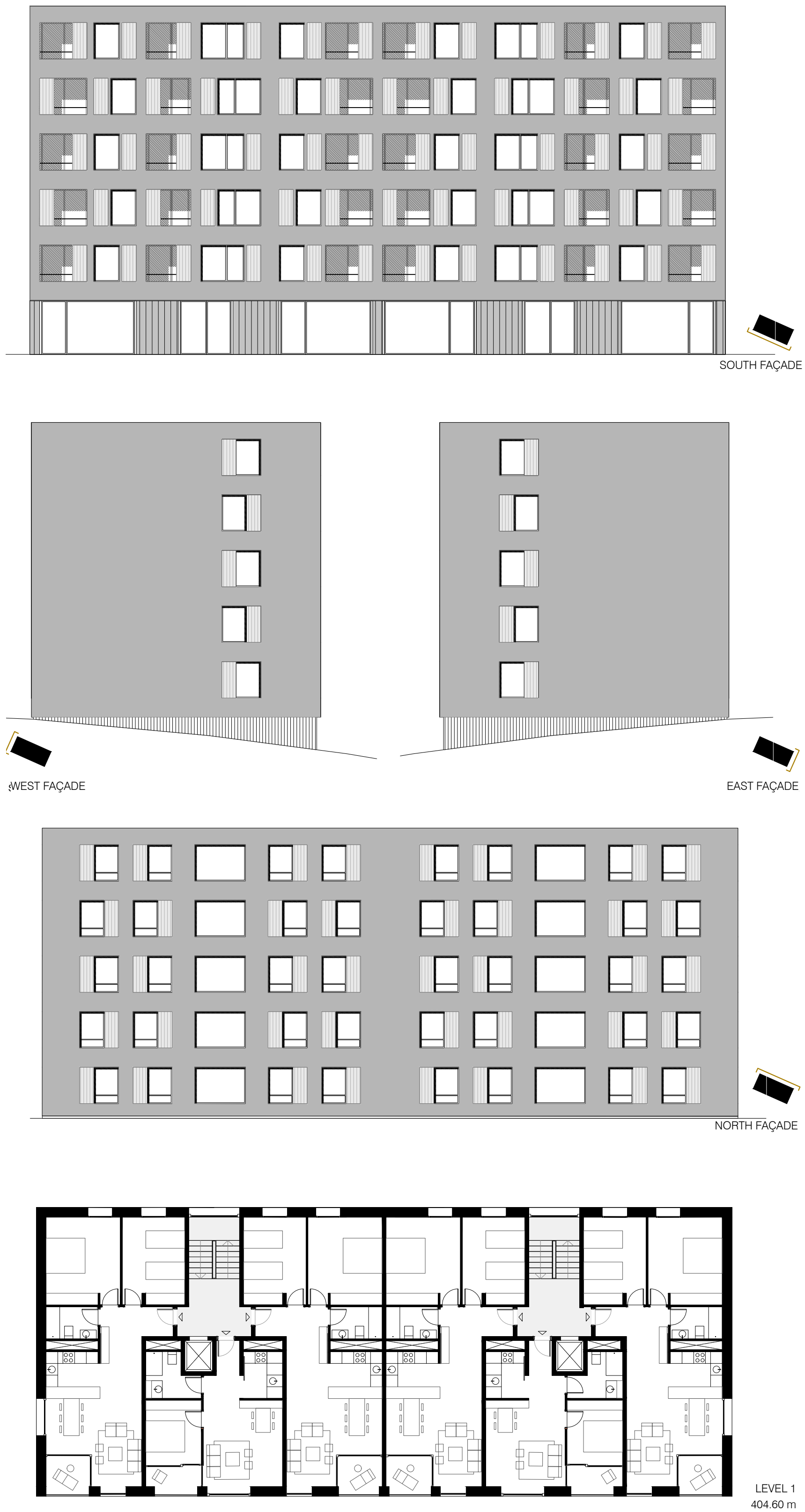


Figure 4.50
Façades elevations and building plans for the AAF building scenario 4A.

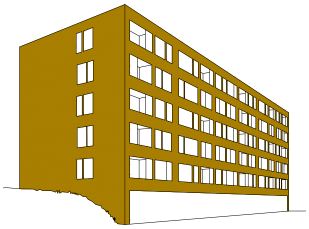


Figure 4.51
Schematic façade BIPV integration. AAF building scenario 4A.

The 4A AAF building scenario combines the *Total volume* façade composition strategy with an opaque BIPV façade cladding.

Façade composition

The *Total volume* façade composition produces a particular image of the building as a monolithic object. In this case, the BIPV system is incorporated as the façade cladding defining a total active skin (Figure 4.51).

There is no particular dimension that predominates in this AAF building scenario. Hence, for a better adaptation of the BIPV formats to the design, a small BIPV panel format is chosen (120 x 85 cm). This allows a more flexible façade design, more economical transportation, and easier handling on the construction site.

Façade morphology

The 4A's façade morphology incorporates *Loggias* to define the apartments exterior spaces (Figure 4.50). This increases the thermal envelope surface while reducing the building's ERA and increasing the building's shape factor to 1.12. A higher shape factor means that the building is less compact, which is an indicator at the preliminary design stage of higher energy demand.

BIPV visual features

This building scenario incorporates a BIPV system that consists of frameless glass-glass opaque BIPV panels, as illustrated in Figure 4.49. The façade displays dark PV technology, which can be Monocrystalline silicon, Thin-Film or Tandem-Perovskite.

BIPV functional features

The BIPV system is integrated as a façade cladding with an invisible ventilated façade substructure, as illustrated in Figure 4.6. The invisible fastening system of the BIPV panels is adhered to the backside of the modules with SSG, according to detail in Figure 4.8.

Design remarks

The AAF building scenario 4A illustrates a contemporary way of constructing façades where the structure is entirely covered by thermal insulation and protected with the façade cladding. This building scenario represents the *sustainable aesthetics* referred by Dahl Rocha in his book [Dahl Rocha *et al.* 2014].

In this particular case, the façade cladding integrates BIPV, transforming the façade into an envelope with electrical generation potential.

Large BIPV installations, such as the one integrated into the building scenario 4A façade, risk to over-generate electricity exceeding the building's energy demand. This issue will be discussed in Chapter 5, where an energy simulation of all AAF building scenarios is assessed, and storage integration is evaluated.

AAF BUILDING SCENARIO 4B

Figure 4.52
Architectural visualization of the AAF building scenario 4B.

BUILDING SCENARIO DATA

TOTAL ACTIVE SURFACE ON FAÇADE:

244 m²

south façade: 98 m²
east façade: 13 m²
west façade: 13 m²
north façade: 120 m²

BIPV SYSTEM:

visual feature: Translucent
functional feature: solar control

FAÇADE DESIGN:

façade composition: total volume
façade morphology: clean volume

MARKET READY PV TECH:
Polycrystalline

HIGH-PERFORMANCE PV TECH:
Tandem-Perovskite

BUILDING

ERA: 2843 m²

A_{th}: 2806 m²

Shape factor (compactness): 1

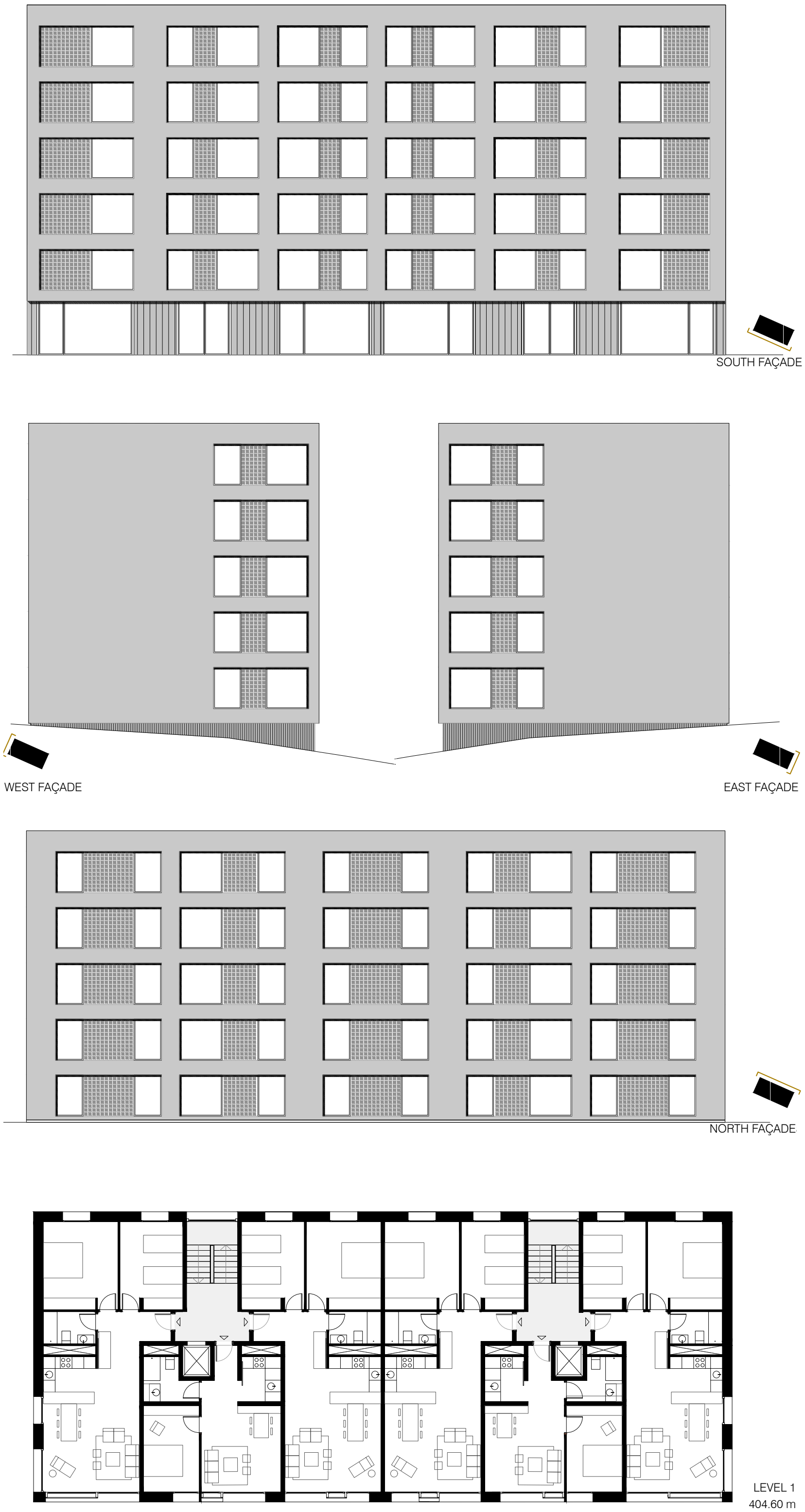


Figure 4.53
Façades elevations and building plans for the AAF building scenario 4B.

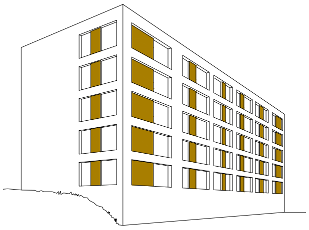


Figure 4.54
Schematic façade BIPV integration. AAF building scenario 4B.

The 4B AAF building scenario combines the *Total volume* façade composition strategy with a translucent BIPV solar control system.

Façade composition

The *Total volume* façade composition produces a particular image of the building as a monolithic object with no particular predominant dimension (Figure 4.54).

In this case, the BIPV system is integrated into the window glazing, as a customised solar control system. The BIPV panel size covers the total area with solar control functions to minimise the undesired visual impact of additional framing.

Façade morphology

The 4B's façade morphology is characterised by the definition of a *Clean volume* (Figure 4.2). The absence of elements protruding from the façade provides design freedom to incorporate active surfaces into any façade element – in this case, as a solar control system integrated into windows (Figure 4.52).

The shape factor of the 4B AAF building scenario is 1.00.

BIPV visual features

This building scenario incorporates a BIPV system that consists of framed glass-glass translucent modules, which integrate wafer-based silicon cells (Monocrystalline, Polycrystalline or Tandem-Perovskite). Panel translucency is achieved through cell spacing: 65% of the BIPV panel is covered with PV cells, and the other 35% is left completely transparent.

BIPV functional features

The BIPV system is integrated as a façade solar control system, as presented in Figure 4.13. The fastening system of the BIPV panels is located at the top and the bottom of the BIPV panel, and the panel is mechanically fixed to a metal frame, as shown in Figure 4.13.

Design remarks

When a translucent or transparent BIPV panel is integrated in front of a reflecting surface – in this case, a window – the BIPV panel can work as a bifacial energy generator. This means that the light that goes through the translucent panel is going to be reflected on the surface behind and go back to the rear face of the BIPV panel, which can also generate electricity if prepared to do so. Bifacial translucent BIPV panels on façades could rise by 30% the BIPV panel's annual energy output [Kreinin *et al.* 2016; Hansen *et al.* 2017].

AAF BUILDING SCENARIO 4C

Figure 4.55
Architectural visualization of the AAF building scenario 4C.

BUILDING SCENARIO DATA

TOTAL ACTIVE SURFACE ON FAÇADE:

105 m²

south façade: 53 m²
east façade: 8 m²
west façade: 8 m²
north façade: 36 m²

BIPV SYSTEM:

visual feature: transparent
functional feature: façade security
FAÇADE DESIGN:

façade composition: total volume
façade morphology: balconies

MARKET READY PV TECH:
Thin-Film

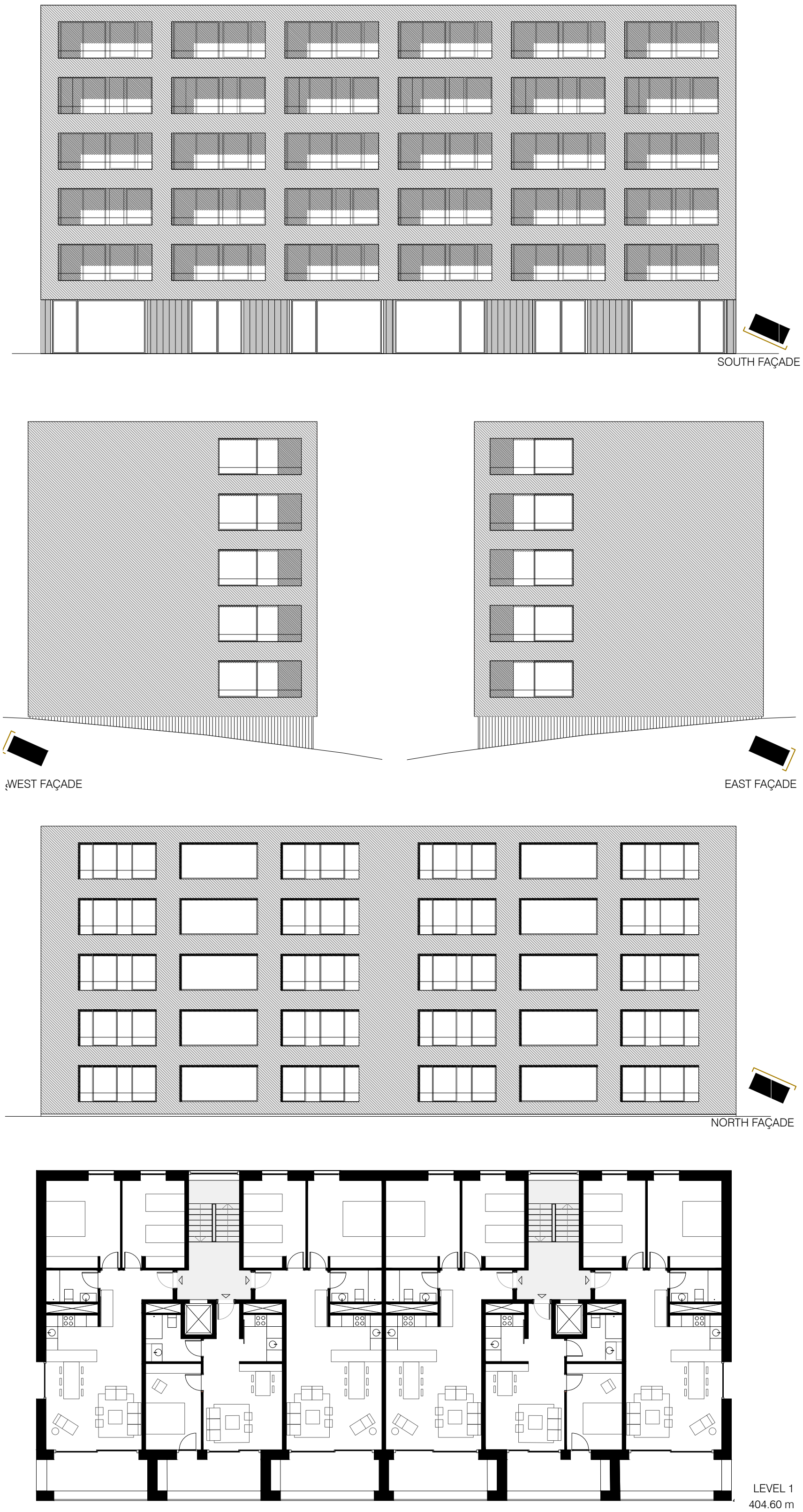
HIGH-PERFORMANCE PV TECH:
Thin-Film

BUILDING

ERA: 2843 m²

A_{th}: 2806 m²

Shape factor (compactness): 1



1 2 5m

Figure 4.56
Façades elevations and building plans for the AAF building scenario 4C.

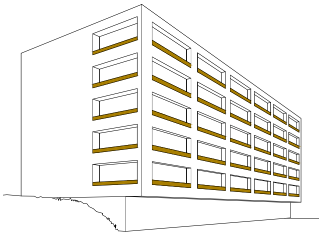


Figure 4.57
Schematic façade BIPV integration. AAF building scenario 4C.

The 4C AAF building scenario combines the of the *Total volume* façade composition strategy with a transparent BIPV balustrade railing.

Façade composition

The *Total volume* façade composition produces a particular image of the building as a monolithic object with no particular predominant dimension (Figure 4.57).

In this case, the BIPV system is integrated into the balcony balustrade as a customised glazed railing, as illustrated in Figure 4.55. The standard dimension of the balustrade (1m) is composed of 40 cm of active glazing and 60 cm of opaque parapet.

Façade morphology

The 4C's façade morphology corresponds to the *Balconies* group. Most of the translucent BIPV system is incorporated as a glazed railing in all four façades.

This façade morphology does not affect the building's shape factor, which is 1.00.

BIPV visual features

This building scenario integrates BIPV panels consisting of transparent Thin-Film photovoltaic technology in a glass-glass BIPV module. The transparency of the BIPV panels is achieved by perforating the Thin-Film layer with laser-based techniques. Panels of different transparencies can be fabricated with this method. The BIPV system displayed on 4C offers a 30% visible light transmittance.

BIPV functional features

The building represented on Figure 4.55 integrates an active glass railing along with the balconies on its four façades and the north façade staircase windows as illustrated in Figure 4.57.

The BIPV system is fastened as a regular glazed balustrade with a metal substructure that includes two metal railings on the top and the bottom of the panels and vertical profiles every 3 metres (Figure 4.11).

Design remarks

Balconies are usually the façade elements that protrude the most from the thermal envelope line. Consequently, there are no other façade elements that can cast a shadow on the balcony's vertical active surface. This guarantees complete solar irradiation throughout the day, considering a stand-alone building with no surrounding shadow casting. For this reason, BIPV integration in balconies is usually an effective and simple integration regarding façade design.

In addition, the maintenance and cleaning of this BIPV system have no complexity due to the small dimensions of the BIPV panels which allow for a man force replacement. Due to its integration as a balcony railing, the BIPV system can be accessed from the building with no need for scaffolding installation.

4.4.2 Implementation step outline

These twelve building scenarios aim at representing a variety of Swiss contemporary façade design practices, based on the analysis of a representative sample of Swiss collective residential buildings. Indeed, this analysis has highlighted four recurrent façade composition patterns and three main façade morphologies (Section 4.2.1.1). The AAF building scenarios do not intend to be singular building projects in their architectural expression, but rather try to represent current contemporary collective residential architecture in which Swiss architects can identify similarities with their work.

The integration of the AAF construction system into the different building scenarios follows the construction definition of the AAF presented in Figure 4.7 to Figure 4.14, incorporating active surfaces as façade cladding, façade glazing, façade security and façade solar control system.

The active façade design follows an *innovative* approach which focuses on maximising the active surfaces in coherence with the façade design project (Section 3.2.2.1). This means that all AAF building scenarios integrate active surfaces in all four façades, even if the energy output of north-oriented BIPV surfaces is significantly lower than south-oriented BIPV surfaces (in the northern hemisphere). As a reminder, the *innovative* approach relies on the development of novel energy systems which optimise the consumption of locally generated BIPV energy: Energy Management Strategies (EMS).

The *implementation* step identifies a representative urban context and a representative Swiss collective residential building to integrate the AAF and develop different building scenarios. It consists of a representative residential building in a representative Swiss city – Lausanne – in a plot subject of an urban densification project.

The AAF building scenarios design process aims at displaying the AAF's design flexibility and potential to be incorporated into contemporary residential façade design practices. The different façade and BIPV design aspects identified in the *Analysis* step can be further combined, opening a wide range of design possibilities that can be adapted to different projects, program requirements, urban context, etc. Depending on the objective leading the AAF integration (maximising energy generation, optimising cost or reaching energy efficiency targets), the different façade designs presented in the AAF building scenarios can be modified and adapted to reach the given objective. Additional AAF building scenarios can be developed by the modification of the façade morphology as done in Sick *et al.* research, illustrated in Figure 3.21 of Chapter 3 [Sick *et al.* 1996].

Ultimately, the AAF building scenarios reveal the architectural design potential of the AAF when incorporated into residential façades combining expressive diversity, energy performance, and low environmental impact. In addition, this research phase output provides a base for the quantitative assessment of the AAF at a building scale, which can be compared with current architectural practices.

4.5. Synthesis

The research framework analysis presented in Chapter 3 discusses the potential of façades to improve the building's energy efficiency by integrating passive and active energy strategies. Among the latter, BIPV has the potential of providing buildings with renewable energy in order to reach the energy efficiency targets established for the year 2050. However, existing researches identified BIPV's architectural expression as an obstacle hindering its potential.

This research project addresses this issue from an architectural approach to integrate BIPV technology into energy-efficient façade design practices. To do so, the design approach presented in this chapter defines three steps in its workflow:

- The first step **analyses** contemporary façade and BIPV systems design practices as well as their construction recommendations and requirements.

  The *Analysis* step results in the identification of different façade and BIPV design aspects that define the potential of BIPV systems to be incorporated into contemporary collective residential façades. These design aspects are the façade composition, façade morphology, BIPV visual features and BIPV functional features that define the active surface dimensions, position, visual expression, and façade function.

  These design aspects, along with the analysis of contemporary façade and BIPV construction practices and recommendations, set the basis to develop a new façade construction system which meets the latest energy and construction requirements. This construction system integrates active surfaces in a way that fits the contemporary façade design practices regarding façade's composition and morphology and incorporates BIPV systems fulfilling different façade architectural functions. Both contemporary façade and BIPV design practice analyses determine the design potential of integrating BIPV into façades addressing its architectural expressive issues and meeting contemporary façade requirements.

- In the second step, a new façade construction system is **designed** based on the *Analysis* step results. Entitled the Advanced Active Façade (AAF), it aims at becoming an architectural reference for energy-efficient façade construction in the collective residential building context. The AAF combines passive and active energy design strategies: it is highly insulated, follows low embodied impact construction principles and incorporates BIPV as an integral part of the façade. It outlines a prefabricated, non-loadbearing, wood-panel façade substructure which incorporates blown cellulose as a main insulator and BIPV systems as façade cladding, façade glazing, façade security elements and/or façade solar control systems. Ultimately, the *Design* step aims at providing a façade constructive solution which can potentially simplify energy-efficient façade design and construction practices.

- In a third step, the design output, the AAF, is **implemented** into architectural design practices generating the AAF building scenarios. The *Implementation* step illustrates the design potential of the AAF in common architectural design practices, based on the contemporary façade analysis and on an *innovative* design approach that focuses on maximising BIPV energy generation.

The AAF building scenarios display the architectural design potential of the AAF when integrated into residential façades combining design flexibility, operational energy efficiency and low environmental impact.

In addition, the AAF building scenarios provide a basis to perform energy and economy performance simulations at the building scale that can be compared with current architectural practices enabling the quantitative assessment of the design outcome of this research.

Ultimately, the development of the AAF construction system and AAF building scenarios design process has motivated the formulation of a set of design guidelines promoting the integration of BIPV into residential building façades and aiming at optimising upcoming BIPV architectural design.

BIPV façade design guidelines

Some researchers have formulated BIPV design guidelines [Hestnes 1999; Munari Probst 2008; Munari Probst *et al.* 2012b, 2012a; Farkas *et al.* 2013] which have been referred in Chapter 3 are here gathered. The set of guidelines is completed with new ones to provide the reader with a complete set of design guidelines (GL).

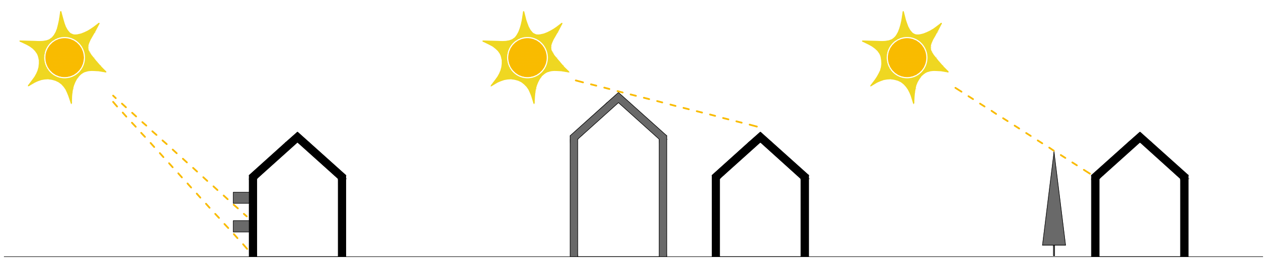
- **GL1:** Integrate BIPV panels in highly irradiated surfaces.

The first guideline is to integrate BIPV panels in highly irradiated surfaces. This entails avoiding permanent or intermittent BIPV panel shading (Figure 4.58) as it can significantly affect the total energy generation of a BIPV façade.

Careful design can minimise negative effects from neighbouring buildings or vegetation's shading [Brinkworth *et al.* 2005]. To avoid BIPV panel shading, surrounding buildings must be studied and considered. For the same reason, high and leafy vegetation near the building should be avoided when plot and landscape planning. BIPV should not be integrated where vegetation entails long-period shaded areas.

Numerous researchers have referred to this guideline in recent years [Munari Probst *et al.* 2012b; SUPSI 2019]. However, PV technology advances at a very fast pace and BIPV panel shading effects can be minimised by choosing the appropriate PV

Figure 4.58
Building shading schemes.



technology and electrical connections among the BIPV modules [Odersun 2011].

New BIPV systems can include microinverters that minimise the negative effect of panel shading [Interview with G. Cattaneo, 2018], although this solution increases the final cost of the BIPV system. A cheaper solution to avoid the negative effects of panel shading is to integrate dummy panels in areas were the casted shadow is more frequent. However, due to the current PV cell cost decrease, the price of a dummy panel is not significantly different from the price of a BIPV panel [Interview with P.O. Couche, 2016]. This problem highlights the importance of a good architectural design that considers BIPV issues from the early stage of the project.

- **GL2:** Avoid self-shading

  The second guideline is related to the first one and focuses on minimising the negative effects from self-shading building morphology, construction elements or façade accessories [Brinkworth *et al.* 2005]. It identifies the façade morphologies (Figure 4.2) to avoid self-shaded BIPV areas. This implies that, at the time of designing an active façade, BIPV should be placed in the outermost surface of the façade, preventing the shape of the building, façade solar protection systems, or other façade accessories from blocking solar irradiation on the active surface. As a general rule, this means that in buildings with balconies, BIPV should be avoided as façade cladding but could be integrated on the balcony balustrade. In the same line, façades with loggias can integrate BIPV as a façade cladding because there is no shadow cast on it. Either way, façade accessories must be studied for each specific case to control potential shading over BIPV elements.

- **GL3:** Facilitate maintenance of façade's BIPV systems

  Active surfaces ask for regular maintenance, unlike common envelope coatings such as brick or roughcast. Even if BIPV façades require a less periodic cleaning than BIPV roofs, due to their vertical orientation, this is something that must be considered in the design phase. BIPV façade design must facilitate cleaning tasks as well as panel replacing in case of malfunction. Small format BIPV panels are, a priori, easier to replace in case of breakage because they require fewer auxiliary facilities and in some cases do not require scaffolding.

  With the same objective of facilitating panel maintenance, BIPV should not be integrated into areas where the likelihood of getting dirty is high. A clear example of this situation is the ground floor level where dirt splashes or even graffiti vandalism can disable a whole array of BIPV panels.

- **GL4:** Keep BIPV panels cool

  The fourth guideline consists of designing a BIPV façade which keeps BIPV panels as cool as possible. BIPV modules, as any surface exposed to the sun, can rapidly increase their temperature. The consequence of BIPV panel overheating is a lower PV energy output [Guiavarch *et al.* 2006].

A correct BIPV façade design must guarantee the active surface's ventilation to keep the surface temperature as low as possible. BIPV can be integrated in several different ways into façades, as shown in Figure 4.59. However, as far as the overheating problem is concerned, the most challenging integration is BIPV as a façade cladding system. In this case, façade integration overheating issues can be minimised when designing a ventilated façade system with a larger air cavity to foster air movement [Brinkworth *et al.* 2005; Maturi *et al.* 2015].

- **GL5:** Minimise the risk of impact

  The fifth guideline deduced from the research design process is to respect BIPV material's fragile nature. Due to its glass composition, BIPV elements should not be integrated into façade areas with a high risk of impact. The integration of BIPV in the ground floor, which is most vulnerable to potential human or vehicle impacts, should be avoided when possible.

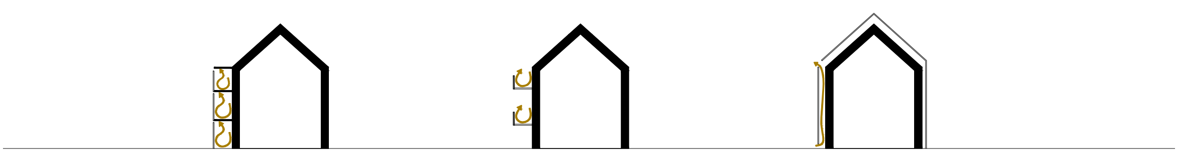
- **GL6:** Benefit from light reflecting features of the context

  The sixth BIPV guideline is to analyse the light reflecting features of the building's surroundings. As mentioned in Chapter 3, there are PV technologies like amorphous silicon that have good performance under indirect or ambience light. Highly reflective surfaces around the building can turn these technologies in a more performant choice throughout the year. This is the case of a BIPV façade near a lake or surrounded by frequently snow-covered landscapes. Similarly, an urban context with light-painted or reflective façade cladding buildings can also improve the annual energy performance of a BIPV façade if it integrates the appropriate PV technology to take advantage of this situation.

- **GL7:** Consider interior comfort over energy generation

  The seventh guideline is directly deduced from developing the AAF building scenario 1C and has already been applied to AAF building scenario 2C. It consists of avoiding transparent BIPV glazing in highly irradiated windows. When integrating this technology in façades, especially in windows of residential buildings, exterior solar control devices are required, which might block direct sunlight from irradiating the active surface. Architects must, therefore, evaluate how it is going to affect the interior comfort conditions of the building because exterior solar shading devices might significantly reduce the BIPV output.

Figure 4.59
Ventilated BIPV elements.



- **GL8:** Study BIPV bifacial generation potential.

  Depending on the way they are integrated, some BIPV systems can generate energy from both sides of the solar cell if they are irradiated with direct or indirect light on both front and rear face of the BIPV panel. A bifacial generation can increase up to 30% the energy output of a BIPV panel, which in turn can increase the annual output of the active façade significantly [Gan 2009; Kreinin *et al*. 2016; Hansen *et al*. 2017].

This list of energy-efficient façade design-guidelines is drafted within an architectural approach, and it does not purport to cover all issues raised by the integration of BIPV. Other more technical-oriented researches may complete this list. To foster the building's energy efficiency, these guidelines can be combined with the low embodied impact construction principles presented in Section 4.2.1.2, which refer to the use of fewer, natural and local materials; the design for prefabrication and dismounting; and the reuse and recycle of the façade's construction materials.

In a context marked by a growing interest in the energy transition issues, which have among their objectives the reduction of the building sector's environmental impact, the development of the new Advanced Active Façade (AAF) highlights the potential of integrating active façades into residential building construction practices. This approach reveals the architectural design potential of residential façades combining expressive diversity, energy performance and low environmental impact.

5. Quantitative Assessment

The design approach outcome presented in Chapter 4 presents the development of the Advanced Active Façade (AAF), a façade construction system that provides a solution for energy-efficient façades. The AAF aims at contributing to the energy transition by increasing the energy performance of residential buildings. Taking into consideration the current energy distribution system, energy savings lead to economic savings. The latter can be a decisive incentive to boost energy efficiency measures, especially in the residential sector [Sauter *et al.* 2013]. For this reason, energy and economic performance assessments are frequently interconnected.

Based on the design approach outcome, the objective of this integrated design research phase is to perform a quantitative assessment of the AAF and, more specifically, of the AAF building scenarios, which illustrate the implementation of energy-efficient design strategies into façade design practices. In this regard, this chapter presents the assessment of the AAF's energy and economic performances. The results of this assessment process allow investigating the potential of energy-efficient façades to contribute to the energy transition.

Thus, the current research phase takes the form of a quantitative assessment that evaluates the different building scenarios based on a comparative assessment method. This method helps architects to better understand energy and economic performances of the AAF when compared to current construction practices. First, we explain the general approach adopted, which is introduced as a workflow composed of the different research steps. Second, the comparative assessment framework is presented, introducing the different construction systems and scenarios to be assessed and compared. Then, we perform the energy efficiency and economic efficiency quantitative assessment. Finally, a synthesis of the results allows discussing the potential of the AAF to reach the energy transition targets and its economic impact on the global building's economic performance.

5.1. Workflow

Three main steps define the workflow of this research phase, which enables the assessment of the energy and economic performance of the AAF.

The first step consists of defining a comparative assessment framework with the different building scenarios to be assessed and compared. The comparative assessment framework is based on the AAF building scenarios presented in Section 4.4.1. It is paired with two different non-active façade construction current practices: The *Common practice* façade (CP) and the *Best practice* façade (BP). These construction practices allow outlining three main scenario variants: CP, BP and AAF. In addition, the comparative assessment framework proposes and assesses different PV technologies – *Market-Ready* (MR) and *High-Performance* (HP) –, various building PV systems – BAPV-roof and BAPV-façade –, and the possible integration of batteries. This comparative assessment framework contributes to defining the degree of energy efficiency improvement that can be achieved by implementing the AAF into a building.

The second step consists of performing the energy efficiency assessment of the building scenarios defined in the previous step. To do so, embodied and operational energy calculations and simulations are carried out. Ultimately, the combined energy efficiency is calculated, and all results are confronted with the SIA 2040 energy efficiency target values [SIA 2040 2017]. The energy efficiency assessment is designed as follows:

- The embodied energy analysis implies the quantification of the building's embodied impacts through performing the Life Cycle Assessment (LCA) of the different building scenarios defined in the previous chapter, and its different variants defined in the comparative framework. This quantification is the sum of the individual environmental impacts of each construction material based on the KBOB database [KBOB 2016].

- The operational energy analysis concerns the building's energy demand and generation to quantify its associated operational impacts. The building energy simulator tool Design-Builder (DB) is used to perform the building energy simulations. All twelve building scenarios presented in Chapter 4 are studied, as well as the variants integrating non-active current practices façades.

- The combined energy analysis calculates the combined embodied and operational impacts of the scenarios specified in the comparative framework and confronts the results with the energy efficiency target values defined by the 2000-Watt Society and included in the SIA 2040 standard [SIA 2040 2017].

In order to optimise the process of the energy simulations output data, a quantitative assessment Excel model has been designed. This Excel model is also the means to integrate the embodied environmental impacts assessment results with the operational energy assessment results of the different variants defined in the first step of this workflow.

To be able to compare the energy efficiency results of the different building scenarios and variants, values must be expressed in comparable units. The SIA 2040 energy efficiency target values are expressed in non-renewable primary energy (NREP) and Global warming potential (GWP) while DB simulation results are expressed in final energy. The latter is transformed into NRPE and GWP values in order to allow comparison with the SIA 2040 energy efficiency target values. To do so, the KBOB database provides the correspondent coefficients, establishing for the Swiss context[1] a multiplier of 2.52 to transform final energy into the NRPE indicator, and a multiplier 0.102 to transform final energy into the GWP indicator [KBOB 2016].

Finally, the third step of the workflow assesses the economic performance of the different scenarios to evaluate the economic impact of the AAF on the building costs, from a real estate developer perspective. Higher initial investment is expected when incorporating energy-efficient façades compared to current practices. However, a construction that is initially more expensive can turn out to be a good long-term investment [Rütter-Fischbacher *et al.* 2010]. In this regard, 30-year and 10-year investment periods are analysed, and four different economic indicators are calculated:

- The Life-cycle cost (LCC), which is the total sum of all relevant costs associated with a building over the analysis period

- The Net present value (NPV), which is the total sum of all past, present and future cashflows.

1
These values refer to the 45.020 reference on the KBOB database: Consumer mix CH, with no renewable products.

- The Internal rate of return (IRR), which is an indicator of the annual return on investment.
- The Discounted payback (DPB), which is the time required to find benefits offsetting the initial investment costs.

These four indicators are calculated considering the time value of money, within levered[2] and un-levered assumptions.

Moreover, this quantitative assessment presents the energy and economic efficiency assessment results through a transversal analysis of all the simulated building scenarios and their variants as well as the detailed presentation of one particular building scenario and its variants to better illustrate its energy and economic performance. The chosen scenario to present further result details is the building scenario 2A because it incorporates the largest surface of the novel BIPV panels developed within the context of the PV2050 research project by CSEM researchers in Neuchatel. However, the simulation results of all building scenarios can be found in Appendix A.5.3.

As detailed in the previous chapter, building scenario 2A incorporates a BIPV system as an opaque façade cladding (Figure 5.1). Its façade composition corresponds to a *Total storey* façade composition and a *Loggias* façade morphology.

The building scenario 2A analysis results are integrated at the end of both energy and economic assessments. This analysis presents the CP, BP and AAF building scenarios as well as all the variants referred in Section 5.2: the integration of MR and HP BIPV technologies, the integration of a battery in the BIPV system, the incorporation of a BAPV-roof and the incorporation of BAPV-façades in non-active scenarios (CP and BP).

2
To lever a project means to use debt or borrowed funds to finance it.

Figure *5.1*
Building scenario 2A.

5.2. Comparative assessment framework

Energy and economic performance assessments are presented through a comparative assessment framework to evaluate the potential contribution of the AAF to the energy transition regarding current practices. The comparison is established with common examples of façade construction systems to analyse the energy and economic efficiency improvements achieved through façade design.

The comparative research method is a theoretical method of scientific research which, according to Novikov *et al.*, *serves to identify quantitative and qualitative characteristics of objects as well as to classify, order and assess them* [Novikov *et al.* 2013]. In the present case, the comparative research method takes the form of a comparative framework to analyse energy and economic performance by comparing the assessment results of the AAF with those of two other widely-used façade construction practices. This comparative framework allows non-energy-specialised construction professionals to use and integrate performance assessment results in architectural design processes.

The comparison is established between 1) a basic commonly-used brick façade system entitled *Common practice* (CP), 2) a timber frame façade entitled *Best Practice* (BP), and 3) the AAF, which can be considered as an *Advanced practice*. These three façade systems are illustrated in Figure 5.2, with their respective construction details. The CP and BP references are taken from the OFEN's *New Construction Catalogue* [OFEN 2002], which gathers most of the construction systems currently used in Switzerland. They correspond respectively to W01: *Masonry with a single brick wall plastered external thermal insulation* and Wi01: *Wood frame wall with intermediate thermal insulation*.

The *Common practice* is defined by the reference W01 [OFEN 2002], due to the remarkable number of insulated roughcast façades found throughout the analysis of the Swiss residential building stock (Section 4.2.1.1). This construction system has widespread practice in Switzerland because of its low cost compared to other façade construction systems [Bec Partners SA 2015a]. The CP façade system is composed of 12.5 cm bricks, 22 cm of polystyrene insulation and exterior cement mortar roughcast. This system has a thermal transmittance value of 0.2 W/m^2 K, which is the value required by the Swiss norm SIA 380/1 [SIA 380/1 2009]. Figure 5.2 contains further information about the construction system and its composition.

The *Best practice* is defined by the reference Wi01 [OFEN 2002], although wood constructions in Switzerland are not a widespread practice. The Wi01 construction system has been selected because it represents a simple timber frame construction, which is highly insulated and is expected to be comparable with the AAF construction system regarding embodied carbon targets – the main difference being that it is not active. The BP façade system is composed of a solid pine wood wall frame with 27 cm of rock wool insulation and a wooden façade cladding fixed on a ventilated façade wooden substructure. It has a thermal transmittance value of 0.15 W/m^2 K, which is the limit value of the Swiss construction recommendation Minergie [Minergie 2018]. Figure 5.2 contains further information about the construction system and its composition.

As defined in Chapter 4, the AAF presents four different variants: incorporating BIPV as façade cladding, as façade glazing, as façade security elements or as solar control systems. In all cases, the active surface's environmental impact and economic costs are integrated and calculated as an integral component of the façade.

The AAF building scenarios integrate BIPV exclusively into the façades to assess the specific potential contribution of BIPV façades to reach the energy transition objectives. However, BAPV-roofs have a significant and demonstrated potential to improve buildings' energy efficiency [Heinstein *et al.* 2013; Assouline *et al.* 2017]. Similarly, the integration of BAPV-façades can also improve the building's energy efficiency. For this reason, the three main building façade systems – CP, BP and AAF - are provided with additional variants to assess their energy and economic performances, which are:

- The integration of *Market-Ready* (MR) BIPV technology

  There is a large number of BIPV technologies in the market. This energy and economic assessment consider the energy performance, embodied environmental impact and economic cost of MR BIPV technology. Every building scenario assessment indicates the specific BIPV technology integrated: Opaque, translucent or transparent Monocrystalline, Polycrystalline, Thin-Film or DSSC technology.

- The integration of *High-Performance* (HP) BIPV technology

  Additionally, the assessment incorporates the HP BIPV technology variant to evaluate the potential of some promising BIPV technologies towards meeting the energy targets. The HP technologies integrated into the assessment process are Tandem-Perovskite [Interview with G. Cattaneo, 2018] and high performance Thin-Films [Interview with P.O. Couche, 2016].

  The differences between MR and HP BIPV façades generate two additional variant scenarios, per type of façade: MR AAF and HP AAF.

- The integration of a battery into the BIPV system

  The integration of energy storage systems into BIPV systems is discussed in Chapter 3. Among the different existing energy storage systems, batteries are the most frequently used when paired with PV in buildings [Zhang *et al.* 2015]. For this reason, the integration of a battery is studied and assessed in this research phase.

  Integrating batteries in the assessment process as a variable generates additional variant scenarios: MR AAF + Battery and HP AAF + Battery.

- The incorporation of a BAPV-roof

  Current practices – CP and BP – tend to incorporate PV systems on the roof (BAPV) to improve the building's energy efficiency [Tiwari *et al.* 2016]. For this reason, a simulation of the maximum potential of a BAPV-roof has been performed to check if buildings with current façade construction practices – CP and BP – can reach operational energy efficiency targets.

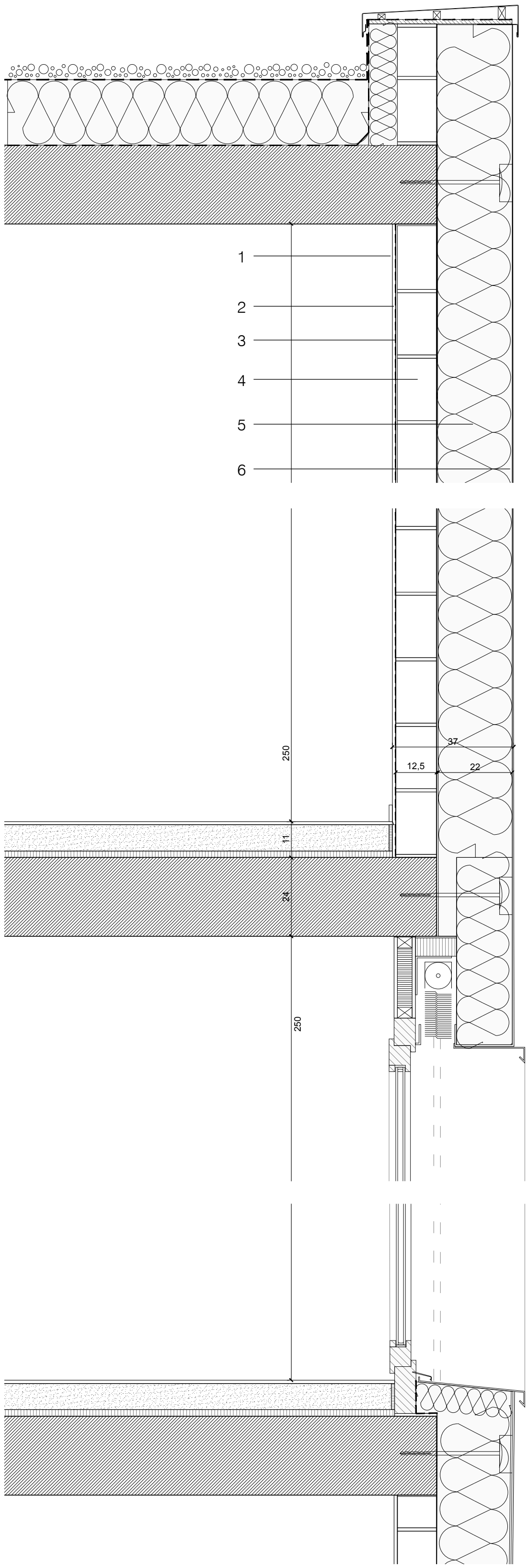
  This variable generates three additional variant scenarios: CP + BAPV-roof, BP + BAPV-roof and AAF + BAPV-roof. Their assessment provides information about the potential of the BAPV-roof in collective residential buildings towards the energy transition.

- The incorporation of BAPV-façades.

  This research project addresses the integration of PV in buildings from a design perspective and to minimise the façade's embodied impacts

Figure *5.2*
Three different façade compositions to be compared regarding environmental and financial impact: Common Practice Façade, Best Practice and Advanced Active Façade.

COMMON PRACTICE
W 01



COMMON PRACTICE (CP)

1.	INTERIOR COATING: PAINT	
2.	INTERIOR FINISH: LIME PLASTER	1 cm
3.	VAPOUR BARRIER	0.2 cm
4.	CERAMIC BRICKS	12.5 cm
5.	POLYSTYRENE INSULATION	22 cm
6.	ROUGHCAST EXTERIOR COATING	1.5 cm

CP FAÇADE THERMAL TRASMITTANCE VALUE (U): 0.2 W/m²K

BEST PRACTICE (BP)

1.	INTERIOR COATING: PAINT	
2.	PLASTERBOARD	1.25 cm
3.	VAPOUR BARRIER	0.2 cm
4.	MEDIUM DENSITY FIBREBOARD (MDF)	1 cm
5.	ROCKWOOL INSULATION	27 cm
6.	SOLID WOOD FRAME	27 cm
7.	MEDIUM DENSITY FIBREBOARD (MDF)	1 cm
8.	SOLID WOOD SUBSTRUCTURE / AIR CAVITY	6 cm
9.	WOOD FAÇADE CLADDING	

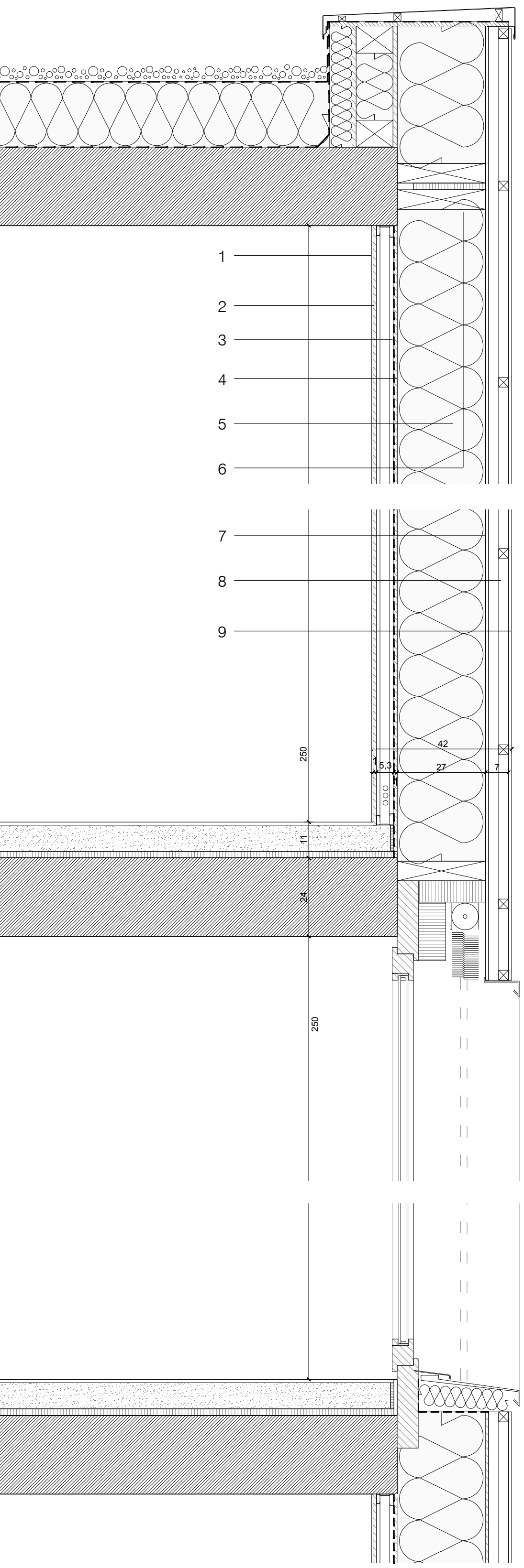
BP FAÇADE THERMAL TRASMITTANCE VALUE (U): 0.15 W/m²K

ADVANCED PRACTICE (AAF)

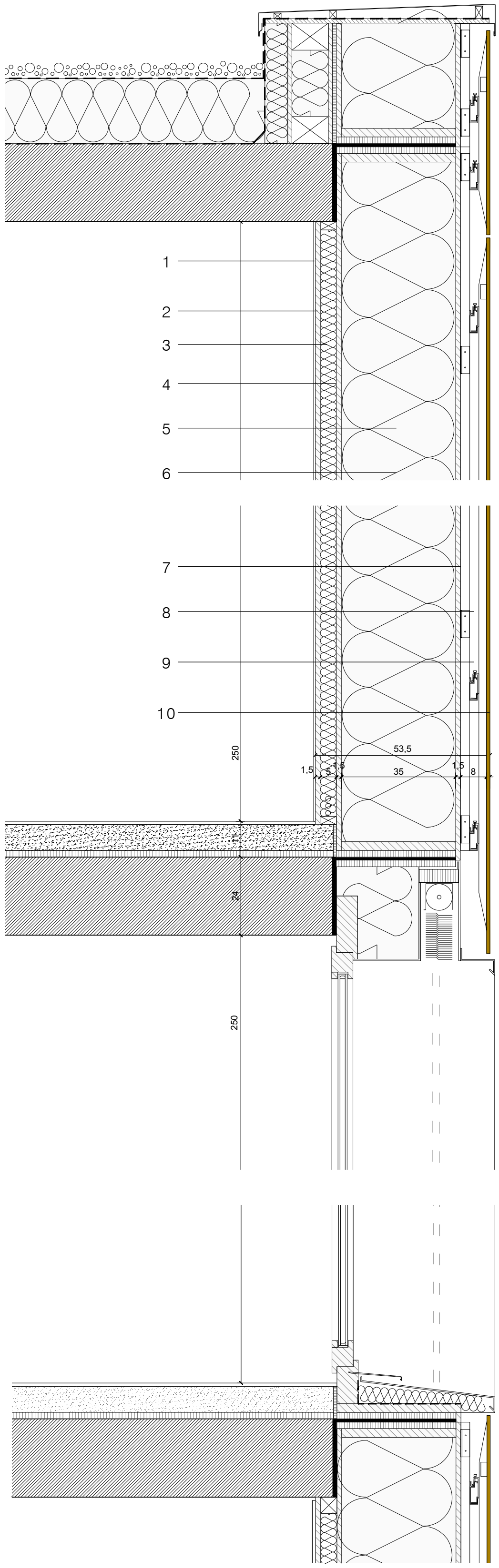
1.	INTERIOR COATING: PAINT	
2.	PLASTER BOARD	1.5 cm
3.	WOOD FIBRE INSULATION	5 cm
4.	OSB PANELS WITH SEALED JOINTS	1.5 cm
5.	WOOD FAÇADE SUBSTRUCTURE	35 cm
6.	BLOWN CELLULOSE INSULATION	35 cm
7.	FIBROCEMENT PANELS WITH SEALED JOINTS	1.25 cm
8.	BIPV FASTENING SYSTEM	8 cm
9.	VENTILATED AIR CAVITY	8 cm
10.	BIPV PANELS	

AAF FAÇADE THERMAL TRASMITTANCE VALUE (U): 0.09 W/m²K

BEST PRACTICE
Wi 01



ADVANCED PRACTICE
AAF



and cost. However, the attachment of BAPV on current practice façades has also the potential of meeting energy targets, even if it is with a higher embodied environmental impact and cost. To integrate BAPV-façades into the research process, the non-active building scenarios – CP and BP – are provided with an additional BAPV surface of the exact dimensions as the AAF scenarios. The BAPV-façade can as well incorporate MR or HP PV technology.

This integration generates four additional variant scenarios: CP + MR BAPV-façade, CP + HP BAPV-façade, BP + MR BAPV-façade, and BP + HP BAPV-façade.

The different construction systems described above – CP, BP and AAF – set the comparative framework for the energy and economic performance quantitative assessment. Ultimately, the change of parameters generates a total of 11 additional variant scenarios (Table 5.1) for each AAF building scenario defined in Chapter 4. The quantitative assessment thus evaluates and compares 168 building variations. The comparison of each AAF scenario and its variations provides architects with familiar examples of façade construction systems and facilitates understanding the benefits of BIPV and low embodied impact façades over current practices. The following sections describe the assessment processes of both energy and economic efficiencies.

Table *5.1*
Quantitative assessment scenarios to be analysed.

	CP	BP	AAF	
1A	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	*Market-ready* OPAQUE MONOCRYSTALLINE + BAPV roof *High-Performance* OPAQUE TANDEM-PEROVSKITE + BAPV roof	No battery Battery No battery Battery
1B	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	*Market-ready* TRANSLUCENT MONOCRYSTALLINE + BAPV roof *High-Performance* TRANSLUCENT TANDEM-PEROVSKITE + BAPV roof	No battery Battery No battery Battery
1C	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	*Market-ready* TRANSPARENT THIN-FILM + BAPV roof *High-Performance* TRANSPARENT THIN-FILM + BAPV roof	No battery Battery No battery Battery
2A	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	*Market-ready* OPAQUE MONOCRYSTALLINE filtered + BAPV roof *High-Performance* OPAQUE TANDEM PEROVSKITE filtered + BAPV roof	No battery Battery No battery Battery
2B	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	*Market-ready* TRANSLUCENT POLYCRYSTALLINE + BAPV roof *High-Performance* TRANSLUCENT TANDEM-PEROVSKITE + BAPV roof	No battery Battery No battery Battery
2C	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	*Market-ready* TRANSPARENT THIN-FILM + BAPV roof *High-Performance* TRANSPARENT THIN-FILM + BAPV roof	No battery Battery No battery Battery
3A	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	*Market-ready* OPAQUE MONOCRYSTALLINE filtered + BAPV roof *High-Performance* OPAQUE TANDEM PEROVSKITE filtered + BAPV roof	No battery Battery No battery Battery
3B	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	*Market-ready* TRANSLUCENT DSSC + BAPV roof *High-Performance* TRANSLUCENT THIN-FILM + BAPV roof	No battery Battery No battery Battery
3C	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	*Market-ready* TRANSPARENT THIN-FILM + BAPV roof *High-Performance* TRANSPARENT THIN-FILM + BAPV roof	No battery Battery No battery Battery
4A	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	*Market-ready* OPAQUE MONOCRYSTALLINE + BAPV roof *High-Performance* OPAQUE TANDEM-PEROVSKITE + BAPV roof	No battery Battery No battery Battery
4B	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	*Market-ready* TRANSLUCENT POLYCRYSTALLINE + BAPV roof *High-Performance* TRANSLUCENT TANDEM-PEROVSKITE + BAPV roof	No battery Battery No battery Battery
4C	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	non-active + BAPV roof + BAPV façade MR + BAPV façade HP	*Market-ready* TRANSPARENT THIN-FILM + BAPV roof *High-Performance* TRANSPARENT THIN-FILM + BAPV roof	No battery Battery No battery Battery

5.3. Energy efficiency

The Advanced Active Façade has been developed to move towards the fulfilment of the energy efficiency requirements introduced in Chapter 3, concerning building construction and operation while dealing with the architectural expression issues of existing integrated energy-generation solutions such as BIPV. To evaluate the contribution of this research work to the ongoing energy transition, the energy performance assessment presented in this section includes an embodied energy analysis, an operational energy analysis and a combined energy analysis. Ultimately, each energy performance result is confronted to the energy performance targets of the 2000-Watt Society for the year 2050 to assess the contribution of the AAF towards the energy transition [Suisse Energie 2015; SIA 2040 2017].

These targets are included in the Swiss construction norm: SIA 2040:2017 [SIA 2040 2017], which specifically defines the energy efficiency targets by NRPE and GWP indicators. SIA 2040:2017 provides the NRPE and GWP limit values allowed for a standard residential building with a corresponding standard building surface of 60 m^2 per person. These target values correspond to Table 3 of the SIA 2040:2017 norm and distinguish between embodied and operational energy. Regarding embodied energy, the target values are 30 kWh/m^2 per year for NRPE and 9 kg $CO_{2\,eq}$ / m^2 per year for GWP. Regarding operational energy, the target values are 60 kWh/m^2 per year for NRPE and 3 kg $CO_{2\,eq}$ / m^2 per year for GWP. All values are expressed per square meters, referring to the building's ERA. SIA 2040:2017 also establishes a combined energy efficiency target for embodied energy + operational energy which must not exceed 90 kWh/m^2 per year (NRPE) and 12 kg $CO_{2\,eq}$ / m^2 per year (GWP). This combined target focuses on tackling the current issue of increasing the building's embodied energy while lowering the building's operational energy demand. This increase in embodied energy is associated with the increase of insulation and high-performance building energy systems [Koezjakov *et al.* 2018].

*

The total active surface and BIPV performance determine the size of the BIPV installation (Table 5.2), which is ex-pressed in Kilowatt peak (kWp) and is directly related to the final energy output.

Table *5.2*
Design and technology elements affecting the building's energy performance.

BUILDING SCENARIO	FAÇADE MORPHOLOGY	BUILDING SHAPE FACTOR	BIPV FAÇADE FUNCTION	TOTAL ACTIVE SURFACE (m²)	BIPV TECHNOLOGY	BIPV PERF.	BIPV INSTALLATION SIZE (kWp)*
1A	Clean volume	1	Cladding	825	MR Opaque Monocrystalline	21%	17,3
					HP Opaque Tandem Perovskite	28%	23,1
1B	Balconies	1	Solar control	377	MR Translucent Monocrystalline	14%	5,1
					HP Translucent Tandem Perovskite	18%	6,9
1C	Loggias	1,1	Glazing	272	MR Transparent Thin-Film	3%	0,8
					HP Transparent Thin-Film	5%	1,4
2A	Loggias	1,1	Cladding	843	MR Opaque filtered Monocystalline	12%	10,1
					HP Opaque filtered Tandem-Perovskite	18%	15,3
2B	Balconies	1	Solar control	356	MR Translucent Polycristalline	12%	4,2
					HP Translucent Tandem Perovskite	18%	6,5
2C	Clean volume	1	Glazing	258	MR Transparent Thin-Film	3%	0,8
					HP Transparent Thin-Film	5%	1,3
3A	Balconies	1	Security	558	MR Opaque filtered Monocystalline	12%	6,7
					HP Opaque filtered Tandem-Perovskite	18%	10,2
3B	Loggias	1,1	Security	208	MR Translucent DSSC	2%	0,5
					HP Translucent Thin-Film	7%	1,5
3C	Balconies	1	Security	335	MR Transparent Thin-Film	3%	1
					HP Transparent Thin-Film	5%	1,7
4A	Loggias	1,1	Cladding	1128	MR Opaque Monocrystalline	21%	23,7
					HP Opaque Tandem Perovskite	28%	31,6
4B	Clean volume	1	Solar control	244	MR Translucent Polycristalline	12%	9
					HP Translucent Tandem Perovskite	18%	4,4
4C	Balconies	1	Security	105	MR Transparent Thin-Film	3%	0,3
					HP Transparent Thin-Film	5%	0,5

The energy performance of the different building scenarios is expected to depend on various parameters: the building compactness, which is related to the façade morphology; the type of BIPV technology integrated, which affects the total embodied impacts and its performance; and finally the total active surface integrated into the façade and its orientation (Table 5.2).

5.3.1 Embodied energy efficiency analysis

Minimising GHG emissions within the building sector is commonly focused on reducing the operational energy of buildings [Lützkendorf *et al.* 2015]. The building's operational energy reduction achieved in recent years has highlighted the impact of building's embodied energy, whose share increases while operational energy's share decreases [Koezjakov *et al.* 2018]. As previously mentioned, the reduction of the building's operational energy is mainly achieved through the increase of thermally insulating materials [Ruggieri *et al.* 2013], which leads to higher embodied environmental impacts [Crawford *et al.* 2016].

Today, embodied environmental impacts are included in building construction recommendations [SIA 2032 2010; SIA 112 2017; SIA 2040 2017], which define embodied impacts target values for the year 2050.

A simplified LCA methodology has been followed to quantify and assess the embodied impacts of the AAF building scenarios and their non-active variants – CP and BP. This simplified methodology is based on the LCA's standard methodology to assess the environmental impact of construction products, defined by ISO 14040 and ISO 14044 [El Khouli *et al.* 2015; Finnegan 2018]. The methodology implies: first, defining the goal and scope of the analysis; second, choosing a database to gather embodied impacts intensities; third, delimiting the system boundaries; fourth, determining the embodied impacts indicators; fifth, quantifying the embodied impacts; and sixth, analysing the results.

Goal and scope of the analysis

The main objective of this embodied energy analysis is to quantify the embodied impacts of the AAF and compare it to the embodied impacts of CP and BP façades. The façade embodied impacts quantification is complemented with the whole building embodied impacts quantification. Totals can be compared to the SIA:2040 energy efficiency target values to assess the potential contribution of the AAF to reach the embodied impacts targets defined within the energy transition vision.

Embodied impact database

Quantifying embodied carbon involves working with many uncertain parameters [Gantner *et al.* 2018]. A reliable database must be chosen to minimise uncertainty and improve data quality when running LCA calculations [El Khouli *et al.* 2015]. If available, national databases can further reduce uncertainty because they contain accurate information regarding raw material transportation and national electrical grid's environmental impact [Cihan Kayaçetin *et al.* 2018].

In Switzerland, the Swiss LCA Database of Construction (the KBOB-database) contains information on the average environmental impacts of construction materials, building technical facilities, energy supply, transport and disposal processes used on the Swiss market [KBOB 2016]. This database is freely available online and is utilised to give Swiss energy certificates to buildings, which makes it the most commonly used data source in Switzerland [Hauke *et al.* 2016]. KBOB environmental database is used by the majority of Swiss construction stakeholders, and it is the Swiss norm's reference when addressing environmental embodied impacts [SIA 2031 2009; SIA 2032 2010; SIA 2039 2016; SIA 2040 2017]. In addition, KBOB's environmental impact values are updated regularly based on the Ecoinvent v2.2 database, which presents a high level of data transparency [El Khouli *et al.* 2015].

The Ecoinvent database and the KBOB database assume a building lifespan of 60 years and give information about specific stages: product, replacement and disposal [Moncaster *et al.* 2018].

Define system boundaries

Typically, a system boundary is defined following the ISO Standards [ISO 2016], which define four main cycle stages that determine the environmental impact of a building: product, construction, use and end-of-life [Moncaster *et al.* 2018]. In this simplified façade embodied impacts assessment, the system boundaries are given by the selection of the embodied impacts database (KBOB) and includes: A) the product stages: A1 raw material, A2 transport, and A3 manufacturing; B) the use stage: B4 replacement; and C) the end-of-life stages: C3 waste processing and C4 disposal. In other words, the following LCA identifies the environmental impacts of every construction material's fabrication, replacement, and disposal processes. Fabrication includes extraction, transportation, and manufacture of raw material. Replacement includes the maintenance and substitution of materials that have reached the end-of-life point. Disposal includes the disassembling process of the construction material [KBOB 2016].

Embodied impact indicators

LCA results can be expressed in many different environmental impact indicators: climate change, acidification, ozone depletion, atmospheric aerosol loading, eutrophication, air pollution, ionising radiation, photochemical ozone formation or chemical pollution indicators, among others [Dong *et al.* 2017]. Within this simplified LCA, a limited selection of environmental impact indicators is calculated. The selection of the environmental impact indicators to be calculated relies on the indicators provided in the KBOB database [KBOB 2016] and on the indicators referred to in norm SIA 2040 to define the building's energy efficiency target values [SIA 2040 2017].

On the one hand, the KBOB database refers to three environmental indicators: 1) Ecopoints expressed in UBP[3]; 2) primary energy (PE) expressed in kWh and divided into renewable primary energy (RPE) and non-renewable primary energy (NRPE); and 3) global warming potential (GWP) defined by the greenhouse gas emissions' CO_2 equivalent and expressed in kg $CO_{2\ eq}$. On the other hand, the SIA 2040 defines its energy efficiency targets by setting target values to NRPE and GWP of buildings. For this reason, the simplified LCA presented in the following pages quantifies the NRPE and the GWP, to compare the results with SIA's energy efficiency targets.

Quantify embodied impacts

Several databases and analysis software can be utilised to perform a façade construction system's LCA: SimaPro, GaBi, Umberto, OpenLCA, BEES tool, etc. [El Khouli *et al.* 2015]. However, due to the particular novelty of the AAF composition

3

The Ecopoints (UBP) quantify the environmental burdens resulting from the use of material and energy resources, land and fresh water, emissions to air, water and soil, from residues waste treatment and traffic noise [KBOB 2016].

and the intention of optimising the façade design through an iterative process, focused on lowering the embodied impacts of the AAF construction system, all calculations are performed manually. This procedure enables higher control of the embodied impacts quantification process and higher awareness of each material's embodied impacts. Ultimately, results enable the comparison of the AAF embodied environmental impact with existing construction systems' impact – CP and BP.

To quantify the embodied impacts of the different scenarios and variants, the construction systems, façade designs and average building impacts are analysed. First, embodied impacts are quantified at the construction system level, per façade square meter. Second, embodied impacts are quantified at the façade level per façade surface, and then normalised per building ERA. Third, embodied impacts of the different active and non-active complete building scenarios are quantified, per building ERA.

Construction system embodied impacts

In this first step, the façade construction system analysis consists in the identification of every construction material composing the construction system. The construction system composition is broken down indicating material quantities expressed in kilograms or meters, according to KBOB database references.

The components of the analysed construction systems are located in the KBOB database to identify their corresponding embodied impact values per reference unit. In the case of missing data, a) the embodied impacts values of similar construction materials are chosen, or b) the embodied impacts value is calculated based on a combination of materials from the list. This data replacement is done following the recommendations of experts in the field, through a collaboration with the Institute of Natural Resource Sciences of the Zurich University of Applied Sciences (ZHAW) [Collaboration with R. Itten, 2018]. The replaced data corresponding to the missing construction materials in the KBOB database are indicated in Appendix A.5.1.

The embodied impacts of the façade construction systems described in Section 5.2 is quantified for 1 m^2 of opaque façade. Table 5.3 displays the material breakdown and quantified embodied impact of 1 m^2 of the AAF construction system with BIPV façade cladding. Regarding current practices, Table 5.4 displays the embodied impacts of 1 m^2 of CP façade construction system and Table 5.5 shows the corresponding values of the embodied impacts of 1 m^2 of BP façade construction system.

Façade embodied impacts

In this second step, to quantify the embodied impacts of the different façades, the above-presented construction system impacts are integrated into the calculation of the embodied impacts of the total opaque façade surface, including all BIPV elements. Figure 5.3 displays the annual embodied impacts of the façades of twelve AAF building scenarios presented in Chapter 4. These results are expressed per opaque façade square meters and specify the different active façade elements integrated into the design. The complete calculation results can be consulted in Appendix A.5.3.

There is very little information in the literature regarding the embodied impacts of BIPV panels and the KBOB database only includes the embodied impacts of standard Monocrystalline PV panels. Based on the collaboration with the ZHAW institute [Collaboration with R. Itten, 2018], assumed embodied impact values are

AAF | BIPV FAÇADE CLADDING

n.	material	KBOB ref	Thickness (m)	Density (kg/m³)	Weight (kg)	NRPE (kWh)	GWP (kg CO2-eq)
1	Interior Coating: Paint	14.001	-	0,3	0,26	1,09	0,35
2	Plasterboard	03.008	0,015	850	9,32	12,58	2,73
3	Wood fibre insulation	10.009.01	0,05	140	6,14	19,28	2,73
3.1	Timber interior substructure	07.009.01	0,05	485	1,42	0,65	0,12
4	OSB 3	07.013	0,015	605	6,05	16,70	3,71
5	Cellulose insulation	10.010	0,35	50	16,29	12,79	3,31
5.1	Timber frame	07.009.01	0,35	485	13,58	6,23	1,18
6	Fibrocement board	03.002	0,012	15	15	36,00	10,91
7	Aluminium substructure	06.002.01	-	2690	1,35	18,36	3,97
8	OPAQUE TANDEM-PEROVSKITE	*	1 m²		25	1188,6	369,6
	Total weight				94,41		
1 to 6	Total environmental impact façade substructure					105,33	25,05
7 to 8	Total environmental impact façade cladding					1206,96	373,57
	TOTAL ENVIRONMENTAL IMPACT AAF					1312,29	398,62
	ANNUAL IMPACT**					**21,87**	**6,64**

Table 5.3
LCA for 1 m² of opaque façade: AAF construction system | BIPV façade cladding construction system.

Source: KBOB database [KBOB 2016]

COMMON PRACTICE | ROUGHCAST

n.	material	KBOB ref	Thickness (m)	Density (kg/m³)	Weight (kg)	NRPE (kWh)	GWP (kg CO2-eq)
1	Interior Coating: Paint	14.001	-	0,3	0,26	1,09	0,35
2	Lime plaster	04.001	0,0015	1100	1,43	0,99	0,21
3	Vapour barrier	09.002	0,005	920	4,03	99,94	21,48
4	Ceramic bricks	02.001	0,125	1200	144	113,90	37,15
4.1	Mortar	04.008	0,01	1400	20	32,00	8,12
5	Polystyrene insulation (EPS)	10.004	0,22	30	6,6	196,68	50,42
5.1	Insulation anchors	06.003	0,008	7850	0,95	3,37	0,65
6	Cement coating	04.009	0,04	1550	62	45,14	16,68
6.1	Steel Roughcast reinforcement	**			3,5	12,50	2,40
6.2	Roughcast exterior coating	04.014	0,005	1550	7,75	7,75	2,54
7	Exterior finish: paint	14.002		30	0,3	1,95	0,48
	Total weight				250,82		
	Total environmental impact façade substructure (1 to 6)					493,12	135,07
	Total environmental impact façade finish (7 to 8)					22,20	5,42
	TOTAL ENVIRONMENTAL IMPACT CP					515,32	140,49
	ANNUAL IMPACT **					**8,59**	**2,34**

Table 5.4
LCA for 1 m² of opaque façade: CP construction system.

Source: KBOB database [KBOB 2016]

BEST PRACTICE | WOOD FAÇADE CLADDING

n.	material	KBOB ref	Thickness (m)	Density (kg/m³)	Weight (kg)	NRPE (kWh)	GWP (kg CO2-eq)
1	Interior Coating: Paint	14.001	-	0,3	0,26	1,09	0,35
2	Plasterboard	03.008	0,0125	850	9,32	12,58	2,73
2.1	Steel substructure	06.012	-	7850	1,75	6,06	1,28
3	Vapour barrier	09.002	0,005	920	4,03	99,94	21,48
4	Medium Density Fibreboard	07.012	0,01	682	5,98	29,18	6,22
5	Rockwool insulation	10.008	0,27	60	14,14	61,23	15,98
6	Timber frame	07.009	0,27	485	24,11	12,15	2,44
7	Medium Density Fibreboard	07.012	0,01	682	6,82	33,28	7,09
8	Timber substructure	07.009	0,03	485	1,35	0,68	0,14
9	Wood façade cladding	07.009	0,018	485	8,73	4,40	0,88
9.1	Autoclave wood treatment					1,58	0,5
	Total weight				76,49		
1 to 6	Total environmental impact façade substructure					255,52	57,57
7 to 9	Total environmental impact façade cladding					6,66	1,52
	TOTAL ENVIRONMENTAL IMPACT BP					262,18	59,09
	ANNUAL IMPACT**					**4,37**	**0,98**

Table 5.5
LCA for 1 m² of opaque façade: BP construction system.

Source: KBOB database [KBOB 2016]

*

Data furnished by the Institute of Natural Resource Sciences of the Zurich University of Applied Sciences (ZHAW).

**

60 years (BIPV's life span of 30 years is considered in KBOB data).

taken for the different BIPV technologies here analysed. These values can be found in Appendix A.5.1.

Building embodied impacts

To quantify the embodied impacts of the different building scenarios per building ERA, the research process defines 3 steps (Figure 5.4): 1) taking the average embodied impacts of a collective residential building based on existing studies [Drouilles *et al.* 2019]; 2) subtracting the average opaque façade embodied impacts [SIA 2032 2010]; and 3) adding the specific environmental impacts of each façade quantified throughout this research phase.

First, this research project relies on existing studies that have analysed and quantified the average environmental impact of a collective residential building. In this case, the building scenario's LCA is based on the work of Drouilles *et al.*, who have taken the building scenario 1A presented in Section 4.4.1 as a representative residential building to calculate total embodied energy [Drouilles *et al.* 2019]. Throughout their work, they have taken the same façade construction systems as this research project, enhancing the accuracy of the data contained in this section: W01 for CP and Wi01 for BP [OFEN 2002]. Table 5.6 gathers some of their research results used in this research phase.

Second, the embodied impact share of a façade regarding the whole building can significantly vary depending on the building type, location, morphology and function [Victoria *et al.* 2018]. However, to define a representative share of the façade's embodied impact, the Swiss norm SIA 2032: The embodied energy of buildings, in its Appendix E, presents the distribution of NRPE and GWP of a residential building example [SIA 2032 2010]. According to this document, façades account for 11% of the building's annual NRPE and 9% of the building's annual GWP. This information is taken as representative to extract the façade embodied impact from the representative residential building's total embodied impacts, identified by Drouilles *et al.* [Drouilles *et al.* 2019].

Third, the specific embodied impact of each façade analysed in this research process can be incorporated into the representative building impact. That is to say, values presented in Figure 5.5 and Figure 5.6 are the sum of the average embodied impact of a residential building without the average impact of the façade, plus the specific embodied impact of each façade design, per building ERA. As a reminder, façade environmental impacts have been calculated per façade surface that are then normalised per building ERA to be combined with the building's embodied impacts and compared to SIA 2040 target values.

Results discussion

At the construction system level, the AAF (Table 5.3) is focused on lowering the environmental impacts of its substructure to compensate for the high embodied impacts associated with the integration of BIPV. This results in an AAF façade substructure, which presents 1/2 of the embodied impacts associated with BP façade substructure and 1/5 of the embodied impacts associated with a CP façade. This impact reduction is mainly achieved by replacing highly embodied impact insulation, such as EPS, with natural insulators, such as wood-fibre insulation and cellulose. Besides, removing the vapour barrier and replacing it with a vapour-tight material such as OSB 3 panels, which simultaneously fulfil the vapour barrier function and other structural functions has a significant positive impact on reducing embodied impacts when designing the AAF construction system.

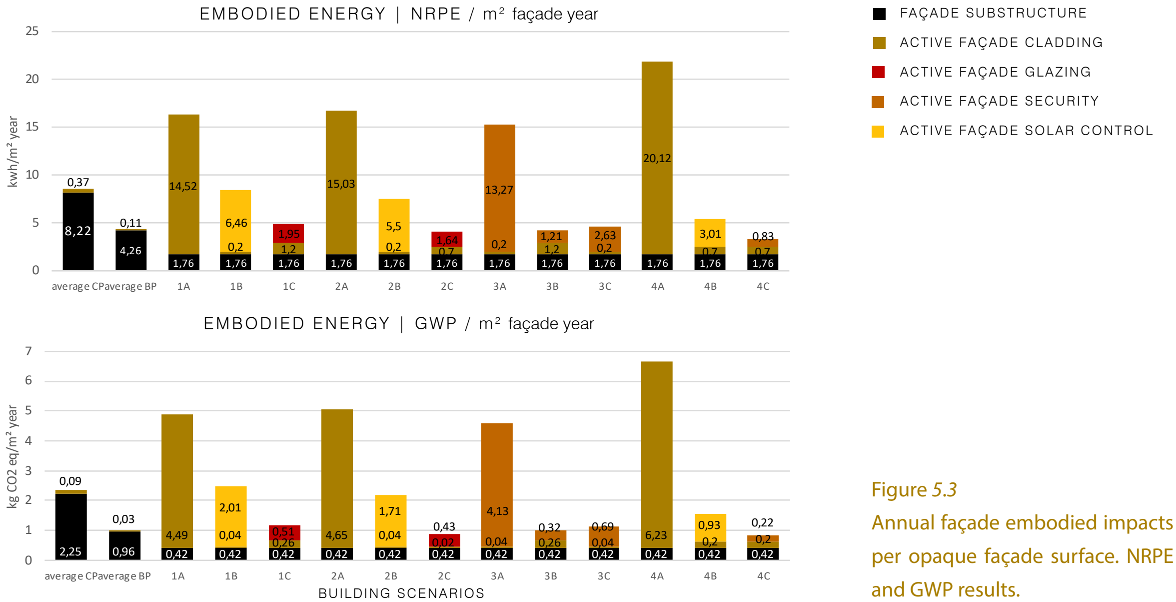


Figure 5.3
Annual façade embodied impacts per opaque façade surface. NRPE and GWP results.

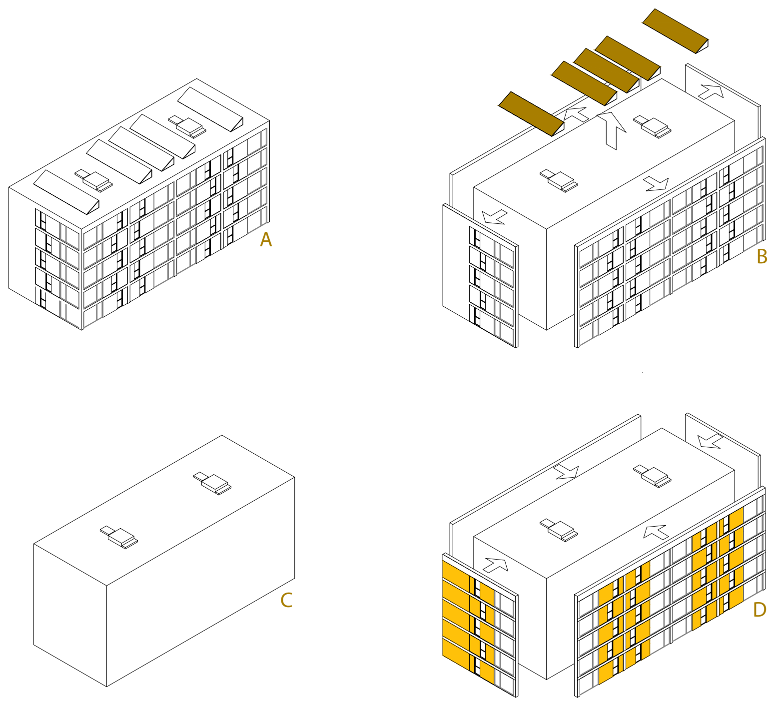


Figure 5.4
Scheme of building's embodied impact calculation method:

A. Representative building analysed by Drouilles et al.

B. Façade and PV impact substraction

C. Representative building base

D. Addition of AAF - or correspondent façade for embodied impact quantification.

Building Embodied impact

		Vertical elements	Horizontal elements	Equipements	Outside parking	Total
Common Practice	NRPE	15,58	8,61	7,31	1,99	33,49
*Current practice S0**	GWP	2,73	3,05	1,68	0,24	7,70
Best Practice	NRPE	11,50	6,04	9,85	0,76	28,14
*Best practice S1**	GWP	1,52	2,23	2,43	0,22	6,40
Advanced practice	NRPE	11,59	6,42	12,53	0,74	31,28
*Best practice S3**	GWP	1,62	2,25	0,21	0,22	4,29

		BAPV roof surface (m²)	BAPV impact considered*	**Total Building impacts without BAPV**
Common Practice	NRPE	0	0,00	**33,49**
*Current practice S0**	GWP		0,00	**7,70**
Best Practice	NRPE	170	2,69	**25,45**
*Best practice S1**	GWP		0,78	**5,62**
Advanced practice	NRPE	342	5,42	**25,86**
*Best practice S3**	GWP		1,57	**2,72**

*

Drouilles et al. 2018 reference

NRPE (kWh/m² yr)

GWP (kg CO_2 eq/m² yr)

Table 5.6
Building embodied impact. Research results from Drouilles et al.

Source: [Drouilles *et al.* 2019]

However, BIPV embodied impacts account for more than 90% of the AAF total embodied impacts when designed with active façade cladding. Compared to current practices, 1 m^2 of an AAF façade has 5 times more embodied impacts than 1 m^2 of a BP façade and 2.5 times more embodied impacts than 1 m^2 of a CP façade (Table 5.3, Table 5.4, and Table 5.5).

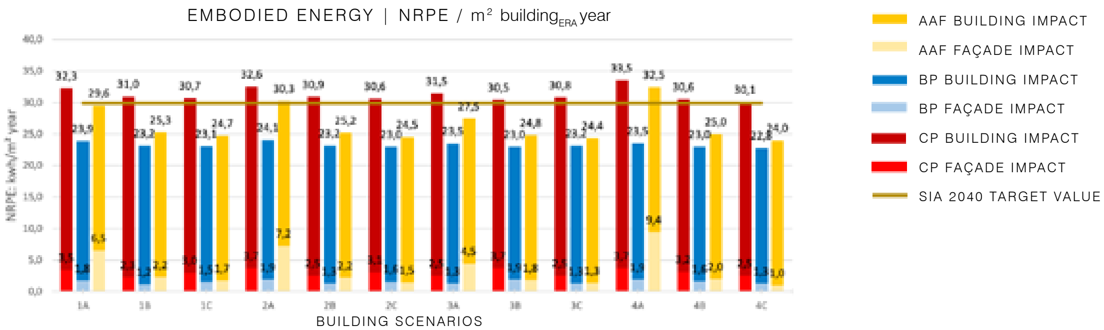
Throughout the AAF construction system design process, the biggest challenge is to define the façade substructure's exterior layer (number 6 on Table 5.3). This layer must be water- and windproof, fire-resistant [AEAI 2015], and must have a low embodied impact in order to achieve the core objective of the AAF design: contribute to the energy transition. The study of several options led to the most efficient choice which integrates a fibro-cement panel, which resists fire and is water- and windproof. Even though this type of panel has been considered as the most adequate regarding normative and functional façade requirements, this element has the highest embodied impacts of the whole AAF substructure. This highlights that more research is needed towards finding low embodied impact materials with fire resistance features.

At the façade level (Figure 5.3), the different AAF designs have different embodied impacts depending mostly on the total active surface incorporated and the chosen BIPV system. BIPV façade cladding accounts for more than 90% of the total embodied carbon of the AAF system – 1A, 2A, 4A –, whereas AAF building scenarios with alternative BIPV integrations – glazing, security or solar control – have lower impacts (Figure 5.3). This is mostly due to the large surfaces designed with active façade cladding – 900 m^2 in average – and to the smaller active surfaces designed as façade glazing, security or solar control accessories – 300 m^2 in average. The significant difference between the twelve AAF designs is related as well to the visual features of the BIPV system and their associated environmental impacts. Opaque BIPV systems – Group A – have higher environmental impacts than translucent – Group B – or transparent BIPV systems – Group C – due to the higher density of PV material associated with its opacity. The translucent BIPV panels integrated into Group B scenarios have, in average 65% fewer PV cells than Group A BIPV systems, which guarantees a minimum of 35% transparency. Ultimately, Group C BIPV systems integrate transparent Thin-Film BIPV systems which have up to 10 times less environmental impacts than Monocrystalline PV cells due to their low energy consumer fabrication process [Tiwari *et al.* 2016].

At the building level, CP variants have the highest embodied impacts in each building scenario, both for NRPE and GWP (Appendix A.5.3). BP building scenarios have lower embodied impacts than all AAF building scenarios, even if some AAF have lower façade impacts (Figure 5.3). The higher impacts of the AAF building scenarios at building scale relate to the technical equipment installed to optimise the advanced-practice building's energy efficiency, as considered by Drouilles *et al.* (Table 5.6) [Drouilles *et al.* 2019].

Regarding other scenario variants, the integration of MR Monocrystalline silicon has higher embodied impacts, according to the environmental data provided in the KBOB database and the ZHAW [KBOB 2016] than HP Tandem-Perovskite BIPV technology.

Ultimately, the installation of a BAPV-roof increases the building's embodied impacts of all variants, CP, BP and AAF. This installation increases the building's NRPE values by 4 kWh/m^2yr and the building's GWP values by 1,07 $CO_{2\ eq}$/m^2yr (Appendix A.5.3).



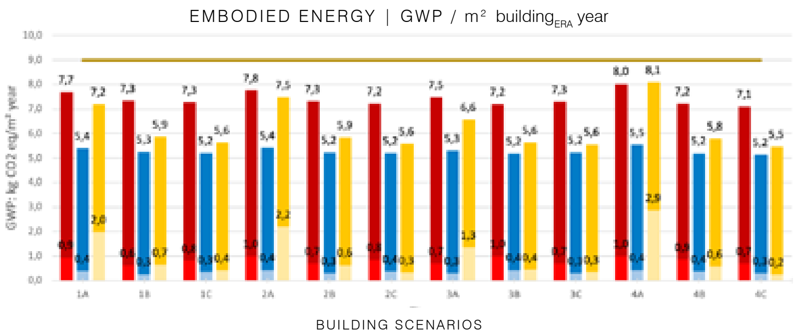
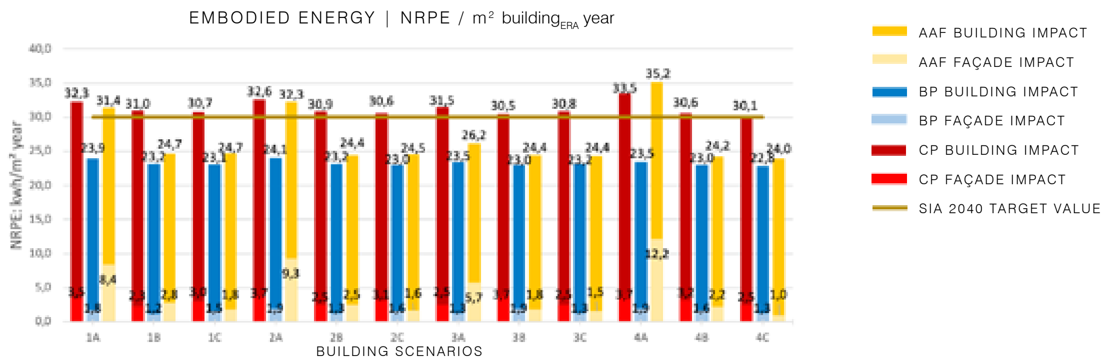


Figure 5.5
Annual total building's embodied impact per building's ERA.

NRPE and GWP.

High-Performance variant.



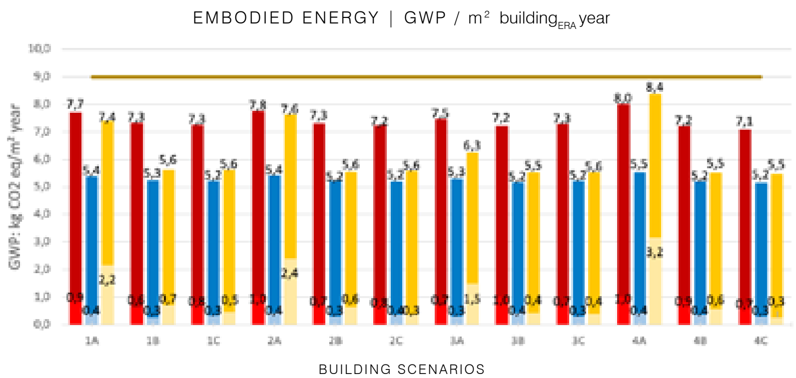


Figure 5.6
Annual total building's embodied impact per building's ERA.

NRPE and GWP.

Market-Ready variant.

Comparing results to the energy transition targets

As mentioned at the beginning of this section (Section 5.3), embodied energy quantification results are compared to the energy transition targets defined by the 2000-Watt Society and specified in the norm SIA 2040 [Suisse Energie 2015; SIA 2040 2017]. These targets establish a maximum building's NRPE value of 30 kWh/m² per year and building ERA and a maximum GWP value of 9 kg $CO_{2\ eq}$ / m² per year and building ERA.

Figure 5.5 and Figure 5.6 show SIA's target values as well as the embodied impacts of each building scenario for the three main variants: CP, BP and AAF. They display results for the HP AAF and MR AAF respectively.

The assessment of the embodied energy analysis results compared to SIA 2040 target values highlights that:

- None of the analysed building scenarios with the CP variant reaches the NRPE embodied energy target values (See further scenario variants on Appendix A.5.3).

- Non-active BP variants meet both NRPE and GWP embodied energy target values. As mentioned above, the incorporation of BAPV-roof entails a similar embodied impact increase for all scenarios. BP+BAPV-roof meets the embodied energy transition target values – NRPE and GWP – in all analysed building scenarios. On the contrary, the incorporation of BAPV-façades depends on the façade design and PV technology. Hence, their impacts vary among building scenarios. Detailed results can be consulted in Appendix A.5.3 and will be further discussed in the combined energy analysis section (Section 5.3.3).

- The AAF building scenarios which integrate large surfaces of opaque BIPV present the highest embodied energy. Results presented in Figure 5.5 show the analysis of the HP integration variable. They highlight how 2A and 4A are close to meeting the NRPE target value but do no reach it. Building scenarios 1A and 3A also have high embodied impacts, although they are beneath the NRPE limit value, like the other AAF building scenarios with smaller BIPV installations. Embodied GWP target values are met by all scenarios.

  Results presented in Figure 5.6 correspond to the MR integration variable. This AAF building scenario analysis shows that all buildings integrating large BIPV systems as opaque façade cladding – 1A, 2A and 4A – do not reach SIA 2040's target values (NRPE). Embodied GWP target values are met by all scenarios.

  The difference between HP and MR AAF building scenarios relates to the integration of Tandem-Perovskite PV technology in HP variants, which has lower embodied impacts than MR Monocrystalline-silicon technology. The fact that the 1A AAF building scenario meets energy efficiency target values with HP PV technology and does not meet the target values with MR PV technology shows that the choice among BIPV technologies also affects the embodied energy assessment results.

To conclude, the embodied impact of CP construction must be lowered to reach embodied energy efficiency target values. BP construction based on timber construction can meet embodied energy efficiency targets. Regarding AAF, the type of BIPV integration and BIPV technology significantly influences the building's embodied impacts. AAF integrating small BIPV surfaces as façade glazing, security or solar control can reach SIA 2040 embodied energy target values. Similarly, AAF integrating façade cladding can meet energy efficiency targets, but results are influenced by the façade design, which determines the total active surface, and the type of BIPV technology. The latter defines the use of a high embodied impact technology or a low embodied impact one.

According to the calculations carried out in this research step, embodied impacts associated to a Monocrystalline BIPV panel should decrease by 50% to enable a total active façade cladding scenario as 4A to meet SIA 2040 embodied impact target values.

However, as introduced at the beginning of this section, SIA 2040 also establishes a combined energy efficiency target, which is defined by the addition of the embodied energy target values and the operational energy target values. This combined target could be specifically applied in cases where the increase of the building's embodied impacts notably reduces the building's operational impacts, as is the case of BIPV systems [SIA 2040 2017].

5.3.2 Operational energy efficiency analysis

The operational energy analysis is based on the energy simulation of the building scenarios and their variants presented in Section 5.2. The simulation research method has been entitled *Sign simulation* by Novikov *et al.* who describe it as *a type of informational modelling that serves as the way of constructing something new that cannot be constructed or at least not entirely* [Novikov *et al.* 2013]. Simulations provide information on a new system's performance when it does not exist, or cannot be used for experimentation [Knepell *et al.* 1993].

The *something new* referred to by Novikov *et al.* is, in this case, the building scenarios, their urban context and their corresponding BIPV systems. Throughout this research process, complete buildings cannot be constructed to assess their energy efficiency. Hence, they are modelled into Design-Builder (DB), an energy building simulation tool, to simulate their operational energy demand and BIPV generation.

DB allows a complete simulation of buildings' energy demand and the simulation of the energy generation of the BIPV façade. All simulation parameters and the weather template details used for the AAF simulation can be found in Appendix A.5.2.

All AAF building scenarios presented in Chapter 4 and their non-active CP and BP variants have been modelled into the building simulation tool. The energy performances of the additional variants presented in Section 5.2 are calculated through the *Quantitative assessment* Excel model developed in the framework of this research phase.

Operational Energy Simulations

DB enables the performance of different and multiple simulations for each AAF building scenario. This building simulation tool provides hourly energy simulation results, which allow enough precision to determine the amount of energy supplied by BIPV façades and that can be locally consumed by the building operation.

The different simulations that have been performed are the following:

- Hourly energy simulations for each AAF building scenario.
- Hourly energy simulations for each façade orientation of each AAF building scenario, independently.
- Hourly energy simulations for each building scenario, integrating the BP construction system.
- Hourly energy simulations for each building scenario, integrating the CP construction system.
- Annual simulations integrating BAPV-roof (maximal surface available).

The results of these DB simulations are expressed in final energy (kWh) and enables the assessment of the building's energy demand, the building's energy generation, the building's self-consumption, the building's self-sufficiency, the seasonal energy balance and the impact of façade's orientation on the final electrical output.

- **The building's energy demand** is the amount of energy consumed by the building's operation, whether it comes from the electric grid or on-site renewable energy sources [SIA 2040 2017]. The building's energy demand analysis of the different façade construction scenarios (CP, BP or AAF) defines the passive energy economy achieved with the use of the AAF construction system over the CP or BP construction systems. The building's energy demand is mostly affected by the design and construction of its building envelope [Ruggieri *et al.* 2013].

- **The building's energy generation** is the energy produced by on-site generating facilities and used wholly or partially within the building [SIA 2040 2017]. The passive use of solar energy and the use of heat extracted from the environment are not considered as on-site energy production [SIA 380 2015].

  The hourly energy generation simulation paired with the building's hourly energy demand simulation shows the number of overgeneration hours and the amount of energy that cannot be directly and locally consumed. This energy can be exported to the grid or locally stored with an energy storage system. Likewise, to increase the share of self-consumed BIPV energy, it is possible to implement Energy Management Systems (EMS) to minimise the hourly mismatch between energy generation and energy consumption [Barbato *et al.* 2012].

- **The building's energy self-consumption** is defined by the previously mentioned energy mismatch issue. According to Swiss norms SIA, the self-consumption *is the part of the energy produced on-site used during a considered period to cover the energy needs during the same period in relation to the total energy produced on-site of the energy agent concerned* [SIA 380 2015]. That is to say, the self-consumption is the PV production consumed in-house [Luthander *et al.* 2015], and it is usually expressed as the share of self-consumed energy of the total energy generation.

  To define a realistic self-consumption value, the building's energy simulations must be run hourly because, without a storage system, the PV electricity that is not consumed at the moment of production must be exported. Also, hourly energy generation simulations allow for an accurate dimensioning of the energy storage system.

- **The building's energy self-sufficiency** can also be referred to as the *autarky* degree, which is defined by the SIA norms as *part of the final energy consumption satisfied by the on-site generated energy* [SIA 380 2015]. That is to say; it is the fraction of consumed electricity that is not bought from the grid and refers to how energy-independent the building is from the grid [Luthander *et al.* 2015].

Figure 5.7 and Figure 5.8 illustrate the self-consumption and self-sufficiency concepts showing the schedule profile of on-site generated BIPV energy and the building's energy demand. The grey area (A) is the total net electricity demand and the yellow area (B) represents the BIPV generation. The overlapping part (C) is the on-site generated BIPV electricity consumed by the building. This is sometimes called absolute self-consumption. However, self-consumption usually refers to the self-consumed part (C) relative to total production (B+C). The self-consumed part (C) relative to the total load (A+C) is the previously defined self-sufficiency. These concepts can be expressed in the above-mentioned simplified nomenclature as:

Self-consumption = C / (B+C)

Self-sufficiency = C / (A+C)

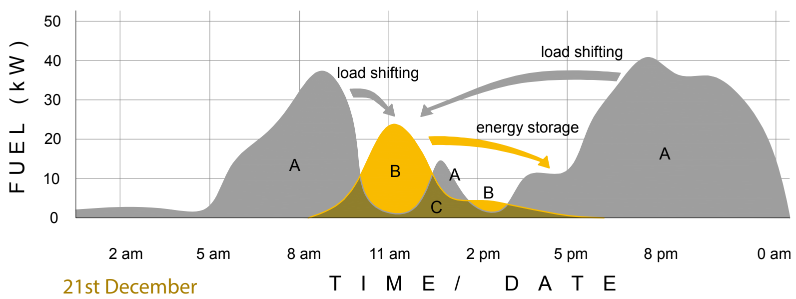


Figure 5.7
Schematic outline of winter daily net load (A+C), net generation (B+C) and absolute self-consumption (C) in a collective residential building with BIPV façades. It also indicates the function of the two main options (load shifting and energy storage) for increasing the self-consumption.

Source: [Luthander et al. 2015]

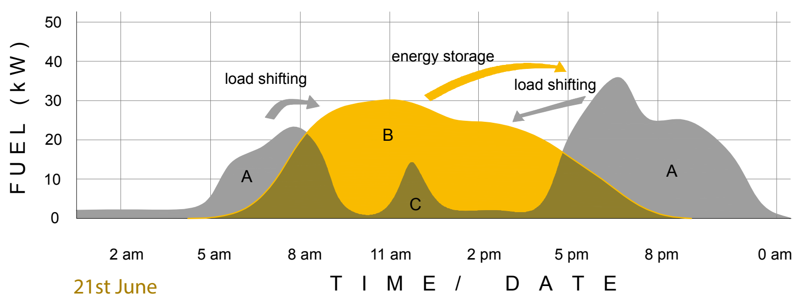


Figure 5.8
Schematic outline of summer daily net load (A+C), net generation (B+C) and absolute self-consumption (C) in a collective residential building with BIPV façades. It also indicates the function of the two main options (load shifting and energy storage) for increasing the self-consumption.

Source: [Luthander et al. 2015]

- **The annual energy balance** is the result of aggregated annual values. This concept defines if a building is an energy consumer, when the energy demand is higher than the energy generation – if there is one –, a net zero energy building (NZEB), when the energy generation equals the energy demand, or a positive energy building, when the energy generation is higher than the energy demand. Annual energy balance calculations do not consider the mismatch between PV energy generation and building's energy demand. Hence, the annual energy balance is calculated under a 100% self-consumption hypothesis [Hall *et al.* 2017; SIA 2040 2017].

- **The seasonal energy balance** refers to the independent study of the energy balance in summer days and winter days. This study shows that the daily generation periods vary throughout the year, as well as the buildings energy demand and generation. Figure 5.7 and Figure 5.8 represent a schematic outline of the daily building loads of a winter and summer day. During winter days, electricity generation cannot supply the building's electricity demand, because daily energy consumption is higher than the daily energy generation. Over these periods, the grid must supply the load because the energy stored in the storage system is not sufficient to supply the load by itself. During summer days, electricity production exceeds the electricity demand of the building, due to higher irradiation. The daily PV generation is higher than the daily consumption; therefore, the storage system is often fully charged. This means that the energy surplus generated must be sent into the grid [Vieira *et al.* 2016].

  To perform the seasonal energy balance analysis, two representative summer and winter days have been selected to calculate and analyse the seasonal variations of the electrical output. These days are the summer solstice (21st June) and the winter solstice (21st December), which are respectively the longest and the shortest days of the year. The study of the seasonal simulation results is extended to a total of twenty-one days for each season: ten days before and ten days after the solstices. These are called the *solstice days* and allow a sharp average to be calculated of the most productive and less productive days of the year. The number of days under study is extended to twenty-one days to integrate an average of the weather effects on BIPV panels. However, the extension of the seasonal study is limited to this number of days to avoid variations of daylight hours and hence, the accuracy of the analysis representing the longer and shorter days of the year. The average output of this short period represents more accurately the maximum annual daily output (in summer) and the minimum daily output (in winter) than the average output of the whole summer and winter seasons.

- **The façade orientation** determines the energy output of each façade and its generation schedule. The latter affects the amount of energy that can be directly self-consumed and the amount of energy that needs to be exported into the grid or stored. The simulated building scenario has two large main façades oriented towards north-east and south-west, which are called north façade and south façade respectively in the following pages, and two smaller lateral façades oriented towards south-east and north-west, which are called east façade and west façade (Figure 5.9).

At an annual scale, south façades are expected to register the highest energy output per square meter. This is the façade energy yield, which results from dividing the independent energy yield of each façade by its active surface. This information allows a reliable comparison among façade performances independently of the façade design. The assessment of these data must be considered during the façade design process to evaluate the energy and cost worthiness of BIPV integration in every façade.

To obtain and analyse the above-mentioned energy concepts, a total of 85 hourly building energy simulations are performed with Design-Builder corresponding to the AAF building scenarios (12), the BP building scenarios (12), the CP building scenarios (12), the individual façades of each AAF building scenarios (48) and the maximum BAPV-roof installation (1). The additional building scenario variants described in Section 5.2 and enumerated in Table 5.1 are calculated with the *Quantitative assessment* Excel model – the HP or MR BIPV technologies variants, the incorporation of the BAPV-roof into AAF, CP and BP building scenarios; and the CP and BP scenarios with BAPV-façades.

The simulation results must be considered as estimation values due to the different limitations of the building simulation tool, which are listed below:

- DB cannot simulate the temperature reached by the BIPV panels. Hence it cannot simulate the performance losses associated with high BIPV panel temperature. Nevertheless, there is always a minimum air cavity of 8 cm guaranteed by the AAF construction system design that is expected to provide the required BIPV panel's rear ventilation [Brinkworth *et al.* 2005; Maturi *et al.* 2015].

- DB does not distinguish among different PV technologies and their different energy performances under low-irradiance values. For instance, Thin-Film technology works well with low irradiance values – 400 to 800 W/m^2 –, typical on north façades, whereas crystalline technology is optimised for 1000 W/m^2 irradiance, while its output decreases rapidly with lower irradiation [Polysolar 2015]. These subtleties are not reflected in DB's simulation results.

- The DB model designed for the simulation of the building scenarios includes the existing urban environment, but not the eventual vegetation that may surround the building. When landscaping, special attention to potential shadowing of the BIPV panels must be paid.

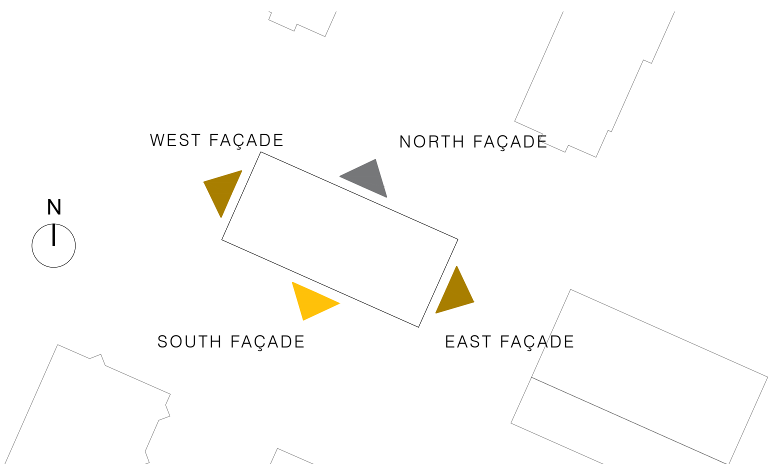


Figure 5.9
Simulated building orientation.

Dummy panels or other non-active façade construction materials must be considered and incorporated into the façade design process in case a permanent shadow is expected in some façade areas.

The following pages present a transversal analysis of the most relevant simulation results compared to SIA 2040 energy efficiency target values.

Building's energy demand and self-sufficiency rate

The study of the twelve different AAF building scenarios and the analysis of their energy simulation results highlight that their energy demand is homogeneous when constructed with the AAF construction system. AAF building scenarios have an average energy demand of 42.5 kWh/m^2. Values vary between 41 and 44 kWh/m^2, the higher ones corresponding to building scenarios with the *Loggias* façade morphology, which are less compact (Section 4.2.1.1) (Table 5.2).

When AAF building scenario simulation results are compared with their non-active variants, it is remarked that BP buildings have an average energy demand 8% higher than AAF. On their side, CP buildings have an average energy demand 13.5% higher than AAF building scenarios. This is due to the increased insulation of the AAF that entails a lower façade thermal transmittance value and a lower building energy demand.

Figure 5.10 and Figure 5.11 show a comparative of the annual energy demand of the average CP, average BP and AAF building scenarios for the HP and MR variants, respectively. These figures display the self-sufficiency of the different building scenarios.

Buildings with high annual energy output (Figure 5.12 and Figure 5.13) have higher self-sufficiency than buildings with low annual energy output. However, even with an annual PV generation, which surpasses the annual energy demand, self-sufficiency does not reach high values due to the mismatch between energy generation and energy demand schedules – no EMS considered.

The self-sufficiency is calculated for the *no-battery* scenario variant and the *with-battery* scenario variant. The calculations of the optimal size of the battery are based on its economic performance and results can be consulted in Appendix A.5.3. The maximum *no-battery* self-sufficiency value is 39% and corresponds to the 4A building scenario integrating HP BIPV systems, which has the largest annual energy output.

To optimise self-sufficiency, EMS can increase self-consumption up to reaching 100% building's self-sufficiency. Self-sufficiency values, under a hypothesis of a 100% BIPV energy self-consumption, are also included in the graphics. These values give information on the maximum potential of the AAF design to contribute to the energy transition.

Building scenarios with large BIPV installations (Table 5.2) – façade cladding scenarios: 1A, 2A and 4A – have the highest self-sufficiency rates, corresponding to their high energy generation. These rates are higher if batteries are integrated into the building scenario. Self-sufficiency rates are also higher when an HP BIPV system is integrated instead of an MR BIPV system. Further energy analysis results can be consulted in Appendix A.5.3.

Small BIPV installations (Table 5.2) with transparent Thin-Film technologies have the lowest self-sufficiency rates, due to the low annual energy output of their BIPV systems. Most of these scenarios do not display a *with-battery* variant because life-cycle cost calculations have resulted in a non-profitable option (Appendix A.5.3).

OPERATIONAL ENERGY | building's final energy demand (MWh)

■ ENERGY DEMAND
● SELF-SUFFICIENCY | NO BATTERY
● SELF-SUFFICIENCY | OPTIMAL BATTERY
● SELF-SUFFICIENCY | 100%
SELF-CONSUMPTION

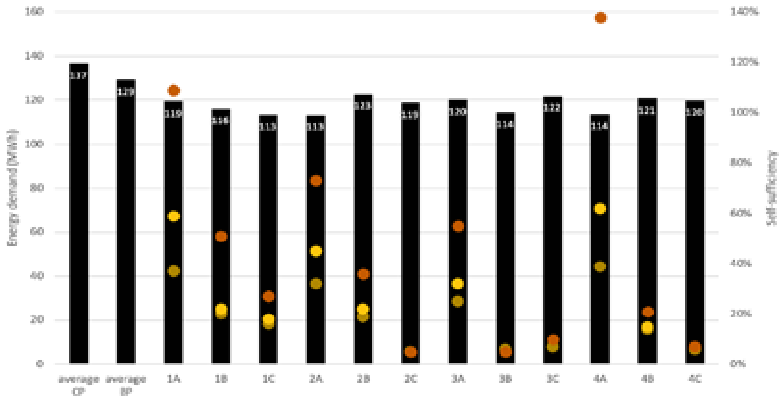


Figure 5.10
Final energy demand and self-sufficiency rates with and without batteries.

High-Performance variant.

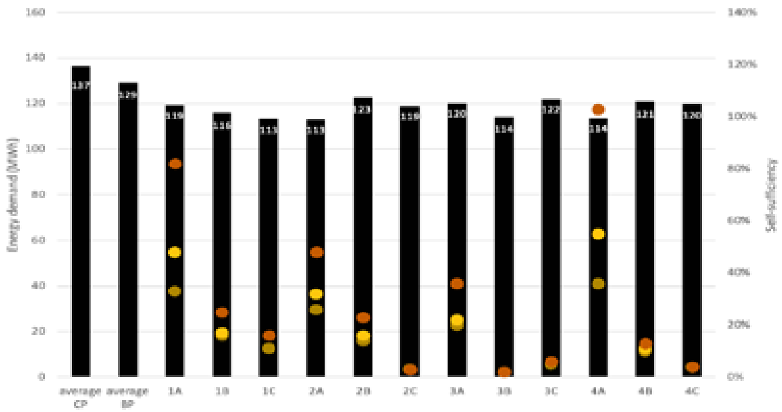


Figure 5.11
Final energy demand and self-sufficiency rates with and without batteries.

Market-Ready variant.

OPERATIONAL ENERGY | building's final energy generation (MWh)

■ ENERGY GENERATION
● SELF-CONSUMPTION | NO BATTERY
● SELF-CONSUMPTION | OPTIMAL BATTERY

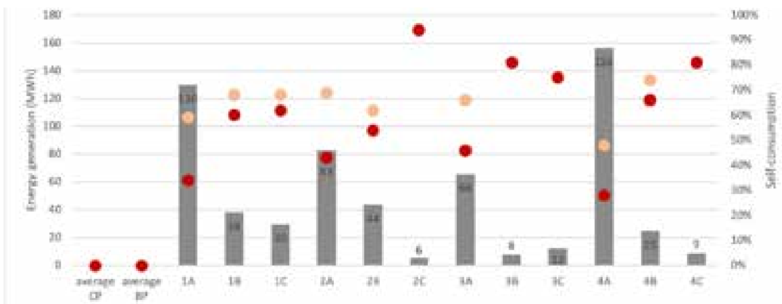


Figure 5.12
Final energy generation and self-consumption rates with and without batteries.

High-Performance variant.

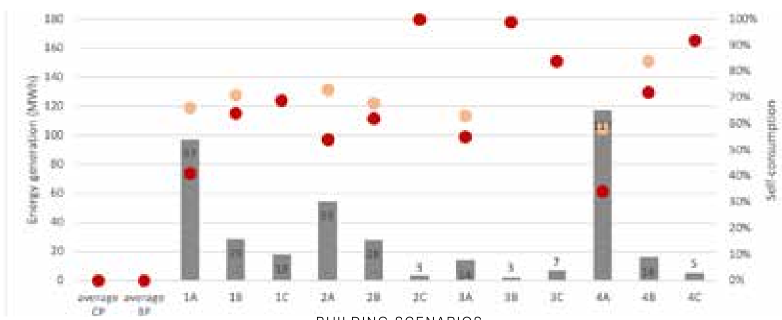


Figure 5.13
Final energy generation and self-consumption rates with and without batteries.

Market-Ready variant.

Building's energy generation, façade orientation and self-consumption rate

The electrical output of the active façades simulated on this chapter depends on the total active surface of BIPV panels, their specific PV technology and their orientation. Each scenario integrates different BIPV systems with different BIPV technologies fulfilling different façade functions, as has been described in Chapter 4.

The energy generation simulation results are displayed in Figure 5.12 and Figure 5.13 showing significant differences among the annual output of the AAF building scenarios. These differences directly correspond to the size of the installation displayed in Table 5.2.

Buildings with a high annual energy output have a lower self-consumption than buildings with low annual energy output. The minimum self-consumption value corresponds to the 4A HP building scenario, which generates 135% of its annual energy demand. The highest self-consumption rate corresponds to the 2C MR building scenario, which generates only 3% of its annual energy demand but can self-consume 100% of it.

Regarding orientation[4], the analysis of the twelve AAF building scenario energy simulations highlights that the south façades have the largest electrical output per square meter (surface-yield). In average, east façades generate 15% less energy per square meter than the south façades, and the west façades of the simulated scenarios generate 35% less than the south façades. Ultimately, the north façades, which have the lowest surface yield, generate on average 54% less than the south façades.

Façade surface-yield data is critical to further assess the financial impact of BIPV integration in different façade orientations. For this reason, BIPV façade design must be an iterative process where environmental impact and cost assessments are related and affect the façade design process.

Annual and seasonal energy balance

To calculate a building's energy balance, the annual energy demand and the annual energy generation are considered. In this case, 100% of the energy generation is taken into account, even if it is not fully consumed by the building [Hall *et al.* 2017; SIA 2040 2017].

Results for both HP variants and MR variants are presented in Figure 5.14, which shows that the larger BIPV installations (Table 5.2) provide the building with a better energy balance (close to 0 or negative). Moreover, two scenarios - 1A and 4A - generate more energy than the building's energy demand. They are, therefore, transformed into positive energy buildings by integrating the AAF.

The seasonal analysis of the simulation results highlights that, during long summer days, BIPV façades generate energy for 16 hours, from 5:00 am to 8:00 pm. During shorter winter days, BIPV façades generate energy for 9 hours, from 9:00 am to 5:00 pm.

The generation schedules of each façade orientation are different, according to the sun trajectory along the day. Different peak generation hours, which vary according to seasons, have been identified for each façade orientation. In contrast, all the different scenario simulations have resulted in similar generation profiles, regardless of the total active surface or BIPV performance.

4
Note that the building façades orientations are called South, East, West and North, but their orientation is not strictly as they are called. The simulated building scenarios have mixed orientations: see Figure 5.9.

The average energy generation schedule shows that: 1) east façades have a peak generation hour between 10:00 am in summer and 11:00 am in winter; 2) south façade's production is higher between 2:00-3:00 pm all year round; 3) west façades have their higher energy output between 16:00 and 17:00 both in summer and in winter; and 4) north façades have a homogeneous generation profile between 7:00 am and 6:00 pm in summer and between 10:00 am and 4:00 pm in winter. In some cases, a slight peak production can be identified on the north façade PV generation, depending on the season: summer days usually present a peak energy output in the very morning, at 9:00 am, while winter days have the largest energy output at around 1:00 pm. This hourly information can be useful to program EMS and to prevent grid overloads.

The seasonal analysis enables the study of the relation between energy demand and energy generation throughout the year. The simulated scenarios have a higher energy generation in summer days and a lower one in winter days. Energy generation is on average 75% lower on winter days than in summer days. On the contrary, energy demand is 43% higher on winter days than in summer days.

Daily energy demand is usually higher than the daily energy generation, both in summer and in winter. This means that all the energy generated by the active façades can be daily and locally consumed by the building. Auto-consumption values can be increased by means of EMS. The objective is to swift the energy demand's schedule to suit the energy generation schedule, which can hardly be modified.

There are only two scenarios where daily summer generation surpasses the average daily energy demand – 1A and 4A –, in these particular cases energy export needs to be studied in terms of smart grid integration or neighbour supply [Khan *et al.* 2015].

The study of the energy demand and energy generation seasonal variations enable a more precise definition of the amount of energy that can be consumed on-site by the building and what type of measures can be defined to increase local energy consumption. Among the latter: DSEMS which, as a reminder, can swift the building's energy demand schedule by adapting it to the BIPV energy generation schedule. For example, laundry or washing machines are programmed to start at noon, and water heaters to produce and stock up hot water at peak generation hours (Section 3.2.2.1).

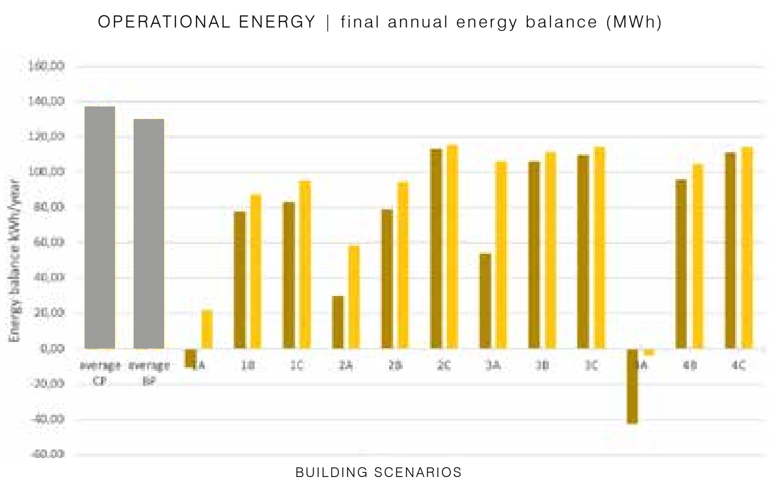


Figure *5.14*
Annual energy balance.

High-Performance and *Market-Ready* variants.

The seasonal analysis highlights the importance of integrating EMS to maximise self-consumption in summer, as well as the importance of combining active strategies with passive ones to minimise the building's energy demand in winter.

Ultimately, the AAF, which combines active and passive energy strategies, has the potential to provide significant energy savings to the building when compared to current practices. The AAF can provide a minimum of 14% (2C MR) and up to 49% (4A HP) energy economy, considering the real self-consumption with no EMS integrated, compared to CP. If a 100% self-consumption is considered, energy savings can reach 100% for the 1A and 4A building scenarios. The latter has been already identified as a positive energy building, generating 108% and 138% of its energy demand, respectively. AAF annual energy potential savings are represented in Figure 5.15.

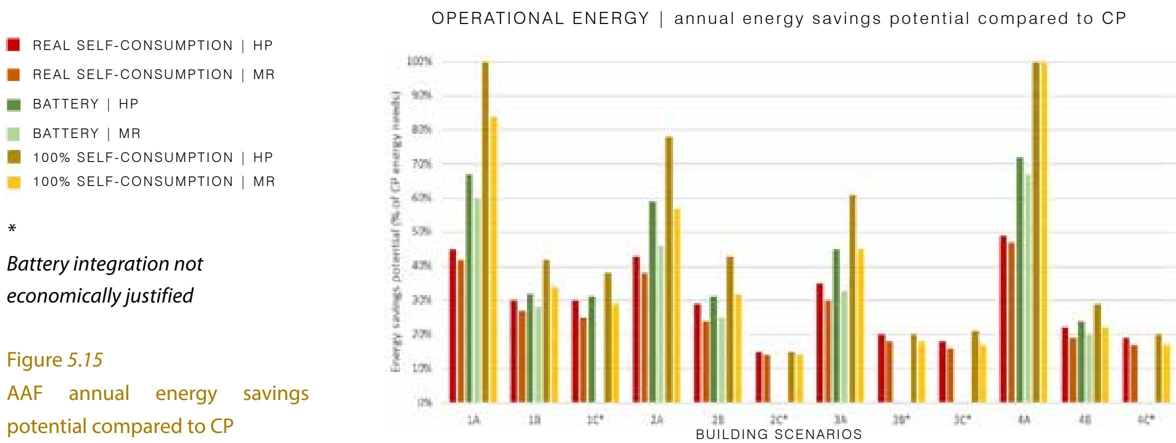
Comparing results to energy transition targets

Operational energy simulation results are obtained and expressed in this section in final energy in an attempt to use the same units like the ones used by energy companies that supply buildings. However, the energy transition's efficiency objectives are expressed in the SIA 2040 with NRPE and GWP target values. To evaluate the environmental impact of the different building scenarios and compare it to SIA 2040's target values, the KBOB database provides the corresponding coefficients to transform final energy results into NRPE and GWP for the Swiss context [KBOB 2016].

Figure 5.16 and Figure 5.17 show the building's annual environmental impacts associated with its operational energy consumption when integrating HP or MR BIPV systems. These figures also display the operational energy target values, which are 60 kWh/m^2 per year (NRPE) and 3 kg $CO_{2\,eq}$ / m^2 per year (GWP) showing that:

- Buildings must integrate a renewable energy source to meet the SIA 2040 target values, or they must lower their final energy balance to 23,81 kWh/m^2 per year by other means. The latter equals 60 kWh/m^2 of primary energy in the Swiss context, considering the Swiss consumer electricity mix.

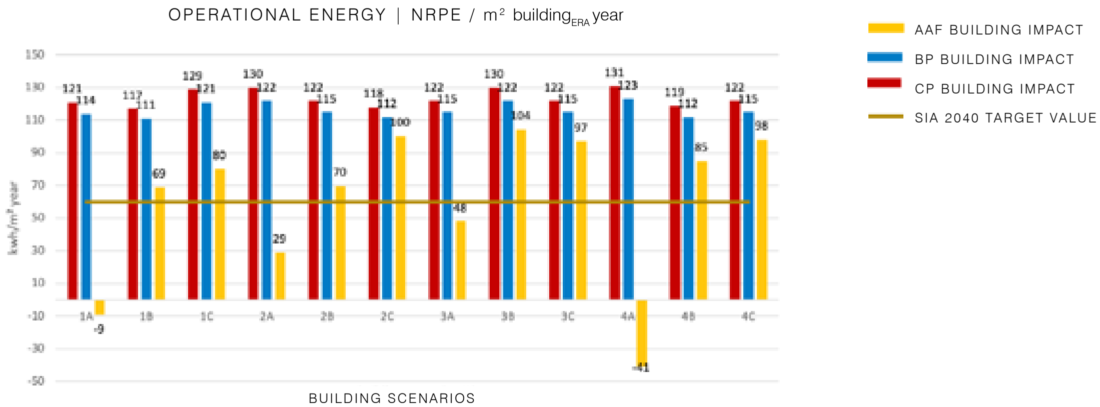
- The integration of BAPV-roofs into the analysed non-active building scenarios – CP and BP – is not sufficient to meet the operational



*

Battery integration not economically justified

Figure *5.15*
AAF annual energy savings potential compared to CP



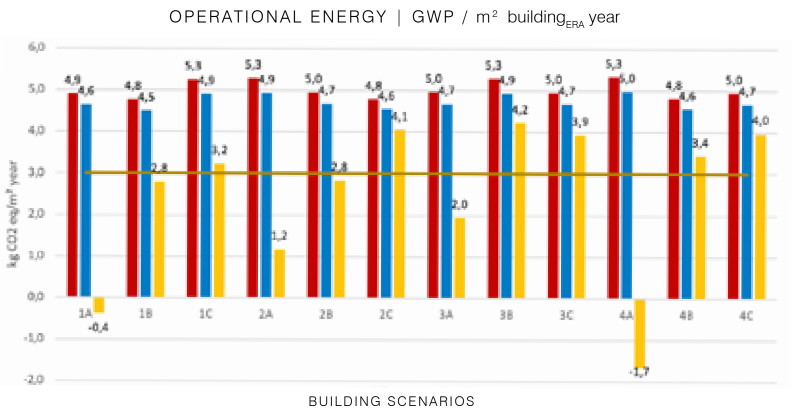
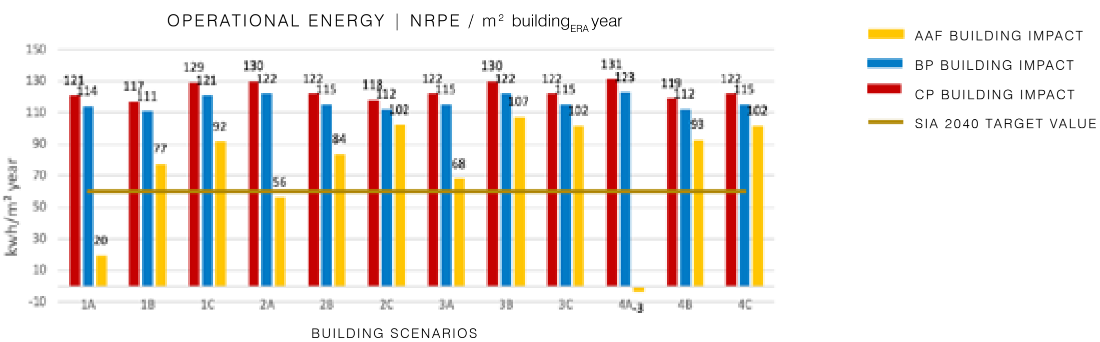


Figure *5.16*
Annual total building's operational impact per building's ERA.

NRPE and GWP.

High-Performance variant.



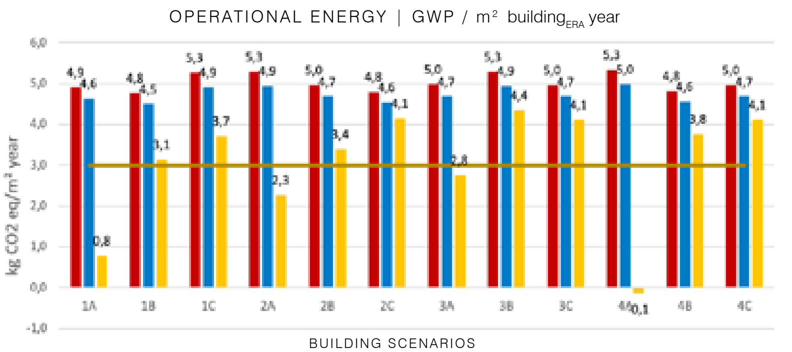


Figure *5.17*
Annual total building's operational impact per building's ERA.

NRPE and GWP.

Market-Ready variant.

energy efficiency targets specified in the SIA 2040 [SIA 2040 2017] (Appendix A.5.3).

- Only the largest BIPV façade integrated installations (Table 5.2) can provide the building with enough energy to meet SIA 2040's target values. As displayed in Figure 5.16 and Figure 5.17, there are two AAF building scenarios – 1A and 4A - provided with MR BIPV technology that generate enough energy to provide the building with a primary energy balance of 60 kWh/m^2 per year or lower. When AAF building scenarios incorporate HP BIPV technology, there are four scenarios – 1A, 2A, 3A and 4A – that can meet the energy transition final energy efficiency objectives. These four façades integrate opaque BIPV systems as façade cladding. Opaque BIPV systems integrate the most performant PV technologies and have higher impacts on the building's final energy balance, as seen in Section 5.3.1.

- BIPV façades integrating BIPV panels classified as B (translucent) or C (transparent) have lower energy performances and, according to the simulations previously presented, their active façades do not provide the building with enough energy to meet the SIA2040 target values. However, these small BIPV installations do contribute to improving the building's energy efficiency. Buildings can integrate different systems to generate on-site renewable energy (e.g. BAPV-roofs), and they can integrate more efficient building services. The combination of different energy efficiency strategies in the conception of a building contributes to reaching the SIA 2040 target values.

5.3.3 Combined energy efficiency analysis

Throughout this energy performance assessment, it has been remarked that large surfaces of BIPV elements result in buildings with higher embodied impacts than those with smaller surfaces of BIPV elements. However, integrating BIPV systems entails the optimisation of the energy balance of the building.

In this section, the embodied and operational energy results are combined to evaluate how the embodied impacts associated with BIPV systems are compensated by the reduction of the building's operational energy balance.

Figure 5.18 and Figure 5.19 show the combined energy efficiency results for NRPE and GWP, respectively. These figures show how the higher impacts associated with BIPV integration identified through the embodied energy analysis (Figure 5.5 and Figure 5.6) combined with lower operational energy balances identified through the operational energy analysis (Figure 5.16 and Figure 5.17) result in lower total environmental impacts. That is to say, the environmental impact associated with BIPV systems is largely compensated by its energy generation, in the case of the building scenarios designed and analysed in throughout this research.

As a reminder, a large percentage of BIPV surfaces is integrated into the north façade (see Section 4.4.1), which entails a lower energy surface yield. The results of the combined energy assessment highlight that even with a large percentage of non-optimally oriented BIPV panels, the façade's total energy output compensates its total embodied impacts (Appendix A.5.3).

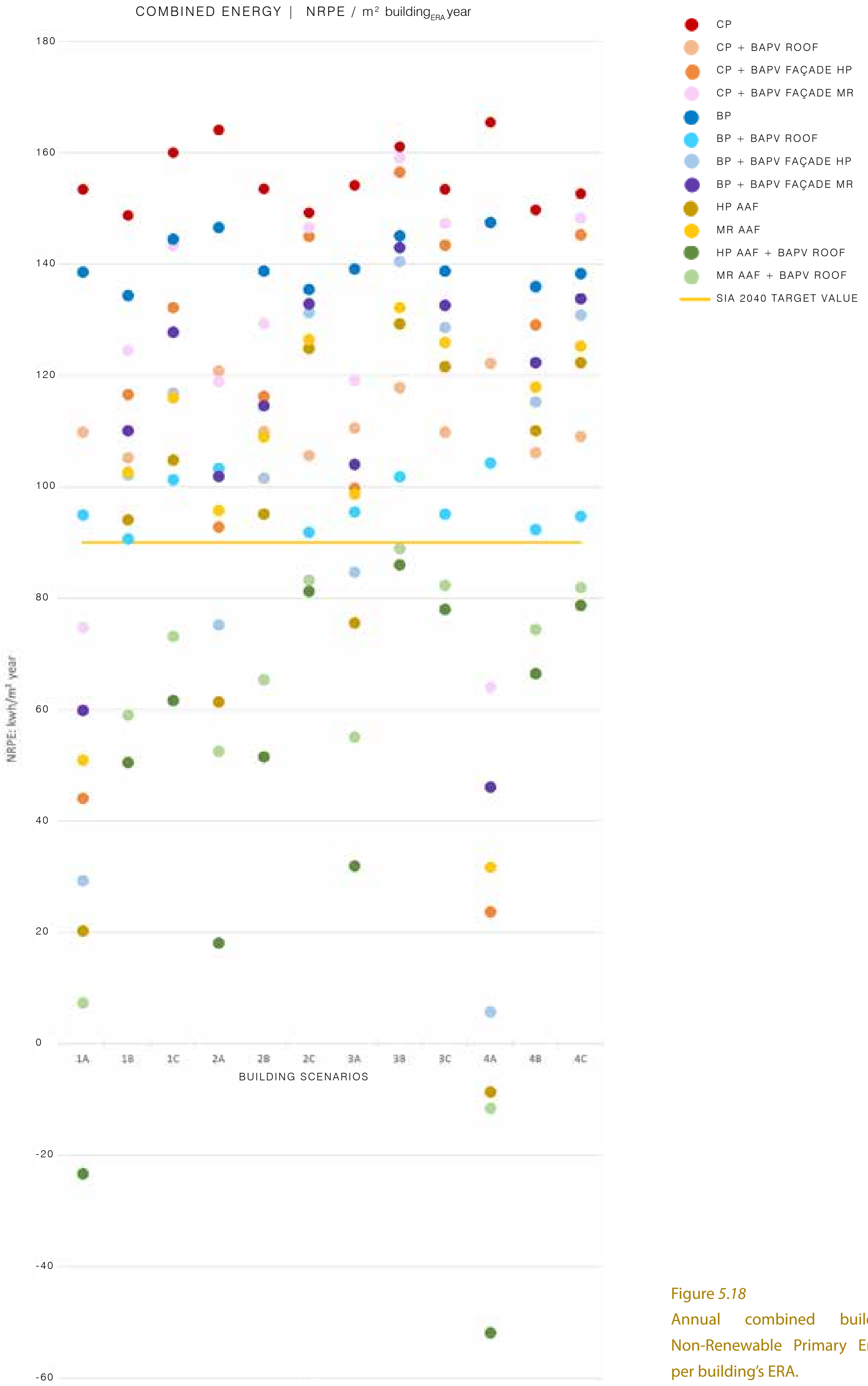


Figure 5.18
Annual combined building's Non-Renewable Primary Energy per building's ERA.

BAPV

This energy assessment also studies the incorporation of BAPV systems into the building envelope to analyse their energy efficiency. These are the BAPV-roof and BAPV-façade variants.

The simulated BAPV-roof system covers 81% of the flat roof surface, which is the maximum available space, in the studied building scenarios, when respecting 1 m from the roof perimeter for maintenance purposes [Mohajeri *et al.* 2016]. In most cases, there would be a percentage of roof occupied by building services such as elevator machinery, ventilation units or chimneys. However, due to the high degree of variation depending on the building typology and geographical context [Melius *et al.* 2013], the most favourable scenario has been simulated to maximise the potential of the BAPV-roof. The maximum available roof area in the simulated building scenarios is 426 m^2. This surface hosts a south-west oriented BAPV system, following the building's morphology and orientation, that generates 18.88 kWh/m^2_{ERA} year of final energy.

The BAPV-façade variants are incorporated to the non-active building scenarios – CP and BP variants – with the same active surface as the AAF building scenario. This results in a better operational energy balance than the corresponding non-active variants but with higher embodied impacts due to the addition of PV systems attached to the building envelope, which do not replace other construction materials. BAPV-façades have been simulated for both HP and MR variants.

Comparing results to energy transition targets

The combined energy efficiency target considers the energy production of BIPV systems to compensate for its embodied impact. The SIA 2040's combined energy efficiency target values establish that the building's primary energy must not exceed 90 kWh/m^2 per year (NRPE) and 12 kg $CO_{2\,eq}$ / m^2 per year (GWP).

The combined impacts of both embodied and operational energy of all building scenarios and their multiple variants are gathered in Figure 5.18 and Figure 5.19.

Advanced Active Façade

- AAF building scenarios can reach the NRPE SIA 2040 limit value when incorporating a large BIPV installation (See Table 5.2). This corresponds, in the building scenarios analysed, to the incorporation of opaque BIPV façade cladding systems – Group A.
- The incorporation of an HP or an MR BIPV technology significantly affects the building's energy efficiency. This is the case for the scenarios 2A and 3A that meet the NRPE limit value when integrating HP technology but do not when integrating MR technology.
- All AAF building scenarios – both HP and MR variants – can reach the NRPE SIA 2040 limit value when provided with a BAPV-roof.
- GWP target values are reached by all AAF building scenario variants.

Best Practice

- BP building scenarios do not reach the NRPE SIA 2040 limit value.

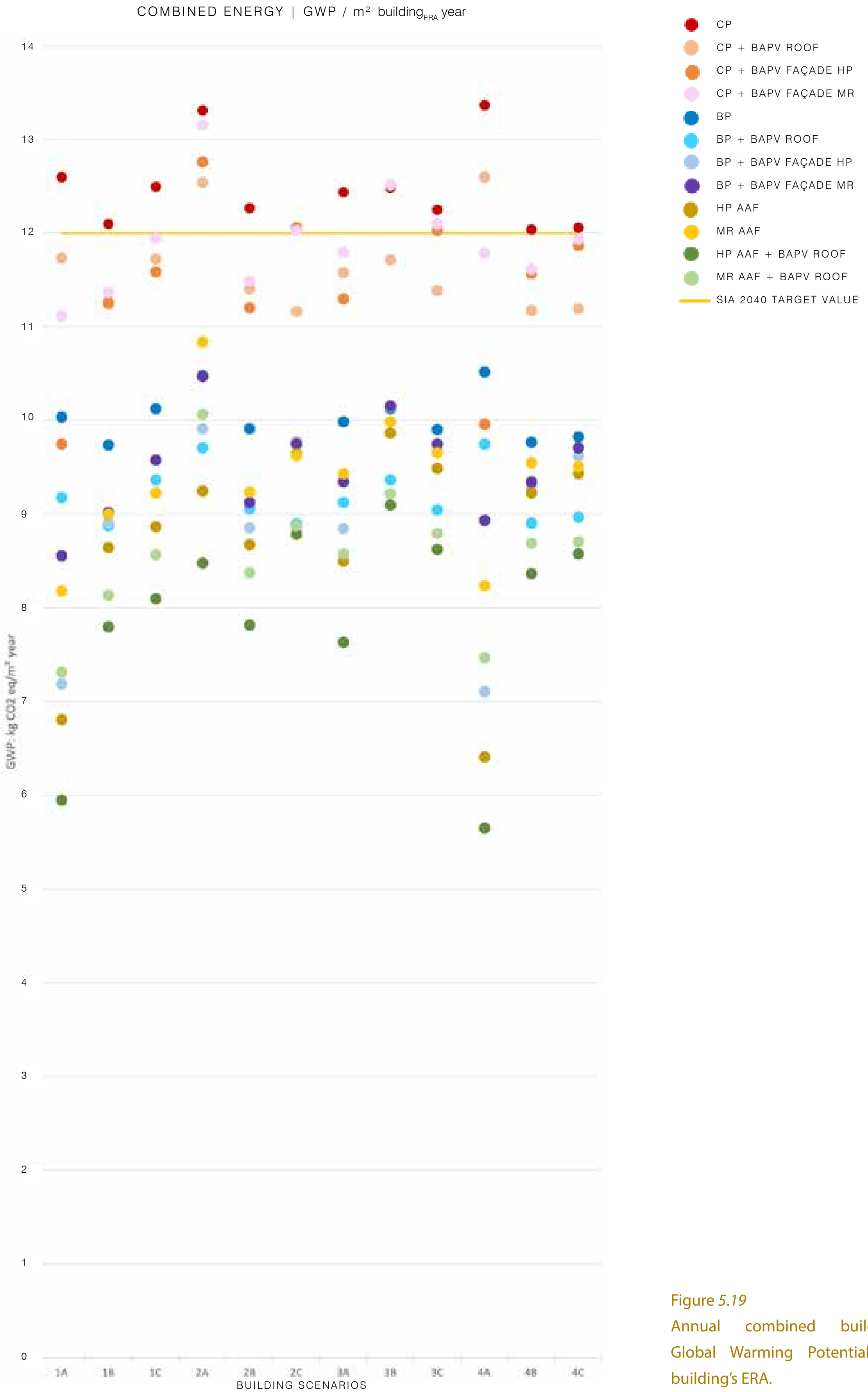


Figure 5.19

Annual combined building's Global Warming Potential per building's ERA.

- BP building scenarios with BAPV-roof do not reach NRPE limit value. However, as illustrated in Figure 5.18, some building scenarios are close to reach the target value – 1B, 2C, and 4B.

- The incorporation of BAPV-façades into BP variants improves the building's energy balance and enables the Group A BP building scenarios to reach NRPE SIA 2040 limit value. However, as for the AAF scenarios, HP variant enables the building scenarios 1A, 2A, 3A and 4A to meet the limit value whereas the MR variant enables only the building scenario 1A and 4A to meet the limit value.

- GWP limit value is reached by all BP scenario variants.

Common Practice

- CP building scenarios do not reach the NRPE SIA 2040 limit value nor the GWP limit value.

- CP building scenarios with BAPV-roof do not reach the NRPE SIA 2040 limit value. However, most of the building scenarios meet the GWP limit value with the BAPV-roof except the 2A and 4A.

- The incorporation of BAPV-façades enables the two building scenarios with the largest BAPV installation – 1A and 4A – to reach NRPE energy efficiency targets – both HP and MR variants. Regarding GWP, 2A, 2C, 3B and 3C building scenarios do not reach the SIA target values as displayed in Figure 5.19.

This analysis highlights the potential of active façades to meet the energy transition's energy efficiency objectives established for the year 2050. Four AAF building scenarios can reach SIA 2040 target values; the remaining eight can reach the SIA 2040 target values with the combination of BIPV façades and BAPV-roof. Therefore, it can be stated that BIPV façades, and more particularly the AAF, significantly contribute to the energy transition and enable the achievement of combined energy target values regarding both NRPE and GWP.

The previous observations conclude that the combined energy target values defined by the norm SIA 2040 for the year 2050 cannot be achieved with exclusively BAPV-roofs, as it is done in current practices. These results match other research results which state that BAPV-roofs are not enough to cover the energy demand of a high-rise building (more than 4-5 floors) [Verberne *et al.* 2014; SUPSI *et al.* 2015]. Other building-integrated renewable energy sources and improved efficiency of building services must be implemented. Among the possible solutions, BIPV façades have been proved to foster building's energy efficiency and can contribute totally or partially to the achievement of the operational energy targets.

It must be noted that in cases where both AAF and CP or BP reach the SIA 2040 target values – CP/BP+BAPV-façade – the AAF is always between 22% and 10% better performing in average (NRPE), respectively for the HP variant; and between 18% and 7% for the MR variant. This result highlights the relevance of combining active and passive energy strategies when targeting building energy efficiency, instead of adding active technology to current practices. In other words, the combination of BIPV with highly insulated and low embodied impact façades, which is the base for the Advanced Active Façade design, leads to a more energy-efficient building. The AAF can provide the means to meet energy efficiency targets, being always more energy-efficient than current practices, even if the latter integrate active surfaces.

COMBINED ENERGY ASSESSMENT HIGHLIGHTS

HP AAF building scenario has in average:

44% less NRPE than CP

30% less GWP than CP

38% less NRPE than BP

13% less GWP than BP

22% less NRPE than CP+ HP BAPV FAÇ

24% less GWP than CP + HP BAPV FAÇ

10% less NRPE than BP+ HP BAPV FAÇ

3% less GWP than BP+ HP BAPV FAÇ

22% less NRPE than CP+ BAPV ROOF

25% less GWP than CP + BAPV ROOF

9% less NRPE than BP + BAPV ROOF

5% less GWP than BP + BAPV ROOF

MR AAF building scenario has in average:

34% less NRPE than CP

25% less GWP than CP

27% less NRPE than BP

6% less GWP than BP

18% less NRPE than CP+MR BAPV FAÇ

21% less GWP than CP +MR BAPV FAÇ

7% less NRPE than BP+MR BAPV FAÇ

1% less GWP than BP+MR BAPV FAÇ

8% less NRPE than CP+ BAPV ROOF

19% less GWP than CP + BAPV ROOF

6% more NRPE than BP + BAPV ROOF

2% more GWP than BP + BAPV ROOF

BUILDING SCENARIO 2A | ENERGY ASSESSMENT RESULTS

MARKET READY: opaque Monocrystalline filtered 12%

HIGHT-PERFORMANCE: opaque Tandem-Perovskite filtered 18%

O P E R A T I O N A L   E N E R G Y   E F F I C I E N C Y

FINAL ENERGY

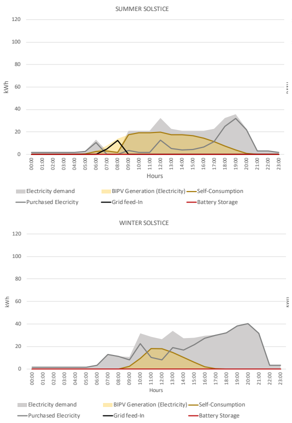
M A R K E T - R E A D Y

Performance

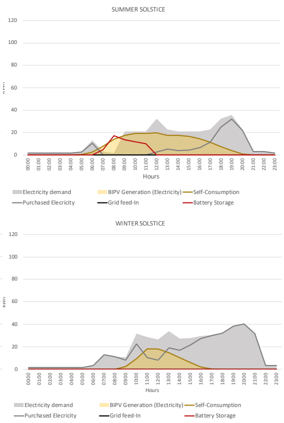
FINAL ENERGY

Building's Energy Demand	113151	kWh /yr
Total Energy Generation	54790	kWh /yr
Nominal Power of the BIPV installatior	10,1	kWp
Building's compactness index	1,1	
Building's Energy demand per m²	43	kWh/m² yr
Buildings Energy generation per m²	21	kWh/m² yr
Façade surface yield (per m² façade)	65	kWh/m² yr
No Battery Scenario		
Self-Sufficiency Rate	26%	
Self-Consumption Rate	54%	
Total Energy Export	25202	kWh
Energy economy to CP	38%	
Energy economy to BP	34%	
Battery Scenario		
Battery Size	40	kWh
Self-Sufficiency Rate	32%	
Self-Consumption Rate	73%	
Total Energy Export	14700	kWh
Energy economy to CP	46%	
Energy economy to BP	42%	
Total Self-Consumption Scenario		
Self-Sufficiency Rate	48%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	57%	
Energy economy to BP	54%	

N O   B A T T E R Y



B A T T E R Y



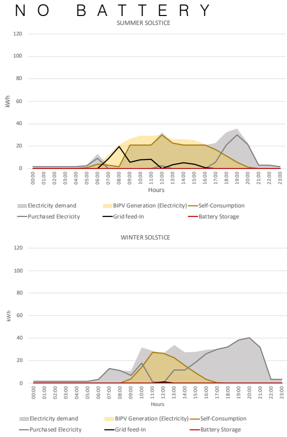
H I G H - P E R F O R M A N C E

Performance

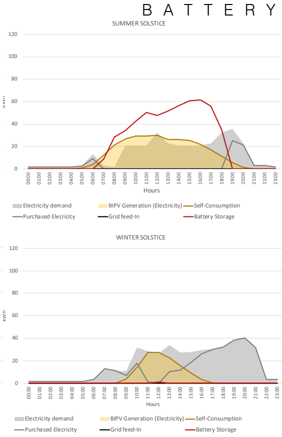
FINAL ENERGY

Building's Energy Demand	113151	kWh /yr
Total Energy Generation	83098	kWh /yr
Nominal Power of the BIPV installatior	15,3	kWp
Building's compactness index	1,1	
Building's Energy demand per m²	43	kWh/m² yr
Buildings Energy generation per m²	32	kWh/m² yr
Façade surface yield (per m² façade)	99	kWh/m² yr
No Battery Scenario		
Self-Sufficiency Rate	32%	
Self-Consumption Rate	43%	
Total Energy Export	47226	kWh
Energy economy to CP	43%	
Energy economy to BP	39%	
Battery Scenarío		
Battery Size	80	kWh
Self-Sufficiency Rate	45%	
Self-Consumption Rate	69%	
Total Energy Export	25990	kWh
Energy economy to CP	59%	
Energy economy to BP	56%	
Total Self-Consumption Scenario		
Self-Sufficiency Rate	73%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	78%	
Energy economy to BP	76%	

N O   B A T T E R Y



B A T T E R Y



PRIMARY ENERGY

Anual environmental impact

Market-Ready

SIA 2040 Limit Values	60	3
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	130,58	5,29
BP	122,03	4,94
AAF	56,19	2,27
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	83,00	3,36
BP	74,46	3,01
AAF	8,61	0,35
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	77,82	3,15
BP	69,28	2,80
AAF	56,19	2,27

High-Performance

SIA 2040 Limit Values	60	3
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	130,58	5,29
BP	122,03	4,94
AAF	28,94	1,17
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	83,00	3,36
BP	74,46	3,01
AAF	-18,64	-0,75
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	50,57	2,05
BP	42,02	1,70
AAF	28,94	1,17

E M B O D I E D   E N E R G Y   E F F I C I E N C Y

PRIMARY ENERGY

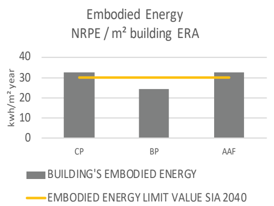
Anual environmental impact

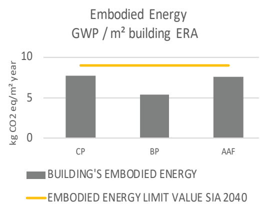
M A R K E T - R E A D Y

SIA 2040 Limit Values	30	9

BASE SCENARIO

	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	32,58	7,77
BP	24,05	5,43
AAF	32,32	7,63





BAPV ROOF SCENARIO

	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	36,92	8,93
BP	28,38	6,59
AAF	36,66	8,79

BAPV FAÇADE SCENARIO

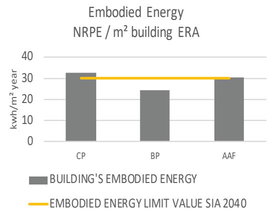
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	41,12	10,01
BP	32,58	7,67
AAF	32,32	7,63

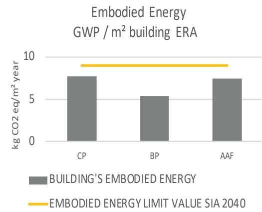
H I G H - P E R F O R M A N C E

SIA 2040 Limit Values	30	9

BASE SCENARIO

	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	32,58	7,77
BP	24,05	5,43
AAF	30,26	7,40





BAPV ROOF SCENARIO

	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	36,92	8,93
BP	28,38	6,59
AAF	34,60	8,56

BAPV FAÇADE SCENARIO

	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	39,06	9,78
BP	30,53	7,44
AAF	30,26	7,40

C O M B I N E D   E N E R G Y   E F F I C I E N C Y

PRIMARY ENERGY

M A R K E T - R E A D Y

PRIMARY ENERGY

Impact Payback Time

No Battery Scenario

	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	1001561	262190
Annual Impact Savings	74563	3018
PBT (Years)	**13,4**	**86,9**

Battery Scenario

	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	1003473	262630
Annual Impact Savings	101027	4089
PBT (Years)	**9,9**	**64,2**

Total Self-Consumption Scenario

	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	1001561	262190
Annual Impact Savings	138071	5589
PBT (Years)	**7,3**	**46,9**

H I G H - P E R F O R M A N C E

PRIMARY ENERGY

Impact Payback Time

No Battery Scenario

	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	760394	235351
Annual Impact Savings	90398	3659
PBT (Years)	**8,4**	**64,3**

Battery Scenario

	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	764218	236231
Annual Impact Savings	143912	5825
PBT (Years)	**5,3**	**40,6**

Total Self-Consumption Scenario

	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	760394	235351
Annual Impact Savings	209408	8476
PBT (Years)	**3,6**	**27,8**

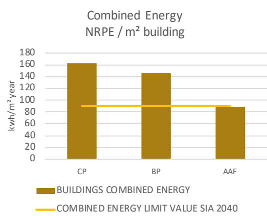
Anual environmental impact

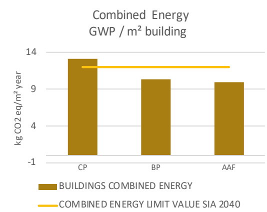
M A R K E T - R E A D Y

SIA 2040 Combined Limit Values	90	12

BASE SCENARIO

	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	163,16	13,06
BP	146,08	10,37
AAF	88,51	9,90
Battery impact per building ERA	0,73	0,17
AAF with Battery	89,24	10,07





BAPV ROOF SCENARIO

	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	119,92	12,29
BP	102,84	9,60
AAF	45,27	9,13

BAPV FAÇADE SCENARIO

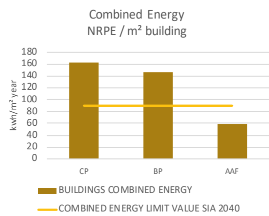
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	118,94	13,16
BP	101,86	10,47
AAF	88,51	9,90

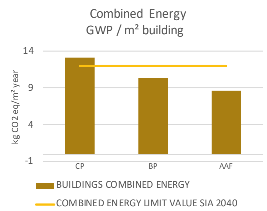
H I G H - P E R F O R M A N C E

SIA 2040 Combined Limit Values	90	12

BASE SCENARIO

	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	163,16	13,06
BP	146,08	10,37
AAF	59,20	8,57
Battery impact per building ERA	1,46	0,34
AAF with Battery	60,66	8,91





BAPV ROOF SCENARIO

	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	119,92	12,29
BP	102,84	9,60
AAF	15,96	7,80

BAPV FAÇADE SCENARIO

	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	89,63	11,82
BP	72,55	9,14
AAF	59,20	8,57

5.4. Economic efficiency

The integration of the previously described energy efficiency strategies, which improve the building's energy performance, has a direct impact on the global economic performance of the building. Higher initial investment is expected when incorporating the Advanced Active Façade, compared to *Best Practices* and *Common Practices.* However, the lower operational energy balance of an AAF building scenario entails lower building operation costs. Moreover, there is a close link between the quality of construction and the subsequent costs. A construction that is initially more expensive can turn out to be a good long-term investment [Rütter-Fischbacher *et al.* 2010].

A simplified economic efficiency assessment of the different building scenarios enables comparisons among the different variants and facilitates to decide on upgrading the energy efficiency of a building.

The objective of this research phase is to evaluate the initial investment increase associated with the AAF and the economic efficiency of the AAF building scenarios compared to current practices. To this end, four different economic indicators, which consider the initial investment, are calculated in this economic efficiency analysis: the life-cycle cost (LCC), the net present value (NPV), the internal rate of return (IRR), and the discounted payback (DPB).

The value of the above-mentioned financial indicators is calculated over an investment period of ten and thirty years. On the one hand, the discounted rate method is usually based on a five to ten year period investment [Rütter-Fischbacher *et al.* 2010]. On the other hand, thirty years is the new building's lifetime, considered as such. This is to say, the period where no major renovations are required in a new building [CRB 2012a].

Within this simplified economic efficiency assessment, the sale of the building is considered at the end of each respective periods. In either scenario, a discount rate of 5% is defined to represent the minimum annual cost of money in the market [SNBS 2013]. The investment period, as well as the discount rate, are assumptions affecting the LCC, NPV, IRR, and DPB.

The LCC *is the sum of all relevant costs associated with a building over the analysis period* [Short *et al.* 2016]. This method is applied to make cost-effective decisions for a given building [Ruegg *et al.* 1990], as it is the decision of designing an Advanced Active Façade or a current practice façade – e.g. CP or BP.

The NPV *is the past, present or future cash flows, all expressed as a lump sum amount as of the present time, taking into account the time value of money* [Short *et al.* 2016]. This metric shows the difference in nominal return on investment across the various building scenarios.

The IRR is an indicator of the annual rate of return on investment. It is *the discount rate that equates total discounted benefits with total discounted costs* [Ruegg *et al.* 1990].

The DPB is *a measure of the elapsed time between the time of initial investment and the point in time at which accumulated discounted savings or benefits are sufficient to offset the initial investment, taking into account the time value of money* [Short *et al.* 2016]. This method enables calculating if the AAF is paid off sooner or later than current practices, from the real estate developer perspective.

5.4.1 Financial model assumptions

To calculate these financial performance indicators, a series of assumptions regarding different economic values must be taken into account [SIA 480 2016], as listed below:

Energy

- Electricity cost: Based on current electricity rates of the local supplier in Lausanne, 0,267 CHF/kWh has been taken as the cost of electricity per kWh [SIL 2019a].

- Annual cost increase: This rate is subject to an annual electricity cost increase of 2.5 % [OFEN 2012, 2013, 2014, 2015, 2016a, 2017].

- Feed-in tariff: According to Lausanne industrial services (SIL), the current feed-in tariff (FIT) varies depending on the BIPV installation size: 0,102 CHF/m^2 for installations equal or smaller than 30kVA, and 0,07 CHF/m^2 for BIPV installations larger than 30kVA [SIL 2019b][5].

- Annual FIT decrease: This research project assumes that the FIT decreases by 5% annually.

- BIPV self-consumption: BIPV electricity self-consumption share is assumed to be of 100% by 2050. A progressive annual increase of the self-consumption is calculated to reach the 100% target in 30 years. This assumption is based on the rapid improvements of DSEMS and the consumer profile adaptation of the building tenants.

BIPV

- Cost: There is a lack of precise and reliable data related to BIPV costs, which is mostly due to its rapid development. BIPV systems are made of five different components with variable costs: 1) The modules cost, which is 40 - 60% of the total BIPV installation cost; 2) the inverter cost, which varies depending on the proportion of the installed power and if the system is designed with micro-inverters or regular inverters; 3) the transport and installation cost, which is being reduced in the last years due to standardization, and in the context of this research have been considered to be 30% of the final cost; 4) the fixing system cost, which depends on the façade design, and in this research is quantified as an independent element; and 5) the wiring cost, which can be minimized with an optimized design of the electrical connection among BIPV modules. Due to economies of scale, the average cost per kWh is inversely proportional to the size of the BIPV installation [SUPSI 2019].

  Façade BIPV prices per square meter significantly vary among different research results and practices. A BIPV cold façade can cost between 120 and 700 CHF/m^2 [SUPSI *et al.* 2015] and high-end solar shading systems and balustrades up to 600 CHF /m^2, fixing included [SUPSI *et al.* 2017].

  Due to the disparity of BIPV prices found in the literature and the lack of information about whether they refer to the whole BIPV system or just the BIPV panels, this research project adopts the results of Aguacil's price parametrisation study to set BIPV prices based on economies of scale [Aguacil 2019]. Aguacil's results integrate the costs of all BIPV

5
1kVA= 1kWp with an assumed power factor of 1.

components mentioned above. This study is based on prices provided by the Swiss Federal Office of Energy [OFEN 2016b] and *Suisse Energie's solar calculator* [Suisse Energie 2019], allowing for a +/- 10% variation. Aguacil's parametrisation study is represented in Figure 5.20.

- Subsidies: Within the Swiss energy efficiency promoting programs, BIPV installations are subsidised by *Pronovo*[6]. *Pronovo* grants a 30% subsidy for installations smaller than 100 kWp [Pronovo 2019].

- Maintenance: Based on the *Suisse Energie's* solar calculator, BIPV maintenance is calculated and assumed to be 1.16% of the BIPV initial installation cost, per year [Suisse Energie 2019].

- BIPV price change: BIPV costs are lower every year [DETEC 2017; IRENA 2019]. Based on the constant cost decrease, a 30% adjusted BIPV cost over 30 years is assumed.

- Lifespan: BIPV panels have a certified lifespan of 30 years, even if some BIPV panels have optimal performances after 35 years of use [Interview with G. Cattaneo, 2018].

- Efficiency: BIPV panels lose efficiency throughout their lifetime. PV manufacturers usually guarantee a maximum loss of 20% by the end of the BIPV panel's lifetime (30 years) [Interview with G. Cattaneo, 2018].

- Use of generated energy: This assessment process assumes that the BIPV generation is sold to the building tenants, who consume it according to the self-consumption rate calculated. The sale price is equivalent to the cost of buying energy from the grid. The BIPV excess that cannot be self-consumed in the building is exported into the grid.

Battery

- Cost: Battery prices vary depending on size and type. In this financial model, a 1000 CHF/kWh price is assumed [DGE 2018].

- Subsidies: The installation of batteries is subsidised by the program *100 million for renewable energies and energy efficiency*. This program subsidises 2000 CHF + 350 CHF/kWh of the battery. However, the total amount cannot be higher than 50 000 CHF or 35% of the total cost [DGE 2018].

- Price change: Within this assessment, an annual battery price decrease of 1.1% is assumed, based on the rapid development of storage technologies pushed by the electric mobility field [Baker 2019].

- Lifespan: Batteries have different lifespans depending on the type of battery. This economic efficiency assessment incorporates Lithium-Ion batteries with a maximum lifespan of 20 years when paired with PV systems [Vieira *et al.* 2016].

- Capacity: Battery capacity decreases throughout the years. A 20% capacity loss is assumed at the end of the battery lifespan.

Building

- Construction cost: The average construction cost of a standard residential building in Switzerland is 759 CHF /m^3 [CRB 2012b].

6

Pronovo SA is the accredited certification body for the registration of guarantees of origin and the implementation of federal renewable energy incentive programs [Pronovo 2019].

- Façade cost: The average construction cost of a standard façade in Switzerland is 495 CHF / m² [CRB 2012b].

- Land price: The average land price in a Swiss city in a mid-dense area is 1000 CHF/m² [Wüest & Partner 2019].

- Architect cost: An average architectural design fee of 10% of the building construction costs is assumed.

- Renovation: The number of years before major building renovations is 30 years [CRB 2012a; SIA 480 2016]. During these 30 years, minor equipment renovations are required, and their costs are included in the building maintenance annual costs.

- The annual building maintenance cost is assumed to be 1% of the building construction cost [Pant 2019].

Financial

- Inflation: The assumed annual inflation is 2% [SNBS 2013].

- Discount rate: The assumed discount rate or cost of capital is 5% [SNBS 2013].

- All-risk yield: The all-risk yield (ARY) in Lausanne city is 3.6% [PwC 2018].

- Loan/leverage: In Switzerland, banks usually finance real estate development at 60% of the asset value.

- Financing cost: 1% assumed loan financing cost.

- Interest rate: 3% assumed loan interest rate.

- Rental revenue: The average apartment rental price in Switzerland is 280 CHF / m² [Wüest & Partner 2019].

This assessment process assumes that the building scenarios rental prices vary depending on the apartment heating charges[7]. For this reason, and to maintain the same final price for the tenant, rental prices of CP and BP scenarios are lowered so that the rental price plus the difference in heating cost are equal to all tenants in all scenarios, i.e. 280 CHF/m². CP and BP rental prices are controlled

7
In Switzerland, most apartment rentals are composed of the net rental cost plus the building charges which mainly include heating, DHW and common spaces operation (lighting and maintenance).

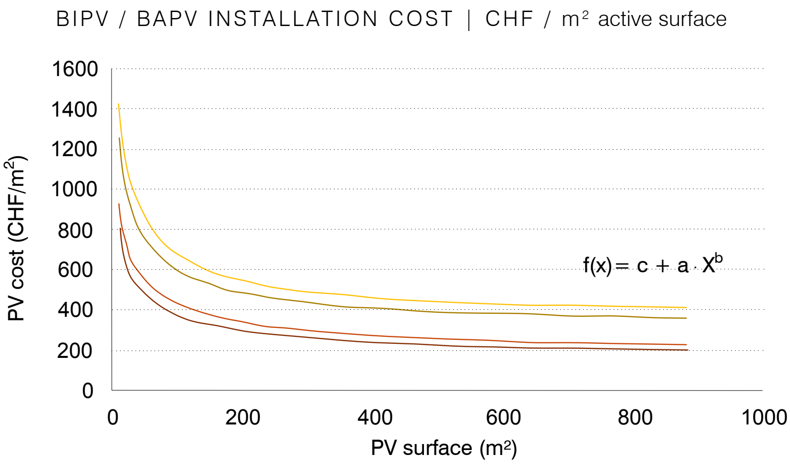


Figure 5.20
Aguacil's BIPV price parametrization study

Source: [Aguacil 2019].

f= price
x= active surface

BIPV façade:	BIPV roof:
a= 3859	*a= 2415*
b= -0.4668	*b= -0.4249*
c= 236.3	*c= 88.98*

BAPV façade:	BAPV roof:
a= 3414	*a= 2129*
b= -0.4667	*b= -0.4227*
c= 209.1	*c= 77.17*

COMMON PRACTICE | ROUGHCAST

eCCC-Bât	Material	Reference	Reference quantity	Price	Supplement
E2.2	Finish plaster.	OFS	1 m²	38,81 CHF	20%
E2.2	EPS external insulation 22mm	GOGNON	1 m²	108,20 CHF	20%
C2.1	Terracotta wall 14/16 cm	OFS	1 m²	88,73 CHF	20%
G3.2	Mortar finish	OFS	1 m²	15,70 CHF	20%
G3.2	Wall dispersion	OFS	1 m²	8,48 CHF	20%
	TOTAL PRICE 1 m² CP FAÇADE			**311,90 CHF**	

BEST PRACTICE | WOOD FAÇADE CLADDING

eCCC-Bât	Material	Reference	Reference quantity	Price	Supplement
G3.2	Interior finish and paint	tiptop service	1 m²	16,00 CHF	20%
G3.1	Plasterboard, Sonicboard	CRB	1 m²	56,21 CHF	20%
G3.1	Waterproof synthetic material	CRB	1 m²	10,32 CHF	20%
C2.1	Outer wall in framing elements	OFS	1 m²	53,76 CHF	20%
C2.1	Outer wall, footing, fixing on concrete	OFS	1 m²	26,01 CHF	20%
C2.1	Vapour barrier. Scotched joints, air tight	OFS	1 m²	11,64 CHF	20%
C2.1	Impregnated wood fiber panels	OFS	1 m²	23,16 CHF	20%
E2.2	Mineral wool insulation 27 cm	Swisspor	1 m²	52,00 CHF	20%
E2.3	Wooden façade cladding. Horizontal	OFS	1 m²	92,50 CHF	20%
E2.3	Ventilation, vertical ventilation slats	OFS	1 m²	11,33 CHF	20%
E2.1	Exterior finish	CRB	1 m²	4,55 CHF	11%
E2.1	Exterior smothing	CRB	1 m²	5,42 CHF	11%
E2.1	Enamel paint, 2 brush applications	CRB	1 m²	23,50 CHF	11%
	TOTAL PRICE 1 m² BP FAÇADE			**441,47 CHF**	

AAF | BIPV FAÇADE CLADDING

eCCC-Bât	Material	Reference	Reference quantity	Price	Supplement
G3.2	Interior finish and paint	tiptop-service.ch	1 m²	16,00 CHF	20%
G3.1	Plasterboard, Sonicboard	Knauf	1 m²	6,34 CHF	20%
G3.1	Wood fibre insulation 5 cm	Isofloc	1 m²	16,35 CHF	20%
G3.1	Wood substructure	CRB	1 m²	14,30 CHF	20%
C2.1	OSB panels, 1.5 cm	OFS	1 m²	29,03 CHF	20%
E2.2	Blown insulation	Isofloc	1 m²	25,00 CHF	20%
C2.1	Timber substructure	OFS	1 m²	53,76 CHF	20%
C2.1	Fibrocement board (A1)	getaz-miauton	1 m²	20,00 CHF	20%
C2.1	Vapour barrier. Scotched joints, air tight		1 m²	11,64 CHF	20%
E2.3	Fixation system (1.6x2 m)	wagner system	1 m²	33,00 CHF	20%
E2.3	BIPV panels (average)	Swiss Energie	1 m²	362,93 CHF	30%
	TOTAL PRICE 1 m² AAF BIPV FAÇADE			**633,43 CHF**	

Table *5.7*
Construction material identification, measurement and pricing per façade square meter for a CP façade, a BP façade and an AAF façade with BIPV façade cladding.

Source: CRB Code de couts pour la construction [SN 506511:2012].

in order to remain among the range of current rental prices in the Lausanne area, which are between 175 and 295 CHF/m^2 [Ville de Lausanne 2019]. The lower CP and BP rental prices entail a lower revenue for the building owner in the current practice scenarios.

This price difference assumption is in line with the KBOB recommendation, which states that when developing a sustainable building, it is possible to address a segment of tenants willing to pay more for an apartment in an energy-efficient building [Rütter-Fischbacher *et al.* 2010]. It is also in line with Fribourg's directive concerning PV integration which states that higher rental revenues can be applied in buildings with BIPV, which is associated with a building operation charges reduction [DAEC 2015]

- Taxes: There are several tax reductions incentives associated with BIPV integration. These tax credits are not considered in this research due to the diversity of investor profile and the lack of publicly available information.

5.4.2 Building Life Cycle Cost (LCC)

The building Life Cycle Cost (LCC) of the different building scenario variants presented in Section 5.2 is calculated. This process considers the initial building investment, maintenance and repair costs, energy purchase, and the building sale of each building scenario to be compared. The time value of money is accounted for by calculating the present values, using a discount rate for each of these costs [Short *et al.* 2016].

The formula to calculate the simplified LCC is*:

$$LCC_{BSX} = I_{BSX} + M_{BSX} + R_{BSX} + E_{BSX}$$

Initial investment (I_{BSX})

To determine the initial investment of each building scenario, the calculation of the costs of each façade is performed. Then, based on standard prices for residential building construction and residential building façades, the total initial investment of each building scenario and its main variants - AAF, CP and BP - is calculated.

Façade cost description

The first step to determine the initial investment is to quantify the costs of the different façades. For this, façade element measurements are performed, and prices per façade square meter are set based on a reliable database that takes into account economies of scale [Bec Partners SA 2015a, 2015b].

To estimate the price per façade's square meter, the different construction systems are assessed similarly: the price of the construction material is considered as well as the cost of its installation. The prices considered do not include transportation costs and are an average of the product price offer in Switzerland. This data has been provided by Bec Partners SA, [Bec Partners SA 2015a, 2015b], who are experts in building cost analysis. Bec Partners' information is based on the Swiss Federal Statistical Office's (SFO) reports and the CRB Construction Standards [CRB 2018]. All references are indicated in Table 5.7.

*

Where:

I_{BSX} is the present-value of the initial investment costs of the building scenario X

M_{BSX} is the present-value of the maintenance costs of the building scenario X

R_{BSX} is the present-value of the repair and replacement costs of the building scenario X

E_{BSX} is the present value of energy costs associated with the building scenario X

The nomenclature assigned to each type of construction products corresponds to the ones established by the CRB and refers to the corresponding construction element.

The construction materials identification and measuring process consist of breaking down the construction system composition indicating material quantities expressed in meters or kilograms, according to CRB database references [CRB 2012b, 2018].

Table 5.7 shows the different façade construction systems analysed as well as the breakdown of their cost: the AAF construction system with its active and non-active façade cladding variants, the CP and the BP façade construction systems. Table 5.7 shows that 1m² of AAF with BIPV façade cladding – façade corresponding to the AAF scenario 2A – is 103% more expensive than a CP façade and 38% more expensive than a BP façade.

Figure 5.21 illustrates the façade costs of the different building scenarios analysed. This Figure shows that CP façades have the lowest costs, followed by the BP façades. AAF façade costs vary depending on the total BIPV surface incorporated into the design. The higher AAF costs per square meter correspond to the 3A building scenario where 558 m² of BIPV balcony balustrades have been implemented. The lower AAF cost per square meter corresponds to the 4C building scenario where 105 m² of BIPV balcony balustrades are implemented.

The higher AAF building scenario costs are associated with larger BIPV surfaces, but also with AAF where the BIPV panels have an accessory function in the façade such as solar control or balustrades. This is due to the fact that non-active CP and BP variants do not include non-active façade accessories in the calculations.

To illustrate this, a façade with balconies is more expensive than the same façade without balconies despite integrating lower BIPV surface. The analysed building scenarios with active balustrades account for the cost of the BIPV surface as an additional façade element: a balustrade. Therefore, 3A building scenario has higher costs than 1A, 2A, and 4A, despite its smaller BIPV installation.

Building construction cost description

The described building cost calculation is similar to the building embodied energy calculation illustrated in Figure 5.4. It is based on existing prices

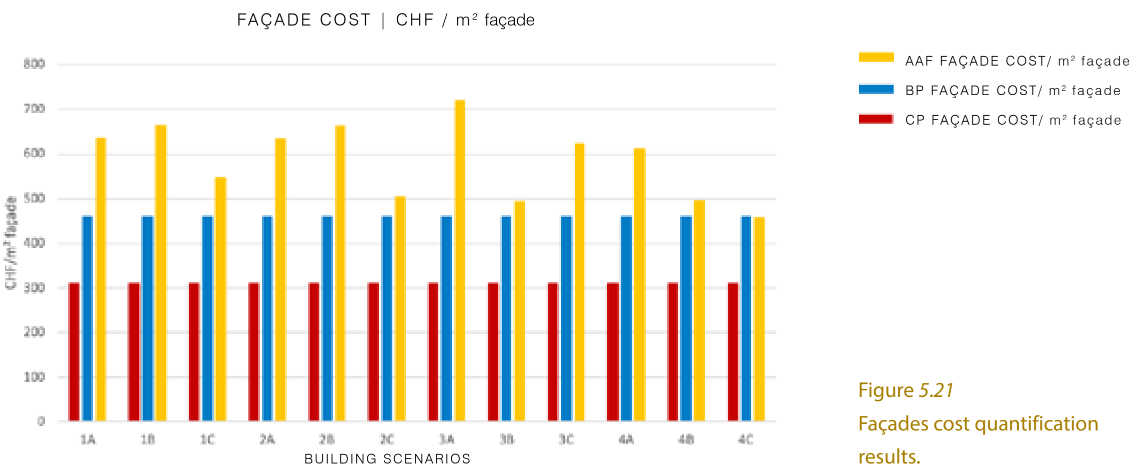


Figure *5.21*
Façades cost quantification results.

of building and façade construction, which can be found in the CRB cost construction code.

The average construction cost of a standard residential building in Switzerland is 759.24 CHF /m³ [Ville de Zurich 2018]. This price is multiplied by the volume of each building scenario and divided by its surface to establish the average building construction cost per square meter.

The average façade construction cost is 494,67 CHF /m² [CRB 2012b]. This value, normalised per building surface, has been subtracted from the previously calculated average building's costs. Then, the addition of the specific costs of each façade variant – CP, BP and AAF – results in the total costs of each building scenario and its variants, which are represented in Figure 5.22.

Ultimately, BIPV and battery subsidies are subtracted from the building's costs.

BIPV subsidies depend on the size of the installation and are up to 30% of the total initial investment. They have only been considered for the initial investment, as subsidies are assumed to disappear in the next 30 years. However, the replacement BIPV system has been considered to be 30% less expensive than the first BIPV installation, based on the rapid price decrease of BIPV systems [Pronovo 2019].

Similarly to BIPV subsidies, it is expected that battery subsidies shall disappear over the coming years. For this reason, battery subsidy has only been considered for the first battery installation and not in their replacements, which are programmed every 20 years as defined for this economic performance assessment.

Building construction and operational costs are the total costs considered in this LCC evaluation process, which aims at enabling comparative analysis of all building scenarios and their variants.

The analysis of the different façade costs regarding total construction costs and total initial investment costs highlight that the different AAF designs account on average for 10% of the building construction costs. To contrast these values to current practices, CP façades account on average for 5% of the building construction costs and BP façades account on average for 7.5% of the building construction costs (see Appendix A.5.3 for further details of each specific scenario).

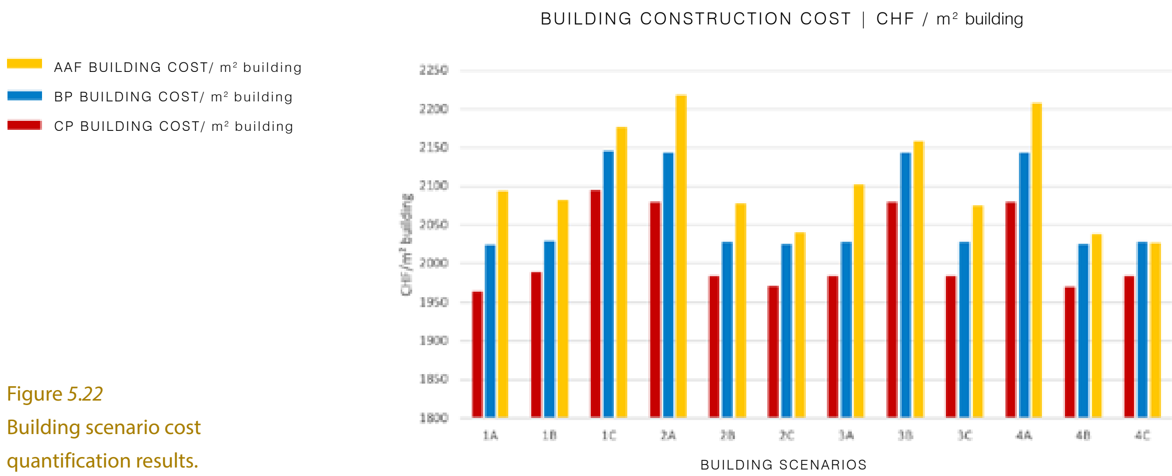


Figure 5.22
Building scenario cost quantification results.

Figure 5.22 shows the different building scenario costs. All AAF building scenarios are more expensive than non-active ones (CP and BP). Differences among the AAF scenarios partially correspond to their façade morphology. Large building envelopes defined by loggias have an economic impact on the building cost higher than the different size of the BIPV installation. This is illustrated with the costs of 1C or 3B, which have small BIPV installations in their façades, a *Loggias* façade morphology and higher cost than 1A which has a larger BIPV installation and a *Clean volume* façade morphology.

Based on building construction costs, the architecture design fee, which is assumed to be 10% of total construction costs, is added to the initial investment cost.

Maintenance (M_{BSX}) and repair costs (R_{BSX})

Building maintenance costs include the costs of all the measures required to maintain the correct functioning of the building [Le *et al.* 2018]. They include direct costs such as spares, repairs, equipment and tools as well as indirect costs such as management, administration and general costs [El-Haram *et al.* 2002]. Throughout this economic performance assessment, annual average building maintenance costs of 1% of the initial investment are considered [Pant 2019]. This assumption takes into account that there is no major renovation in the first 30 years of a residential building's lifetime.

Regarding BIPV, a maintenance cost of 1.16% of the initial BIPV investment is included according to *SuisseEnergie's* solar calculator [Suisse Energie 2019].

Energy purchase costs (E_{BSX})

The energy purchase costs depend on the price of energy, which according to SIL is 0.267 CHF/kWh [SIL 2019a], and on the annual increase of the price of energy, which is assumed at 2.5 %.

The total energy cost quantification multiplies these values by the building's annual energy demand minus the self-consumed PV energy in both scenarios: *no-battery* and *with-battery*. For this reason, the energy cost of each building scenario and its variants differs with each other and set a significant difference among current practices and the AAF.

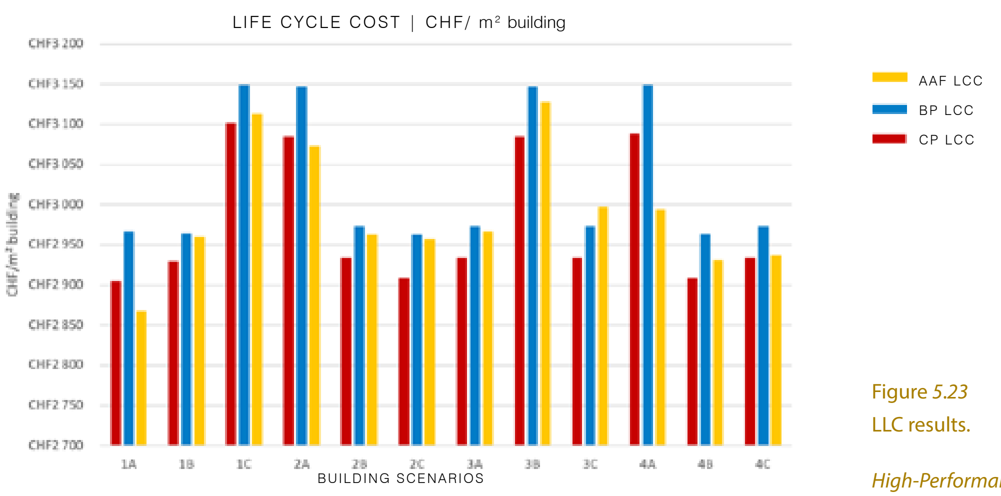


Figure *5.23*
LLC results.

High-Performance variant.

Results in discussion

LCC results are displayed in Figure 5.23 per building's m^2. Similar to the building costs results shown in Figure 5.22, the LCC is higher for building scenarios with larger building envelope: 1C, 2A, 3B and 4A, which have a *Loggias* façade morphology. However, the LLC comparative among the different building scenario variants – CP, BP and AAF – highlights that the energy economy provided by the AAF significantly affects the LCC. All AAF building scenarios except 3C have a lower LCC than BP. Building scenario 3C has the largest transparent Thin-Film surface, which has very low performance. For this reason, its LCC remains high.

Comparing with CP, only the large BIPV installations provide the building with enough energy to lower the AAF's LCC below CP's LCC. This is also true for building scenario 4C due to the small BIPV surface integrated into the façade.

These results highlight the fact that both BIPV size and the façade's total surface affect the building's LCC. Large façades with low-performance BIPV technology have higher LCC than smaller façades with *High-Performance* BIPV technology. These results relate to BIPV prices that are based exclusively on economies of scale, without distinction among the different BIPV technologies. Further details on the price of each PV technology could provide more accuracy to the previously presented LCC results.

5.4.3 Net Present Value

The Net Present Value (NPV) is one of the most common economic metrics in financial assessments. It shows the excess of benefits over costs [Short *et al.* 2016] considering the value of money over time.

The NPV of the different scenarios takes into account the building costs previously described in the LCC method and revenues generated by the apartment rental and the sale of BIPV electricity, all of it discounted for their time value [Short *et al.* 2016].

The formula to calculate the NPV is *:

$$NPV=\sum((RE_t - C_t) / (1+ d)^t)$$

Revenue (RE_t)

The revenue is generated by the apartment rental and the sale of BIPV electricity to the building tenants, as indicated in the *Assumptions* section (Section 5.4.1). The non-self-consumed electricity is injected into the grid, which also generates a revenue according to the FIT applied. In addition, the subsidies received for BIPV and batteries installation are also considered revenue (Section 5.4.1).

The rental revenue has been calculated based on the average apartment rental price in Switzerland, which is 280 CHF/m^2, excluding charges [Wüest & Partner 2019]. Prices vary from CP to BP and AAF according to the different energy charges (Section 5.4.1).

As a reminder, the *Assumptions* section has specified that the building owner sells the electricity to the apartment tenants (the self-consumed share) at the same price that it is bought from the grid. This generates additional revenue for the building owner of active building scenarios which have PV integrated into the façade or the roof.

*

Where:

REt is the benefits in year t and include energy savings associated with BIPV energy self-consumption

Ct is the costs in year t

d is the discount rate

t is the time in years

Costs

The considered costs are previously described in the LCC calculation method. Additionally, the land cost is incorporated into the cost calculations to obtain a realistic number of present value and real gains.

Land price can significantly vary depending on the city and the neighbourhood. This research considers 1000 CHF/m^2 based on the Immo-Monitoring 2019 publication [Wüest & Partner 2018].

Leverage

According to a real estate developer's practice, a loan of 60% of the construction cost is considered in the financial model. This means that an investor must bring 40% of the capital to fully finance the asset. Bringing debt into a real estate investment is called *leverage*. The real estate developer is leveraging the debt to bring less capital.

An interest rate of 3% is considered with a repayment life of 30 years. Although the debt is set for repayment over 30 years, the debt will be repaid when the building is sold. Leveraging debt enhances the NPV and IRR metrics. The latter is then called Levered NPV and Levered IRR respectively to show the effect of the debt during the lifetime of the investment.

Results in discussion

Figure 5.24 gathers the results of the levered NPV calculations. It shows how the AAF building scenarios have the highest NPV after 30 years, followed by the BP building scenarios and the CP building scenarios. These results are in line with the affirmation of Rütter-Fischbacher *et al.*, who state that high initial investments can lead to better long-term investments [Rütter-Fischbacher *et al.* 2010].

The AAF's higher NPV shows that the economic barrier blocking the widespread use of BIPV is exclusively related to the initial investment and that long-term economic assessments need to be performed to demonstrate the economic efficiency advantages of both BIPV and highly insulated façades.

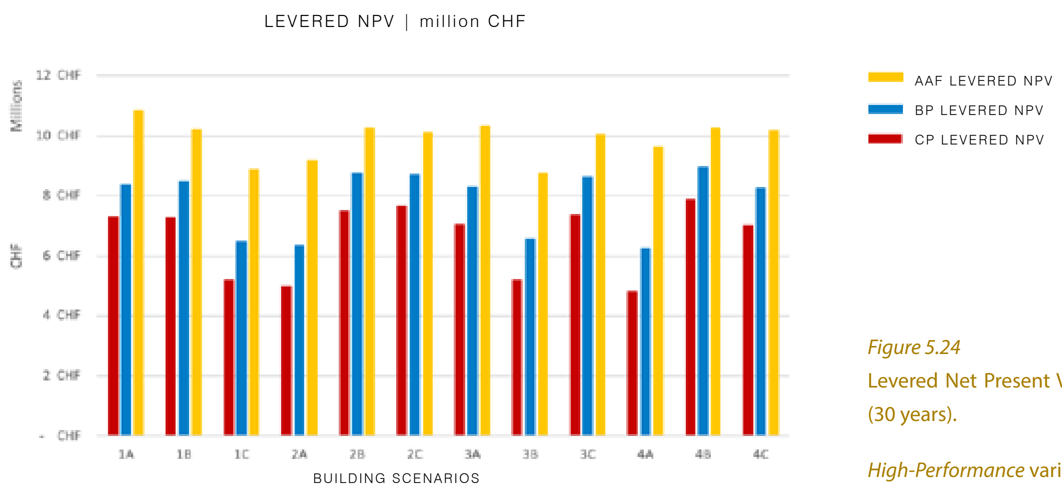


Figure 5.24
Levered Net Present Value results (30 years).

High-Performance variant.

NPV results involving BAPV-roofs can be found in Appendix A.5.3. They show how AAF scenarios are more profitable than current practices with BAPV-roofs. However, CP and BP building scenarios have a higher NPV when incorporating BAPV-roofs. This is directly related to the energy generation of the BAPV-roof, which provides additional revenue to the building owner.

5.4.4 Internal Rate of Return

The Internal Rate of Return (IRR) is the rate of return on the investment, which in this case is the residential building construction for apartment rentals. It is calculated with the same formula as NPV and makes the NPV of all cash flows equal to zero. The IRR represents the annual return yield on investment over the lifetime of the investment. This metric is highly regarded by investors in order to understand if their money has been performing well annually over the course of an investment [Ruegg *et al.* 1990].

The formula to calculate the IRR is *:

$$NPV=\sum((RE_t - C_t) / (1+IRR)^t)=0$$

All elements are explained through the Net Present Value presentation and calculations.

When the return (IRR) is equal to or greater than the discount rate (assumed to be 5% in this economic assessment), the project is considered profitable [SIA 480 2016].

Results in discussion

Table 5.8 shows the different IRR results for CP, BP, and AAF building scenarios. It displays the different IRR results depending on if the initial investment is levered or not. Leverage conditions are found in the *Assumptions* section (Section 5.4.1). Ultimately, the difference between a 10-year or a 30-year investment period can be appreciated.

As a consequence of higher NPV associated with the AAF scenarios, the rate of return is also higher. Similarly, IRR results highlight the importance of evaluating long-term investments when integrating energy-efficient strategies into building design.

LEVERED IRR	30 - years	1A	1B	1C	2A	2B	2C	3A	3B	3C	4A	4B	4C
CP		7,6%	7,5%	6,0%	5,9%	7,6%	7,7%	7,4%	6,1%	7,6%	5,8%	7,9%	7,4%
BP		7,9%	7,9%	6,6%	6,5%	8,0%	8,0%	7,8%	6,6%	8,0%	6,5%	8,1%	7,8%
AAF		8,9%	8,5%	7,7%	7,9%	8,5%	8,5%	8,5%	7,7%	8,4%	8,2%	8,7%	8,6%
LEVERED IRR	10 - years												
CP		13,5%	13,3%	11,4%	11,3%	13,5%	13,7%	13,3%	11,5%	13,4%	11,2%	13,8%	13,3%
BP		13,6%	13,6%	11,7%	11,7%	13,8%	13,8%	13,6%	11,8%	13,7%	11,6%	13,9%	13,6%
AAF		14,8%	14,2%	12,9%	13,2%	14,3%	14,3%	14,2%	12,9%	14,1%	14,0%	14,5%	14,5%
UNLEVERED IRR	30 - years												
CP		3,1%	3,1%	2,2%	2,1%	3,2%	3,2%	3,0%	2,2%	3,1%	2,1%	3,3%	3,0%
BP		3,4%	3,4%	2,7%	2,6%	3,5%	3,5%	3,4%	2,7%	3,5%	2,6%	3,6%	3,4%
AAF		4,1%	3,9%	3,5%	3,6%	3,9%	3,9%	3,9%	3,5%	3,8%	3,8%	4,0%	4,0%
UNLEVERED IRR	10 - years												
CP		6,3%	6,2%	5,0%	4,9%	6,3%	6,4%	6,1%	5,0%	6,2%	4,9%	6,4%	6,1%
BP		6,4%	6,4%	5,2%	5,2%	6,5%	6,5%	6,3%	5,3%	6,4%	5,2%	6,5%	6,3%
AAF		7,2%	6,8%	6,0%	6,2%	6,8%	6,9%	6,8%	6,0%	6,7%	6,4%	7,0%	6,9%

Table 5.8
Internal rate of return results.

High-Performance variant.

*

Where :

NPV is the Net Present value previously described

REt is the benefits in year t and include energy savings associated with BIPV energy self-consumption

Ct is the costs in year t

t is the time in years

10-year investment periods provide higher revenues due to the time value of money. In a 10-year investment period, the building sale is considered after 10 years instead of 30, which results in a higher revenue when calculating with a discounted cash flow method.

The 10-year IRR results gathered in Table 5.8 are comparable to other expected real estate investment returns. Because the cost of money is 5%, an investor searches to get more than 5% IRR to generate money: 8% to 12% is the minimum expected IRR for an investor, 12-18% is considered a good investment and more than 18% is considered a risky but opportunistic investment [ArborCrowd 2017].

5.4.5 Discounted Payback

The DPB measures the number of years passed since the initial investment to the point when the accumulated benefits are sufficient to offset the initial investment, considering the time value of money [Short *et al.* 2016]. It indicates how long a project should be used to become profitable. A project is profitable if the repayment period is less than the duration of use [SIA 480 2016].

Results in discussion

When the initial investment is levered, the DPB time of the AAF building scenarios is, in most cases, one year shorter than the non-active building scenarios, as shown in Figure 5.25. Detailed results of each variant are included in Appendix A.5.3 and highlight that in each case, for at least a fraction of a year, the DBP is shorter for the AAF building scenarios than for other non-active variants.

Regarding the BAPV-roof variant, calculation results highlight that there is a non-significant DPB difference between non-active CP and their BAPV-roof variant.

AAF revenue higher than:	1A	1B	1C	2A	2B	2C	3A	3B	3C	4A	4B	4C	
BP	3	7	4	3	7	5	8	3	9	1	3	0	years
CP	9	12	9	9	12	12	12	10	13	7	11	8	years

Table *5.9*
Discounted time for higher revenue.

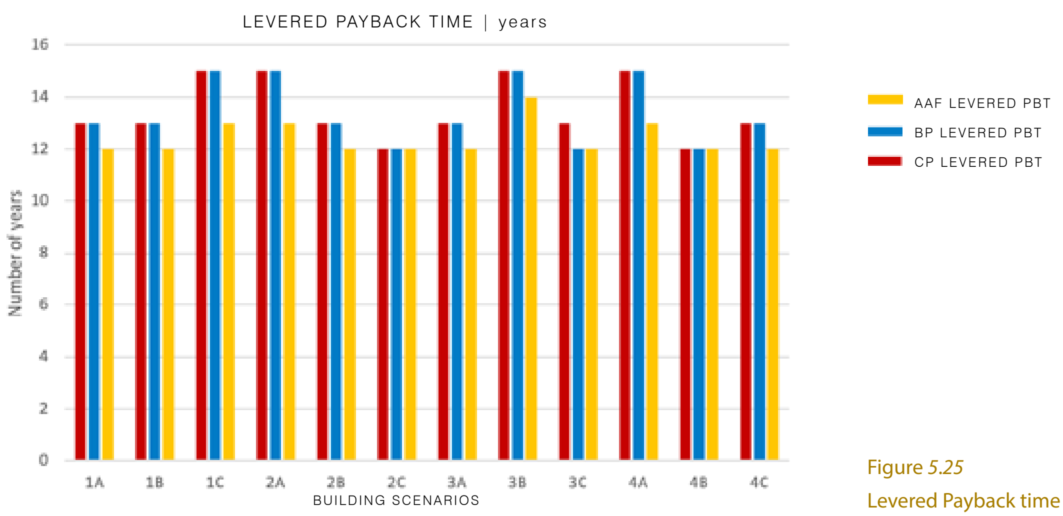


Figure *5.25*
Levered Payback time results.

An interesting result highlighted by the DBP calculations is the time elapsed between the initial investment and the point when AAF is more profitable than CP or BP variants. These results are presented in Table 5.9 and show that in an average of 4.5 years, an AAF building scenario is more profitable than a BP building scenario. Regarding CP, AAF building scenarios are more profitable after an average of 10.3 years.

BUILDING SCENARIO 2A | ECONOMIC ASSESSMENT RESULTS

MARKET READY: opaque Monocrystalline filtered 12%

HIGHT-PERFORMANCE: opaque Tandem-Perovskite filtered 18%

E C O N O M I C   E F F I C I E N C Y

M A R K E T - R E A D Y | H I G H - P E R F O R M A N C E

Life Cycle Cost (LCC)

M A R K E T - R E A D Y

Initial investment

FAÇADE COST

	Façade initial Investment cost per m²	Totals
CP	311,90 CHF	351 828 CHF
BP	460,67 CHF	519 633 CHF
AAF	633,43 CHF	714 509 CHF

	Comparative façade initial investment
AAF to CP	103% more expensive
AAF to BP	38% more expensive

BUILDING COST

	Building construction cost per m²	Totals
CP	2 288 CHF	5 987 579 CHF
BP	2 358 CHF	6 172 165 CHF
AAF	2 440 CHF	6 386 528 CHF

Façades:	% of initial investment	of building construction cost
CP	4%	6%
BP	6%	9%
AAF	8%	12%

30-year investment period	LCC
CP	8 075 062 CHF
BP	8 237 407 CHF
AAF	8 118 417 CHF

Battery cost (subsidies included)	28 000,00 CHF	
Energy purchase reduction associated	31 806,84 CHF	*NPV formula over battery lifetime
Earnings (NPV)	3 625,56 CHF	

H I G H - P E R F O R M A N C E

Initial investment

FAÇADE COST

	Façade initial Investment cost per m²	Totals
CP	311,90 CHF	351 828 CHF
BP	460,67 CHF	519 633 CHF
AAF	633,43 CHF	714 509 CHF

	Comparative façade initial investment
AAF to CP	103% more expensive
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CP	2 288 CHF	5 987 579 CHF
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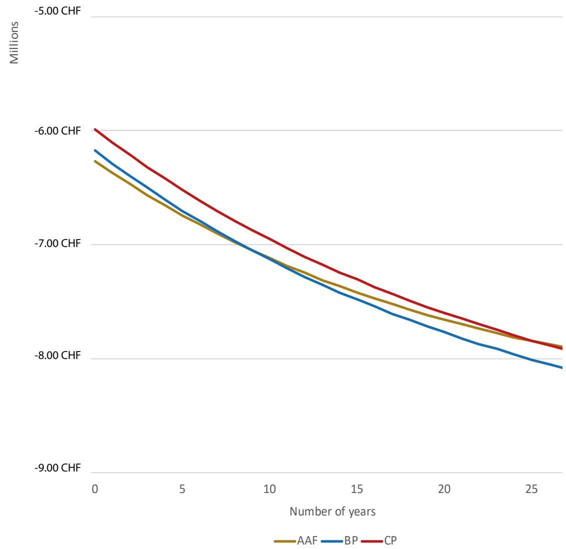
AAF	2 440 CHF	6 386 528 CHF

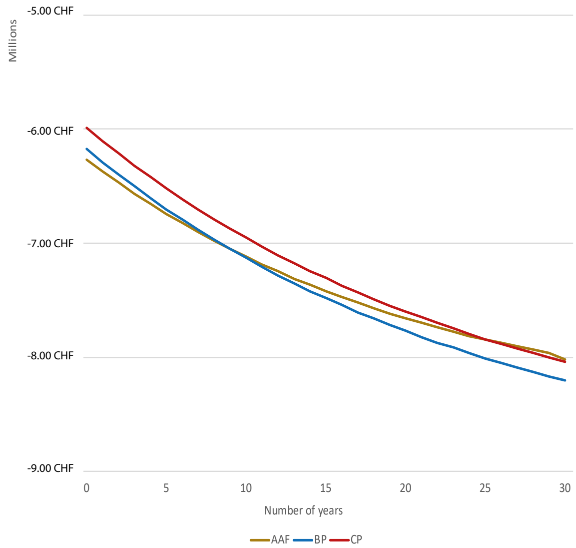
Façades:	% of initial investment	of building construction cost
CP	4%	6%
BP	6%	9%
AAF	8%	12%

30-year investment period	LCC
CP	8 075 062 CHF
BP	8 237 407 CHF
AAF	8 042 587 CHF

Battery cost (subsidies included)	54 000,00 CHF	
Energy purchase reduction associated	64 318,42 CHF	*NPV formula over battery lifetime
Earnings (NPV)	9 827,07 CHF	

Life Cycle cost before sale





Net Present Value (NPV)

NO BATTERY

M A R K E T - R E A D Y

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	3 626 871 CHF	5 009 554 CHF
CP + BAPV ROOF	4 116 641 CHF	5 493 889 CHF
BP	4 960 044 CHF	6 373 160 CHF
BP + BAPV ROOF	5 448 030 CHF	6 855 711 CHF
AAF	7 577 715 CHF	9 006 480 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	4 543 995 CHF	5 305 262 CHF
BP	4 971 739 CHF	5 749 761 CHF
AAF	6 121 883 CHF	6 908 521 CHF

H I G H - P E R F O R M A N C E

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	3 626 871 CHF	5 009 554 CHF
CP + BAPV ROOF	4 116 641 CHF	5 493 889 CHF
BP	4 960 044 CHF	6 373 160 CHF
BP + BAPV ROOF	5 448 030 CHF	6 855 711 CHF
AAF	7 767 271 CHF	9 196 036 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	4 543 995 CHF	5 305 262 CHF
BP	4 971 739 CHF	5 749 761 CHF
AAF	6 232 211 CHF	7 018 850 CHF

BATTERY

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	3 626 871 CHF	5 009 554 CHF
CP + BAPV ROOF	4 145 205 CHF	5 522 453 CHF
BP	4 960 044 CHF	6 373 160 CHF
BP + BAPV ROOF	5 477 335 CHF	6 885 016 CHF
AAF	7 565 330 CHF	8 998 711 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	4 543 995 CHF	5 305 262 CHF
BP	4 971 739 CHF	5 749 761 CHF
AAF	6 145 122 CHF	6 934 302 CHF

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	3 626 871 CHF	5 009 554 CHF
CP + BAPV ROOF	4 164 534 CHF	5 541 782 CHF
BP	4 960 044 CHF	6 373 160 CHF
BP + BAPV ROOF	5 496 969 CHF	6 904 649 CHF
AAF	7 747 791 CHF	9 185 459 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	4 543 995 CHF	5 305 262 CHF
BP	4 971 739 CHF	5 749 761 CHF
AAF	6 286 241 CHF	7 077 781 CHF

Internal Rate of Return (IRR)

NO BATTERY*

30-year investment period	**Unlevered IRR**	**Levered IRR**
CP	2,1%	5,9%
CP + BAPV ROOF	2,4%	6,4%
BP	2,6%	6,5%
BP + BAPV ROOF	2,8%	6,9%
AAF	3,5%	7,8%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	4,9%	11,3%
BP	5,2%	11,7%
AAF	6,1%	13,0%

30-year investment period	**Unlevered IRR**	**Levered IRR**
CP	2,1%	5,9%
CP + BAPV ROOF	2,4%	6,4%
BP	2,6%	6,5%
BP + BAPV ROOF	2,8%	6,9%
AAF	3,6%	7,9%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	4,9%	11,3%
BP	5,2%	11,7%
AAF	6,2%	13,2%

Discounted Payback (DPB)

NO BATTERY*

DPB	Un-levered	Levered
CP	31	15
BP	29	15
AAF	25	13

*no significant differences between CP and BP with their correspondent BAPV roof vari

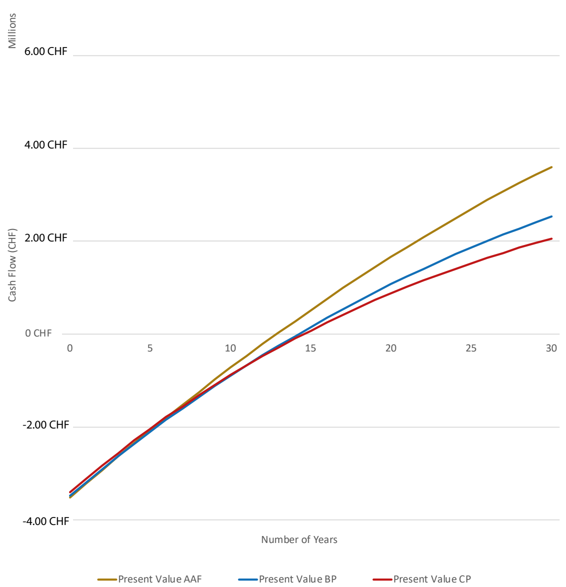
Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	10	4
AAF to BP	years to have higher cummulated revenue	6	10

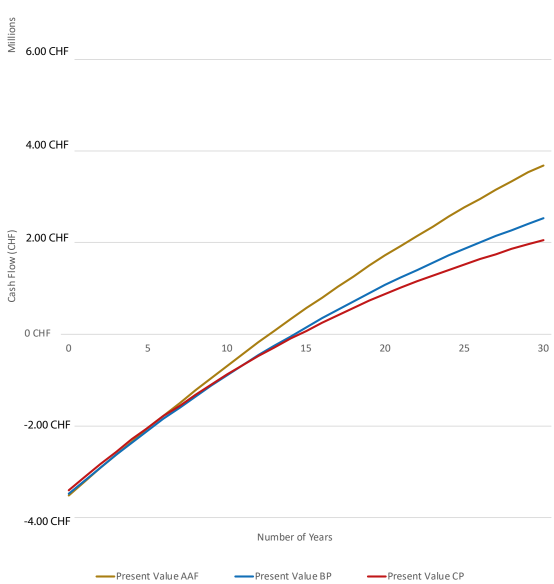
DPB	Un-levered	Levered
CP	31	15
BP	29	15
AAF	25	13

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	9	3
AAF to BP	years to have higher cummulated revenue	5	9

Levered Present Value





5.5. Synthesis

The quantitative assessment presented in this chapter is focused on the outcome of the *Design approach,* the AAF. More specifically, it aims at assessing its energy end economic efficiency.

To this end, a comparative framework with current construction systems is defined to assess the potential energy and economic efficiency improvement achieved through the AAF. This framework integrates the AAF building scenarios presented in Section 4.4.1 and two different non-active façade construction current practices, the *Common practice* (CP) and the *Best practice* (BP), outlining three main scenario variants: CP, BP and AAF. Within this framework, different variants regarding diverse PV technologies, batteries and BAPV systems are also integrated.

To evaluate the contribution of this research to the ongoing energy transition, the energy performance assessment presented in this section includes an embodied energy analysis, an operational energy analysis and a combined energy analysis. Ultimately, results are confronted to the energy performance targets specified in the norm SIA 2040 [SIA 2040 2017].

The embodied energy efficiency analysis is performed based on a simplified LCA methodology, taking data from the KBOB database [KBOB 2016]. This process enables the quantification of the AAF embodied environmental impacts and its assessment in comparison to current practices.

The main output of the embodied impact analysis is that the AAF substructure achieves a significant reduction of the façade embodied impacts when compared to current practices: it presents 1/2 of BP's substructure embodied impacts, and 1/5 of CP's substructure embodied impacts. However, the embodied impacts associated with the incorporation of BIPV surfaces account for up to 90% of the AAF total embodied impacts, depending on the façade design and total active surfaces. This means that 1 m^2 of the AAF has up to 5 times more embodied impacts than 1 m^2 of BP façade and up to 2.5 times more embodied impacts than 1 m^2 of CP.

The iterative design and assessment process of the AAF construction system remarks the high embodied impacts of the BIPV panels, but also the high embodied impacts of the fire-resistant board – fibrocement – required to define the ventilated cavity behind the BIPV panels. This remark leads to the conclusion that further research regarding fire-resistant materials with low embodied impacts must be carried out.

At building scale, embodied impacts results rely on a combination of existing data, which identifies the embodied impacts of a building as a whole [Drouilles *et al.* 2019] and each specific AAF, CP and BP façade's embodied impact quantification. The assessment of the different building scenarios highlights that the CP scenarios have the largest embodied impacts, followed by the different AAF building scenarios. Among AAF building scenarios, the largest BIPV installations induce the highest embodied impacts, and conversely, the smallest BIPV installations have the lowest embodied impacts. Finally, BP building scenarios are the most embodied impact efficient.

The operational energy efficiency analysis is performed through the energy simulations of the different building scenarios. This process provides hourly information on the building's energy demand and generation, as well as the self-consumption share of the generated energy and the building's energy self-sufficiency.

The lower transmittance value of the AAF façade guarantees that AAF building scenarios have at least, on average, 8% less operational energy demand than BP building scenarios and 13.5% less operational energy demand than CP building scenarios. The integration of BIPV systems into the façades provides the building with an on-site energy generator whose output can meet up to 100% of the building energy demand. The energy output of the different AAF designs depends mostly on the size of the BIPV installation, which is expressed in kWp. The largest BIPV installations of the analysed building scenarios integrate a façade cladding surface with opaque BIPV panels; these are building scenarios 1A, 2A and 4A, which can provide up to 109%, 73% and 138% of the building's energy needs respectively when incorporating *High-Performance* PV technology.

All in all, the AAF, by combining passive (energy economy) and active (energy generation) energy design strategies, provides energy savings between 14% (2C) and 49% (4A) when real self-consumption is considered and up to 100% when EMS and storage systems are integrated, turning some of the AAF building scenarios into positive energy buildings. .

Façade orientation significantly affects the annual energy output. South façades have the largest energy surface yield and north façades the smallest one – approximately 50% of the south façade's energy surface yield.

The integration of BIPV cannot be analysed exclusively from an operational energy point of view because it entails a notable increase of the total embodied energy of the building. In the same way, an exclusive embodied energy analysis leaves aside all the renewable energy generation advantages of BIPV systems. For this reason, a combined energy efficiency analysis, as proposed by the norm SIA 2040, is required [SIA 2040 2017].

The combined energy efficiency analysis shows that the higher embodied energy associated with large BIPV installations entails the optimisation of the combined building's energy efficiency. This means that BIPV's high embodied impacts are compensated by its energy generation, even if a large part of BIPV surfaces are integrated into north façades with low energy generation yields, as is the case of all the AAF building scenarios analysed.

The confrontation of the combined energy efficiency results with SIA's energy efficiency target values [SIA 2040 2017] highlights that CP and BP building scenarios do not reach energy efficiency target values. This implies that a decrease of the combined impacts is required through on-site energy generation, the reduction of the energy demand or the supply of energy through alternative renewable sources.

The AAF building scenarios can reach NRPE target values when incorporating large BIPV installations, corresponding to Group A of AAF building scenarios. In addition, the choice of HP PV technologies over MR PV technologies notably enhances the building's energy efficiency. This means that BIPV research results focused on energy efficiency improvements have the potential to reach the energy transition goals.

BAPV-roofs represent a solution for reaching the energy transition objectives for the AAF building scenarios that do not reach the SIA 2040 target values due to their small BIPV installation. However, the simulated BAPV-roofs do not generate enough energy to provide CP and BP building scenarios with the required energy balance to meet the defined target values. BP+BAPV-roof combined results are close to reaching the targets. For this reason, *High-Performance* BAPV-roofs must be further analysed to evaluate their compliance with energy efficiency targets.

The implementation of BAPV-façades into CP and BP practices improves their combined energy efficiency and provides some building scenarios with an optimised energy balance that meets energy efficiency targets. However, when compared to their corresponding AAF building scenarios, the BAPV-façade variants of CP and BP building scenarios are, on average, between 22% and 10% better performing in average (NRPE), respectively for the HP variant; and between 18% and 7% for the MR variant. In some cases, BP building scenarios with BAPV roofs are more performant than the MR AAF building scenarios. However, they do not reach SIA's target values (NRPE) and the addition of BAPV façades on BP building scenarios results in a less performing variant than the AAF building scenarios.

Ultimately, the AAF building scenarios have less impact than current practice (CP and BP) building scenarios. More precisely, HP AAF building scenarios have, on average, 44% less NRPE than CP, 30% less GWP than CP, 38% less NRPE than BP and 13% less GWP than BP. Likewise, MR AAF building scenarios have, on average, 34% less NRPE than CP, 25% less GWP than CP, 27% less NRPE than BP and 6% less GWP than BP

These results highlight the energy efficiency improvement potential of the AAF compared to current construction practices, which can lead architectural practices toward the energy transition of the construction sector.

The economic performance analysis results highlight that the higher initial investment for AAF building scenarios generates a profitable long-term investment.

The LCC analysis highlights that AAF façade construction costs are up to 104% higher than CP façade construction costs, and 38% higher than BP façade construction costs depending on the façade design and size of the BIPV installation.

However, the energy savings provided by the AAF significantly affect the LCC: most AAF building scenarios have lower LCC than BP – all except 3C. Regarding CP's LCC compared to AAF's LCC, only the AAF building scenarios with the largest BIPV installation – 1A, 2A and 4A – have lower LCC than CP due to the significantly lower construction costs of CP compared to AAF.

The LCC results in higher values for building scenarios with the *Loggias* façade morphology. This is associated in the first instance to a larger surface of the building envelope and in a second instance to the slightly higher operational energy demand.

The NPV is higher for all AAF scenarios due to the higher revenues associated with higher rental prices and electricity sale. These results show that the economic barrier blocking a widespread use of BIPV is exclusively related to the high initial investment associated with BIPV technology. This assessment shows that long-term economic assessments must be carried out to financially support the integration of energy-efficient façades into collective residential buildings in mid-dense urban areas.

The IRR values are comparable to other expected real estate IRR values [ArborCrowd 2017]. Associated with higher NPV, AAF building scenario's IRR values are higher than other non-active building scenarios. This highlights, once again, the need for long-term investment assessments over initial investment assessments when integrating energy-efficient design strategies in buildings.

Regarding BAPV-roof, NPV and IRR values (Appendix A.5.3) show that building scenarios with BAPV-roof are more performing than non-active ones. Nevertheless, AAF building scenarios have a better economic performance in every case, regarding NPV and IRR, for its higher energy economy associated with AAF's passive and active energy design strategies.

The DPB is around one year shorter for most AAF building scenarios when compared to non-active building scenarios. Additionally, DPB calculations highlight that after 4.5 and 10.3 years on average, it is more profitable to integrate an AAF over BP and CP, respectively, even if the building cash flows have not reached the breakeven point.

To sum up, this chapter highlights the potential of the AAF to contribute to the energy transition through the improvement of the building's energy and economic efficiency. It also shows that the better economic performances of energy-efficient buildings can motivate real estate development towards the energy transition.

On the one hand, AAF with large BIPV installations can provide a building with the means to reach energy efficiency target values. However, AAF with small BIPV installations cannot reach these values without the complement of a BAPV-roof. With this conclusion, this research aims at motivating active façade cladding design, which provides the largest surface for BIPV integration, resulting in large BIPV installations. Similarly, to increase the size of a BIPV installation (measured in kWp), further research at PV cell level is required to improve its efficiency, which will have a significant impact on the global building's energy performances.

On the other hand, AAF building scenario's initial investment assessment over the long term results in higher revenues than the non-active building variants. With these results, this research aims at motivating a widespread practice of long-term investment assessments when integrating energy efficiency design strategies to overcome the identified BIPV cost barrier blocking its widespread use.

Current limits of this quantitative assessment are the assumptions that EMS is well developed and widely implemented, the lack of detailed environmental impacts of the different PV technologies, and the assumption of equal prices for all BIPV systems. EMS is today at a development stage and primitive implementation. However, it is expected that the electric car industry and the development of smart grids at a national scale will foster a widespread implementation of EMS in the coming years. The available information regarding BIPV environmental impacts is limited today; further research is needed to provide detailed information about the embodied environmental impacts of each type of PV technology. Finally, this assessment process has assumed equal prices for all BIPV technologies based on an economy of scale due to the disparity of prices found in the literature.

Ultimately, the quantitative assessment remarks how the above-mentioned energy and economic efficiency is directly affected by the façade design, which defines the façade composition, the design of the BIPV integration and the size of the PV installation.

6. Transfer potential towards architectural practice

The research work developed in this thesis aims at the immediate application of its outcome to architectural practices. The urgent condition of this objective owes to the imperative energy demands of current construction regulations and energy directives (Chapter 3). For this reason, this chapter explores the applicability of the research outcome, that is to say, the Advanced Active Façade (AAF), and its transferring potential towards architectural practices. This is Phase III of the current research, which is simultaneously developed with Phase II, presented in Chapter 5. Phase III takes the form of interdisciplinary interactions with different professional and non-professional stakeholders.

This chapter presents how the AAF is integrated into professional design processes to transfer the knowledge developed within this research and assess its transferring potential towards professional practices. By addressing design and construction professional processes, it provides concrete information on the willingness to integrate energy-efficient façade design strategies.

To this end, three interactions are defined as the main steps of this research phase: 1) the construction of a real scale AAF demonstrator to assess the professional construction process; 2) the presentation of the AAF to professional and non-professional stakeholders to assess their willingness to adopt advance active architectural practices; and 3) the organization of an architectural competition for students to assess the transferability of the AAF construction system towards design practices.

These three steps confront the research output with three main target groups: architecture professionals, the Swiss population in general and architecture students. These three groups represent the main agents blocking the widespread use of BIPV due to architectural expression issues. Consequently, this chapter allows assessing AAF's potential to contribute to overcoming BIPV's aesthetic barriers, integrating it into design practices. Ultimately, as a knowledge transfer step, this research phase also aims at contributing to overcoming the identified obstacles related to the lack of knowledge of and interest in energy-efficient façades.

6.1. Workflow

This section presents the workflow developed to carry out the last phase of the research, which consists of assessing the AAF's transferring potential towards architectural practice. As mentioned above, it is composed of three steps defined as interdisciplinary interactions that confront the AFF to a variety of stakeholders and processes. Accordingly, the results of each step provide information to measure the transfer potential of the AAF and its applicability into professional practices. It is important to note that these steps are interconnected, the former feeding and being used by the latter.

- The first step of the workflow implies the design and construction of a real scale AAF demonstrator to confront architecture practitioners and professional construction professionals with the research outcome.

The underlying purpose is to optimise the AAF design and assess its transfer potential towards architectural practices (Section 6.2).

The design and construction of the AAF demonstrator imply an interdisciplinary collaboration among architects, façade specialists, timber façade constructors, and BIPV producers. All these façade stakeholders have participated in the AAF demonstrator design and construction process. In the end, the involved stakeholders provide feedback on the design and construction process that, within an iterative design process, enables the AAF optimisation and applicability appraisal.

- The second step of the workflow involves the interaction with different focus groups to confront the design approach output (the AAF) to their opinion and evaluate its architectural design acceptance (Section 6.3). Altogether, the inputs provided by the three focus groups support the AAF design potential assessment and contribute to overcoming BIPV's aesthetic barriers. Ultimately, these interactions measure the willingness of the different focus groups to integrate BIPV and low-carbon principles in architectural practices. The focus groups are:

  - Architecture Practitioners: 50 construction professionals (architects mostly) are invited to visit the AAF demonstrator. After the visit, they can suggest design modifications of the construction system and express their willingness to incorporate it into their professional practice through an online survey.

  - Architecture Experts: 5 experts from Swiss architecture firms with experience in collective residential housing design (Appendix A.3) are contacted and interviewed. Research design results are presented during individual interviews with the experts to record their opinions and comments, which are later analysed. This process allows verifying the accordance of the work developed in this thesis with today's construction practices in Switzerland. In addition, it allows defining the acceptance of the AAF and its potential applications into contemporary architectural practices.

  - Non-experts: Subjects are recruited through an access panel provided by a market-research company with no particular architectural expertise to measure the social acceptance of research results. This measurement is made by the Institute of Sustainable Development of the Zurich University of Applied Sciences (ZHAW) with whom a collaboration was established in the framework of the PV2050 interdisciplinary research project [Perret-Aebi 2019]. Their research team performed a national survey where the social acceptance of BIPV was measured, based on the presentation of five AAF building scenarios (Chapter 4) [Lobsiger-Kägi *et al.* 2018a].

- Finally, the third step consists of the interaction of architecture students with the AAF (Section 6.4). For this, an architecture competition for students is organised to study the applicability of the AAF into architectural practices. Students are asked to design a collective residential building that integrates the AAF construction system. The objective is to test the design potential of the AAF construction system and evaluate the energy efficiency achieved by the AAF.

Besides, the competition entries are expected to enlarge the sample of AAF building scenarios developed and presented in Chapter 4.

This workflow is expected to provide, through three types of interactions, the necessary inputs to measure the transfer potential of BIPV towards the architecture practice. Eventually, this workflow integrates the ultimate objective of this chapter, which is the knowledge transfer of this research outcome, present in all three interactions.

6.2. Constructing the AAF demonstrator

The first step of this transfer potential assessment phase is the construction of a façade demonstrator. The construction of a model or a prototype is a commonly used research method, usually performed in late phases of research processes to optimise the design research output [de Jonge *et al.* 2002]. In this case, the AAF demonstrator construction is a method to optimise the AAF design and assess its transfer potential towards architecture practices.

This step reproduces the architectural process of designing and constructing a BIPV façade, which gathers an interdisciplinary professional team: architects, façade specialists, timber façade constructors, and BIPV producers. Through the interaction with these professionals, the construction of the AAF demonstrator provides the opportunity to analyse the architectural building process.

Objectives

In that respect, the objectives are multiple. First, the construction of the demonstrator allows the analysis of the AAF design performance regarding its building process – prefabrication and mounting processes – and material compatibility. Second, it allows the optimisation of the AAF construction system design. More precisely, the AFF demonstrator construction is part of an iterative design process that contributes to optimising the initial research results presented in Chapter 4.

A fundamental objective of the AAF demonstrator is to be presented to the public during the second step (Section 6.3). Furthermore, it is the occasion to showcase the new BIPV panels produced by the Swiss Centre for Electronics and Microtechnology (CSEM), one of the main partners of this research. The intention is to contribute to overcoming three BIPV remaining barriers, which were previously described in Chapter 3: unconvincing expression of existing BIPV solutions, lack of knowledge, and lack of interest among architects and other building stakeholders [Farkas *et al.* 2012; Bonomo *et al.* 2015].

With regards to the aesthetic barrier, the construction of a façade demonstrator enables the study of the expressive issues of BIPV by recreating the architectural design process of façade composition. With regards to the lack of knowledge and interest barriers, the construction of the AAF demonstrator aims at presenting BIPV systems as an integral part of a complete energy-efficient façade construction system. To this end, the AAF demonstrator must clearly display the material composition and configuration of the AAF construction system to make it understandable.

That way, the façade demonstrator aims at highlighting BIPV's aesthetic potential as well as rising architects' and other construction stakeholders' awareness and interest. This is possible through the public presentation of the AFF demonstrator and by confronting the research output to professional's opinion.

Ultimately, a final objective of the full-scale AAF demonstrator construction is to complement and physically illustrate the architectural reference for energy-efficient façade design developed in Chapter 4. To this end, the AAF demonstrator must represent the energy-efficient façade as an architectural object that can be visited, explored, and analysed with an architectural perspective. This involves a complete façade construction to show that BIPV integration is possible at a design and construction level, meeting both technical and aesthetic requirements. The AAF demonstrator's design must explicitly illustrate the different components of the energy-efficient façade and highlight possible issues related to architectural integration regarding passive and active energy design strategies. This objective differs from other BIPV façade demonstrators or prototypes, which are usually focused on assessing the outermost active layer of the façade (Section 3.2.2.4).

Method

The AAF demonstrator is the result of the joint effort of an interdisciplinary team composed of architects, façade specialists, timber façade constructors and BIPV producers. The following sections explain the AAF demonstrator design and construction process. Ultimately, these processes are discussed, integrating the involved stakeholder's feedback to optimise the AAF and, more particularly, perform a preliminary assessment of its transfer potential towards architectural practice.

As a reminder, the existing BIPV façade prototypes presented in Chapter 3 are mostly designed to monitor the BIPV system's energy performance. We notice a lack of façade prototypes focused on enhancing BIPV's design potential in architectural applications. Similarly, no energy-efficient façade prototype, focusing on both passive and active energy design strategies, has been identified. This observation highlights the relevance of building a new façade demonstrator in order to fill this gap. The latter must be comprehensive to allow for testing the complete AAF façade's design performance: BIPV's architectural expression, material compatibility, construction regulation compliance and energy-efficient façade prefabrication processes. In this respect, a real scale demonstrator of a complete energy-efficient façade construction system must be designed, from the innermost layer to the outermost active surface.

6.2.1 Demonstrator design

Based on the previous observation, the process of the AFF demonstrator construction moves to the design step. The design of the façade demonstrator is jointly led by CSEM and the Laboratory of Architecture and Sustainable Technologies (LAST) of the Ecole Polytechnique Fédérale de Lausanne (EPFL). In order to integrate CSEM's new BIPV panels – as an opaque façade cladding –, an energy-efficient, demountable façade demonstrator was designed as an adaptation of the AAF construction system (Section 4.3.1). In addition, translucent DSSC-based BIPV panels are incorporated into the demonstrator with a façade security function as a window balustrade. CSEM's BIPV panels used in the AAF demonstrator are described in the following section, as well as the AAF demonstrator concept and design.

BIPV panels

The AAF demonstrator displays different BIPV technologies that comply with architectural aesthetic requirements to be integrated as façade elements. Opaque BIPV panels are integrated as the façade cladding and display the new BIPV technology developed by CSEM, described in Chapter 3 [Söderström 2018]. The BIPV panel textures displayed are illustrated in Figure 6.1.

As mentioned above, a second BIPV technology is integrated as the window balustrade. It is a translucent and coloured BIPV panel provided by the Swiss BIPV producer collaborating in this research project [H.Glass 2019]. Figure 6.2

Figure 6.1
CSEM's BIPV panels textures and performances They integrate different filters and different glass treatments. From left to right: Copper metal mesh (can generate up to 168 W/m^2), Fibreglass (can generate up to 229 W/m^2) and Grey metal mesh (can generate up to 182 W/m^2).

Figure 6.2
Translucent BIPV panel: DSSC technology.

Source: H. Glass

Figure 6.3
Architectural visualization of a BIPV scenario integrating opaque and translucent BIPV systems. This building scenario is the base for the AAF demonstrator design.

illustrates this translucent BIPV panel, which generates energy based on DSSC technology (See Chapter 3).

The different BIPV panels displayed on the AAF demonstrator integrate different filters: a grey metal mesh, a copper metal mesh and a fibreglass mesh (Figure 6.1). According to CSEM's simulations, the corresponding BIPV panel's energy efficiency losses are 18% for the fibreglass filter, 35% for the grey metal mesh filter and 40% for the copper metal mesh filter. The performance difference between the two metal filters (grey and copper) is due to the different density of the meshes [Söderström 2018].

Figure 6.1 illustrates the three different BIPV filters with their corresponding energy performances, assuming that Tandem Perovskite PV cells with 28% performance are integrated into the modules.

The efficiency losses related to the reduction of solar irradiated PV surface is not equal among the different filtered BIPV panels. That is to say, for a light transmission decrease of 50% due to the integration of the filter, the performance loss of the BIPV module is observed to be of 37% [Söderström 2018]. In CSEM's report, Söderström explains that *the reduced performance loss can be partially attributed to the light that impinges on a non-planar surface on the fibre is reflected on the cell and not toward the observer.* In other words, due to the light-reflective properties of the chosen filters, light is reflected in the interior of the panel and increases the amount of light that reaches the PV cell and the associated energy output. Söderström adds that BIPV modules output depends on the reflectivity of the mesh coating, not only on the mesh density itself [Söderström 2018].

In addition to the filtered variety displayed on the façade demonstrator, different front glass treatments are tested to provide architects with a broader range of options when composing BIPV façades. The AAF demonstrator displays regular tempered glass panels and sandblasted glass panels. The regular tempered front glass panels allow a direct comprehension of the filter's texture. The sandblasted front glass panels sieve the filter pattern and modify the visual aspect of the BIPV modules, enlarging the final variety of finished products displayed on the AAF demonstrator. Although the performance variations have not been tested, a small performance reduction is expected for the sandblasted front glass modules, according to CSEM PV experts [Interview with G. Cattaneo, 2018].

The translucent panel is based on DSSC technology, which has significantly lower energy output than wafer-based PV technology. DSSC panels incorporate a coloured dye that absorbs light and generates energy replicating the photosynthesis process. The translucent panel integrated into the AAF demonstrator has an energy efficiency between 2% and 3% [Interview with I. Pola, 2017]. This technology is not a novel technology, and further information can be obtained from DSSC BIPV panel producers such as H.glass [H.Glass 2019].

AAF demonstrator concept

The concept of the AAF demonstrator is defined as a three-dimensional object that represents a façade angle to illustrate a building volume. The perception of the demonstrator as a three-dimensional object brings the visitor closer to better understanding the BIPV textures, colours and light reflections, as well as its aesthetic potential. In the same way, a three-dimensional façade demonstrator complexifies the façade composition process, approaching it to the architectural design process. Ultimately, a three-dimensional object defines an inside and an outside. The interior space can represent the interior of an apartment while the exterior space can express the public dimension of the façade, where the architectural process of façade composition takes place.

AAF demonstrator design

The façade demonstrator design is based on the AAF construction system and the AAF building scenarios, both presented in Chapter 4. This real-scale façade demonstrator represents a one storey façade angle of the building displayed in Figure 6.3, which integrates the AAF construction system. The façade incorporates filtered BIPV panels – grey metal mesh filter – as façade cladding and coloured translucent BIPV panels as balustrades. This building scenario has been specifically designed to the AAF demonstrator construction phase and corresponds to an adaptation of the 2A building scenario presented in Section 4.4.1. This building scenario incorporates the novel CSEM's BIPV panels as façade cladding (as the 2A scenario in Chapter 4), and DSSC BIPV panels as translucent balustrades. The resulting building scenario (Figure 6.3) incorporates the PV products of both the research partners: CSEM and H.Glass. With these two different BIPV technologies, the façade demonstrator shows how different façade requirements can be fulfilled with different BIPV systems. To simplify the demonstrator construction, balconies and loggias are avoided, and the façade opening is reduced to a window.

The interior of the AAF demonstrator is designed to inform visitors about its low embodied impact façade construction principles and the selected construction materials and façade components (Section 4.3.1). On the right wall[1], the façade interior layers are progressively removed to leave in sight every component of the AAF construction system: the interior coating, the wood-fibre insulation, the OSB (Oriented Strand Board) panels, the wood-studs substructure, the cellulose insulation, the wood-fibre-cement panels, the dimension of the air cavity and the BIPV panel substructure. This decomposition of the AAF demonstrator leaves the rear face of the BIPV panels visible so that the BIPV fastening system, the electrical wiring and the connexions among BIPV modules are visible and easily explained. The sight of the whole BIPV system installation and its fastening system aims at highlighting its simplicity and demystifying BIPV façade integration's technical complexity.

The demonstrator's outermost active layer is designed to illustrate BIPV façade's composition flexibility. As previously explained, it showcases different types of BIPV panels, offering a variety of formats, textures, colours, light reflections and transparencies. Yet, all this variety has been carefully studied through the demonstrator's design so that the result has a harmonious and unified architectural expression. This aesthetic concern is one of the main differences between the AAF demonstrator and other existing BIPV façade demonstrators (Chapter 3). The AAF demonstrator design enhances the fact that composing a façade with BIPV has significant expressive potential.

The design of the AAF demonstrator integrates a *Slab to slab* openable window on the left wall. This window has been incorporated into the demonstrator's façade design for three reasons. First, to reinforce the idea that the demonstrator represents a façade in its entirety and that it is not limited to the façade's BIPV system. Second, to enhance the domestic character and scale of both the exterior façade design and the interior space of the demonstrator. The window dimensions (100x240 cm) speak of that human and domestic aspect, which is referred to throughout this research, and represents the residential building

1
Façade demonstrator walls are called left and right, according to their situation from a point of view located in the interior space of the demonstrator.

façades [Marchand 2016; Ortelli 2016]. Third, to represent all the main components of a residential building's façade and the different encounters among them.

In the end, the AAF demonstrator results in 3 meters high, 3 meters long and 3 meters wide architectural object, which is conceived as a stand for presenting the AAF in different venues. In addition, it includes a small table in the interior space where printed documentation can be placed to inform visitors about the displayed BIPV technology, its performance, the composition of the BIPV panels and the low environmental impact construction principles adopted.

6.2.2 Demonstrator construction

Based on the previously described AAF demonstrator design, the process of the AAF demonstrator moves to the last step, the construction. Chapter 4 explains how the Advanced Active Façade is conceived to be prefabricated and mounted in modules of variable dimension depending on the construction site and its transport conditions. Similarly, the AAF demonstrator is composed of different prefabricated AAF modules, whose maximum dimensions and total weight are determined by a major constraint: the demonstrator must be mounted and demounted in interior spaces. This entails men workforce handling the modules without any machinery or construction crane, which would be used for constructing an AAF for a real outdoor building. The dimensions of the AAF modules are defined in consensus with the timber construction company in charge of the demonstrator's production and mounting – ERNE – who determined that each AAF module is of maximum 1 meter wide and 3 meters tall.

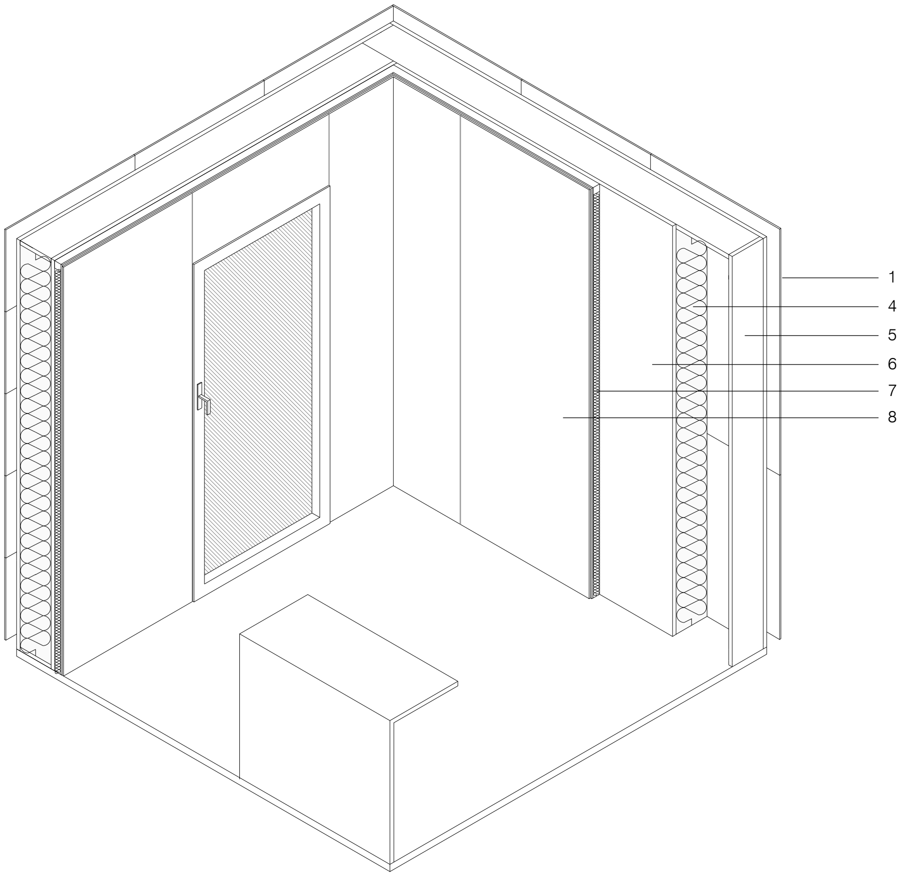
The AAF demonstrator is composed of six prefabricated modules including three regular opaque façade modules, one window module, and two façade-corner modules. These modules are mounted on a wooden base, which in turn is composed of three timber panels. Given the above-mentioned constraints, the construction system of the AAF demonstrator has been slightly modified compared to the original AAF construction system presented in Section 4.3.1. The modifications are oriented to meet the requirements of multiple mounting and demounting processes when presenting the façade demonstrator at different venues. For instance, the timber façade frame elements have a bigger dimension than the original design for stability purposes, due to the lack of an upper and lower solid horizontal slab. Likewise, the vertical timber substructure had to be doubled so that every façade module is independent and stable during the mounting process.

In the last step of the façade demonstrator's construction process, the design team – experts from CSEM and LAST – mount the BIPV panel fastening system and arrange the BIPV panels.

6.2.3 Stakeholders feedback

Regulation

The AAF demonstrator façade design experts – Preface – provide professional consulting services to verify that the AAF meets all norms and requirements regarding thermal and noise insulation targets, fire protection and substructure dimensioning, which are described in Chapter 4.



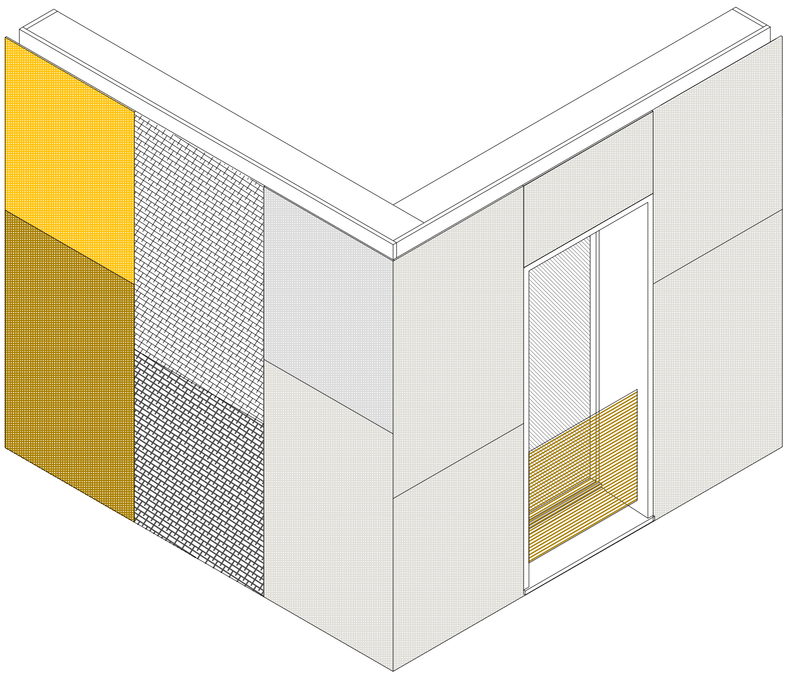
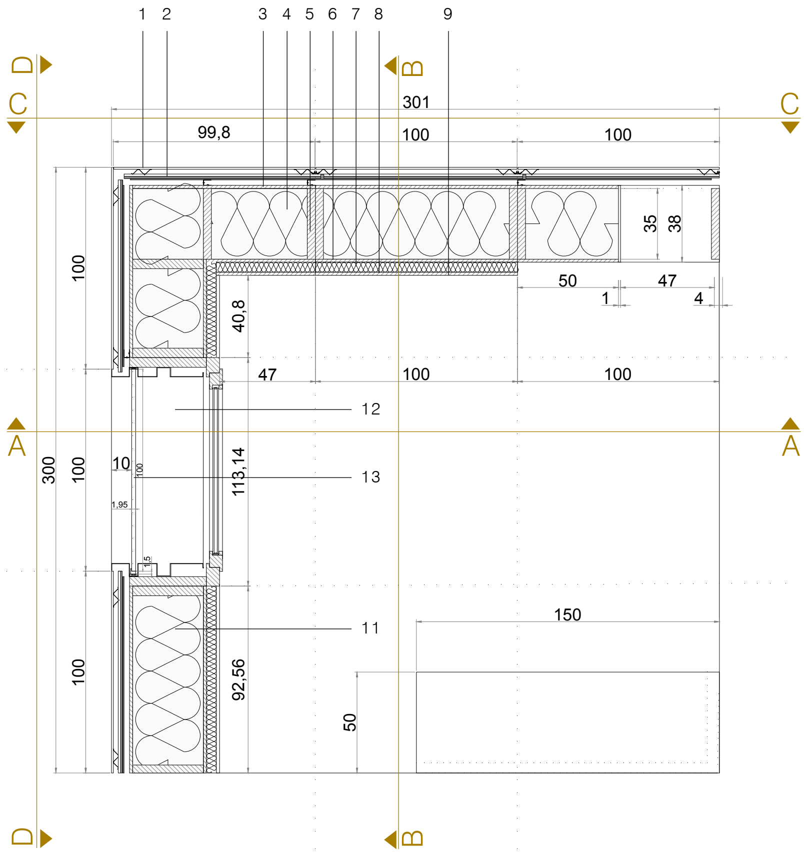
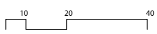


Figure 6.4
AAF demonstrator: interior and exterior axonometric views.

P L A N



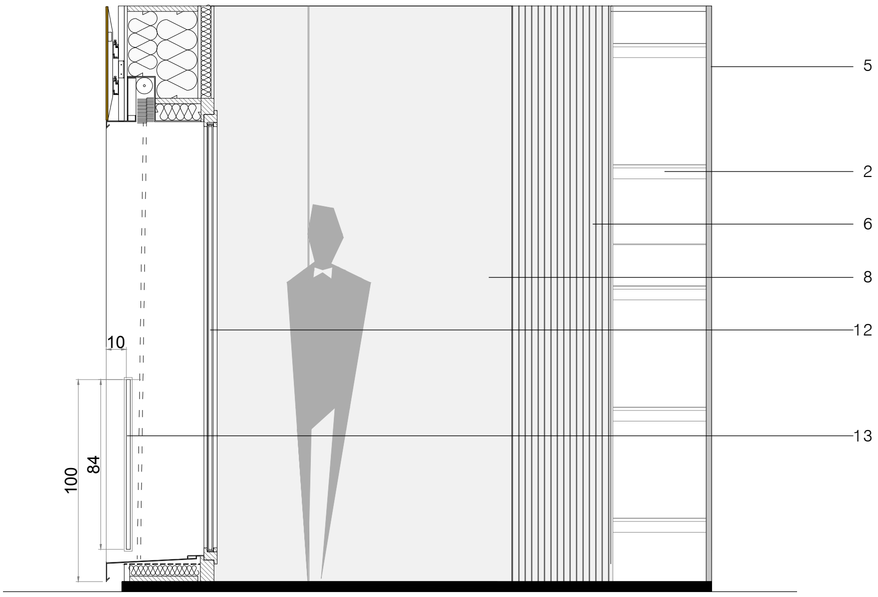


1. BIPV PANELS
2. BIPV PANEL FASTENING SYSTEM
3. FIBROCEMENT PANELS WITH SEALED JOINTS
4. BLOWN CELLULOSE INSULATION
5. TIMBER SUBSTRUCTURE: SOLID WOOD RIBS
6. OSB PANELS WITH SEALED JOINTS
7. WOOD FIBRE INSULATION
8. PLASTER BOARD
9. INTERIOR COATING: PAINT
11. PREFABRICATED AAF MODULE
12. WINDOW FAÇADE MODULE
13. TRANSLUCENT BIPV PANEL: BALUSTRADE

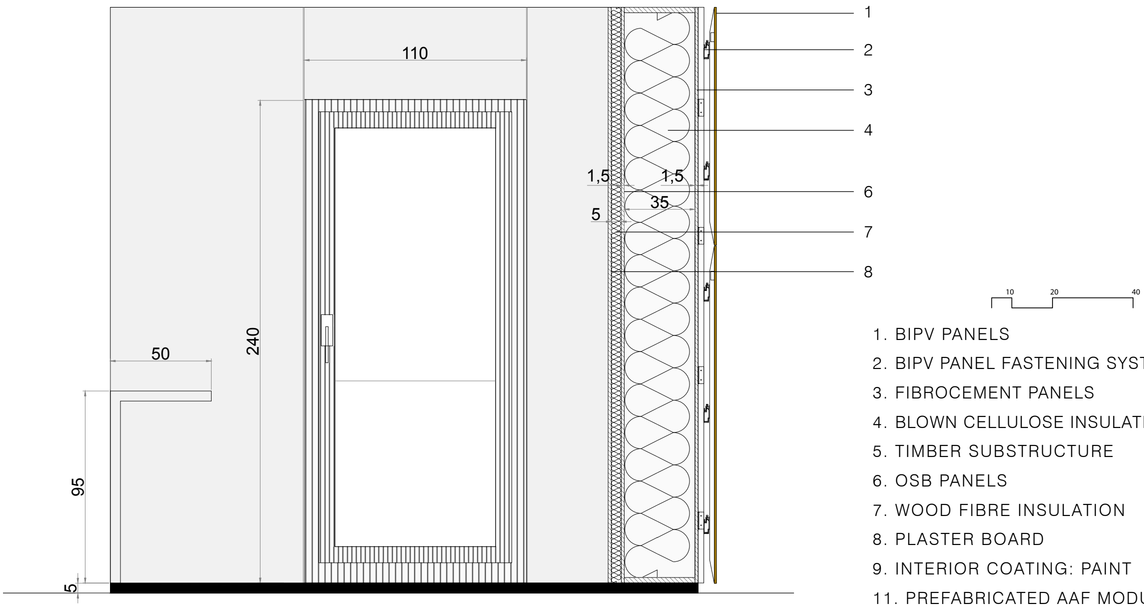
Figure 6.5
AAF demonstrator plan.

S E C T I O N   A A

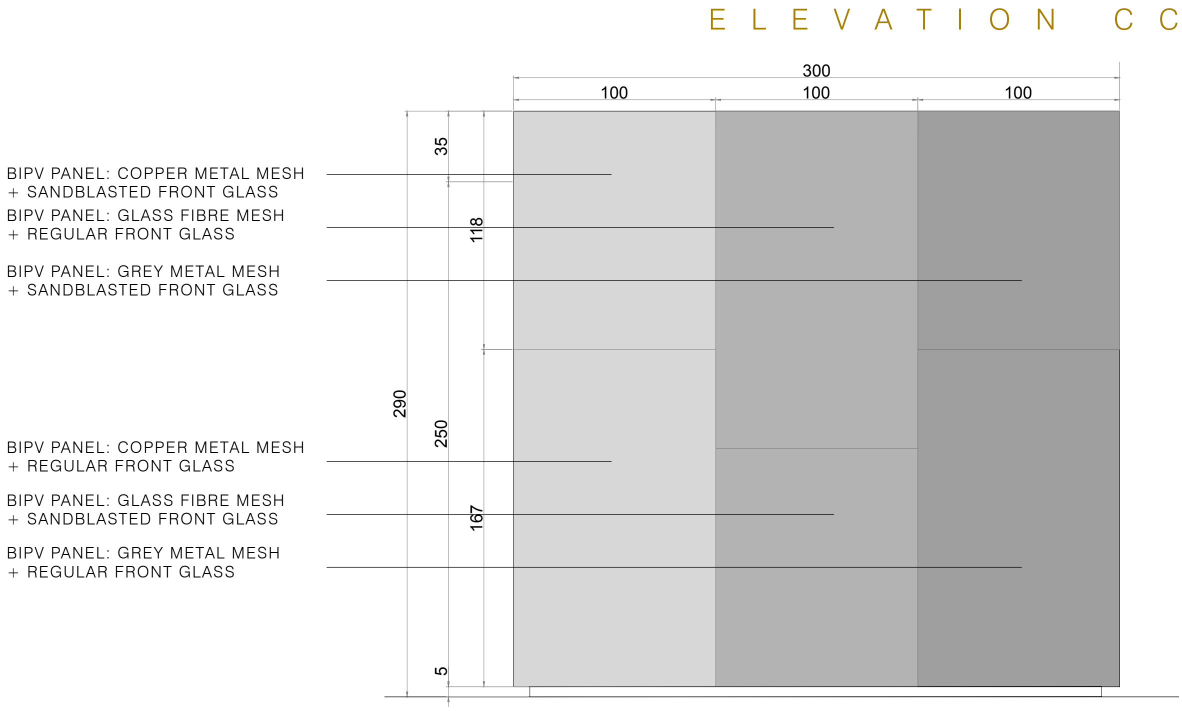
Figure 6.6
AAF demonstrator sections and interior elevations.



S E C T I O N   B B



1. BIPV PANELS
2. BIPV PANEL FASTENING SYSTEM
3. FIBROCEMENT PANELS
4. BLOWN CELLULOSE INSULATION
5. TIMBER SUBSTRUCTURE
6. OSB PANELS
7. WOOD FIBRE INSULATION
8. PLASTER BOARD
9. INTERIOR COATING: PAINT
11. PREFABRICATED AAF MODULE
12. WINDOW FAÇADE MODULE
13. TRANSLUCENT BIPV PANEL: BALUSTRADE



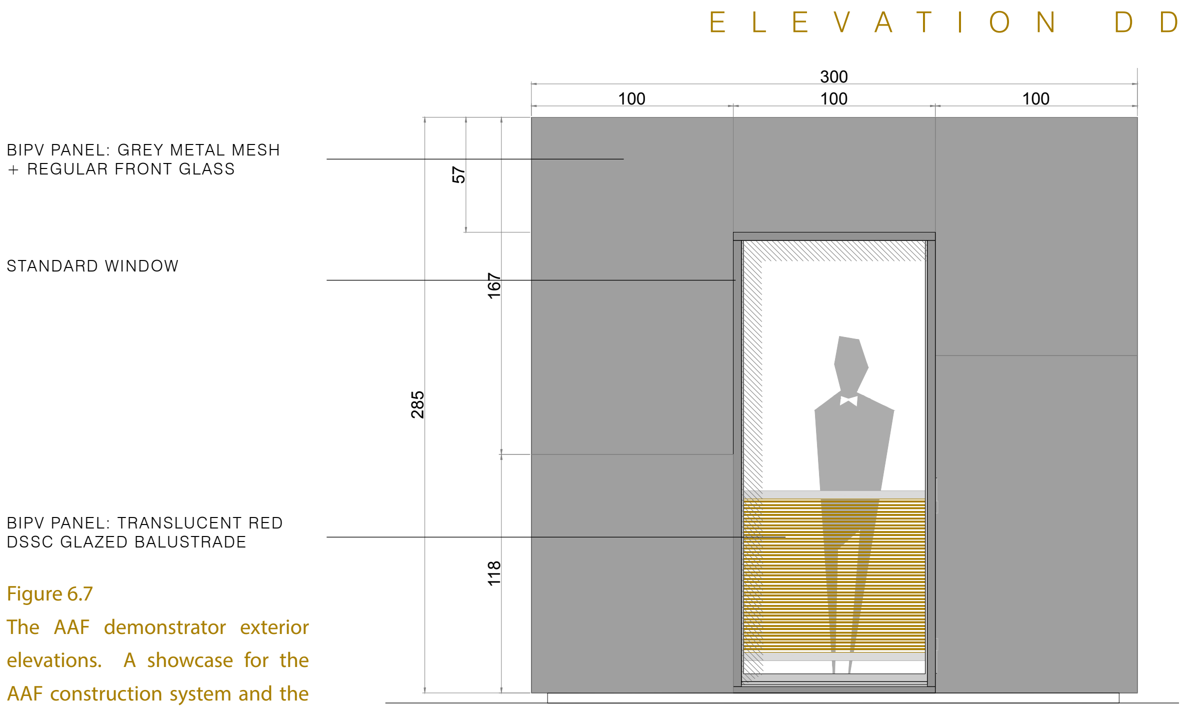
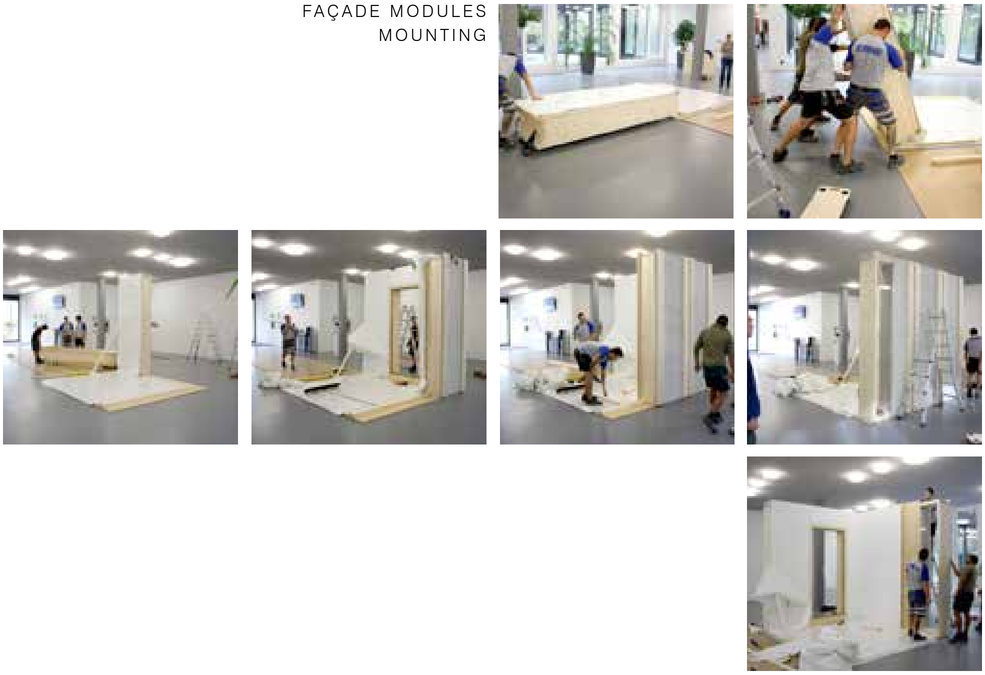


Figure 6.7
The AAF demonstrator exterior elevations. A showcase for the AAF construction system and the latest BIPV panels produced by CSEM laboratory in Neuchâtel (CH).

FAÇADE MODULE
TRANSPORTATION

FAÇADE MODULES
MOUNTING



BIPV FASTENING
SYSTEM AND PANEL
MOUNTING

FINISHED AAF
DEMONSTRATOR

Throughout the collaboration with Preface, the external OSB panel of the wooden case (number 3 in Figure 6.6) is substituted with a fibrocement panel to comply with *Protection against fire* Swiss norm [AEAI 2015]. This optimisation is implemented and has been described in Chapter 4.

Construction

Regarding the BIPV panels, the BIPV fastening system professional – SIKA – remarks that the initial fastening system design (horizontal metal profile adhered to the rear face of the BIPV panel) can cumulate water, which can rapidly deteriorate the quality of the adhesion. He proposes an additional vertical metal profile to be adhered to the rear face of the BIPV panels to avoid stagnant water [Interview with B. Leuenberger, 2017]. This optimisation is implemented and has been described in Chapter 4.

The integration of BIPV panels is expected to lengthen the construction process, according to façade construction expert: ERNE. Regarding on-site façade construction, and more particularly the duration of the façade's assembly, ERNE estimates that the prefabricated façade represented on the AAF demonstrator and illustrated in Figure 6.3 can be mounted on a construction site in three months by four workers. ERNE states that mounting one prefabricated façade module on a building takes twenty minutes. However, a BIPV façade has the particularity of electrical connections between BIPV modules. The process of connecting every module can increase the on-site façade mounting time by around 50%. Besides, electrical cabling must be handled by a specialised workforce, which also increases the construction process price. On-site work can be optimised if the design of the façade modules defines elements of large dimensions. That being said, the size of de module is mostly determined by the site and the different module transportation options [Interview with V. Cuiller, 2018].

In line with the optimisation of the construction process and cost reduction, ERNE's team suggest removing the wood-fibre insulation and augmenting the cellulose insulation layer to keep the same transmittance value. According to ERNE, this modification would optimise the prefabrication construction process regarding time and cost and would remove one layer of the wood board from the initial design, which reduces the total material quantity [Interview with V. Cuiller, 2018]. This optimisation is not implemented and is further discussed in the next section (Section 6.2.4)

Regarding transportation, it is today difficult to transport BIPV façade modules as a finished product because it includes glass elements. It is recommended to transport the prefabricated façade modules and mount the external layer of BIPV panels on-site. However, ERNE affirms that a solution to transport finished BIPV façade modules is not impossible and could be studied to find a way to protect BIPV panels from breakage [Interview with V. Cuiller, 2018].

The constructor highlights that in a prefabricated façade, there must be different connection elements between the prefabricated façade modules that might be visually apparent. This has to be considered by architects at the beginning of the façade design process so that these elements are integrated into the façade composition [Interview with V. Cuiller, 2018].

Most feedbacks have been taken into consideration in the AAF construction system optimisation process (whose results are presented in Chapter 4). The advantages and disadvantages of the application of these suggestions are discussed in the following section.

Figure 6.8
AAF demonstrator mounting process in the entrance hall of Microcity (Neuchatel, CH).

6.2.4 Discussion

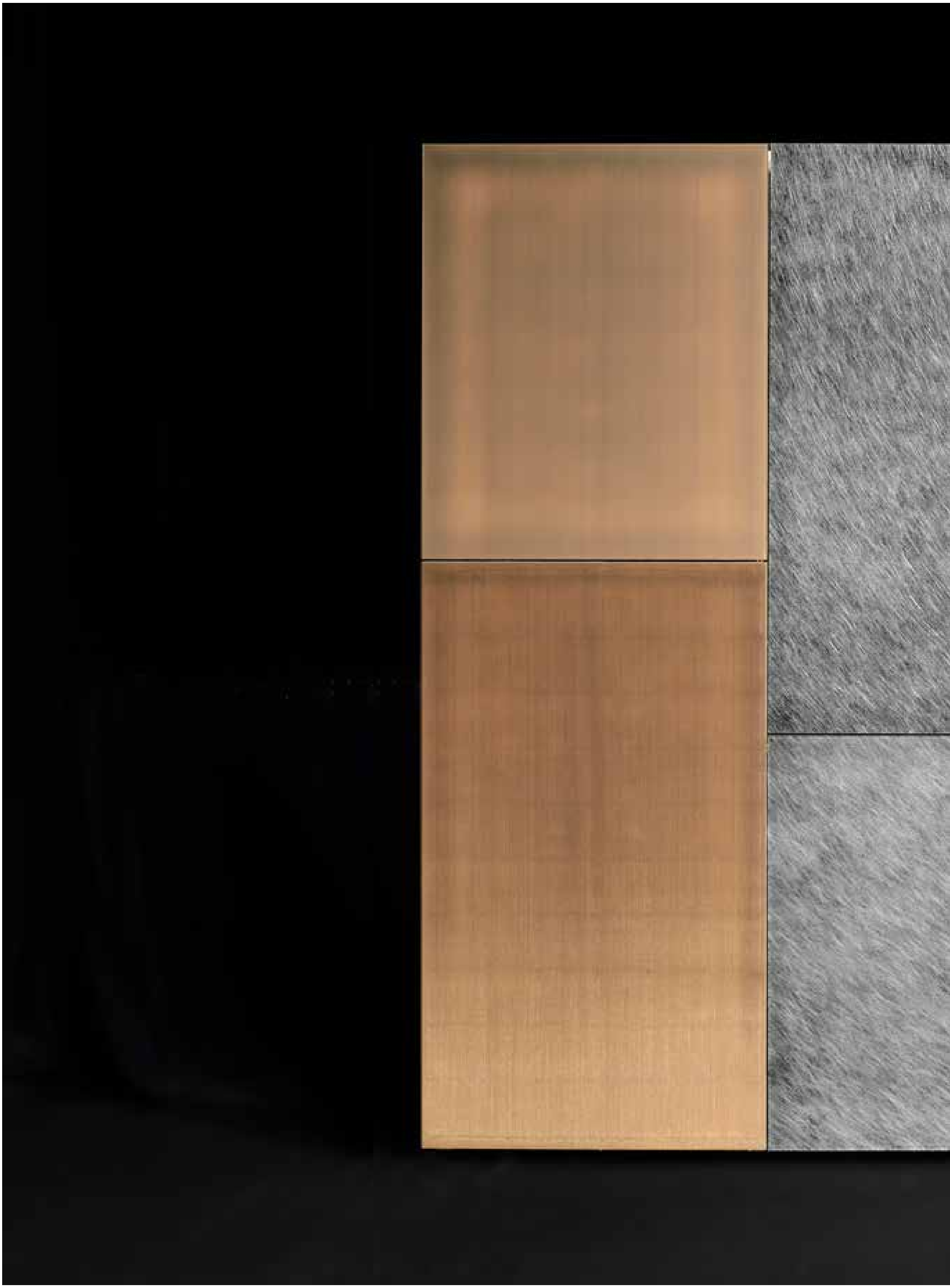
The AAF demonstrator design and construction takes the form of an enriching interdisciplinary and iterative process. For one thing, it helps during the research phase to optimise the AAF construction system (Chapter 4) thanks to a back and forth process involving all stakeholders. Secondly, extrapolated from this experience, it is realised that a balance between efficiency, cost and aesthetics must be found to design and construct BIPV façades. Ultimately, this step provides the research team with a real experience of composing and constructing a BIPV façade. These objectives differ from other BIPV façade demonstrators or prototypes, which are usually focused on the assessment of the outermost active layer of the façade (Chapter 3).

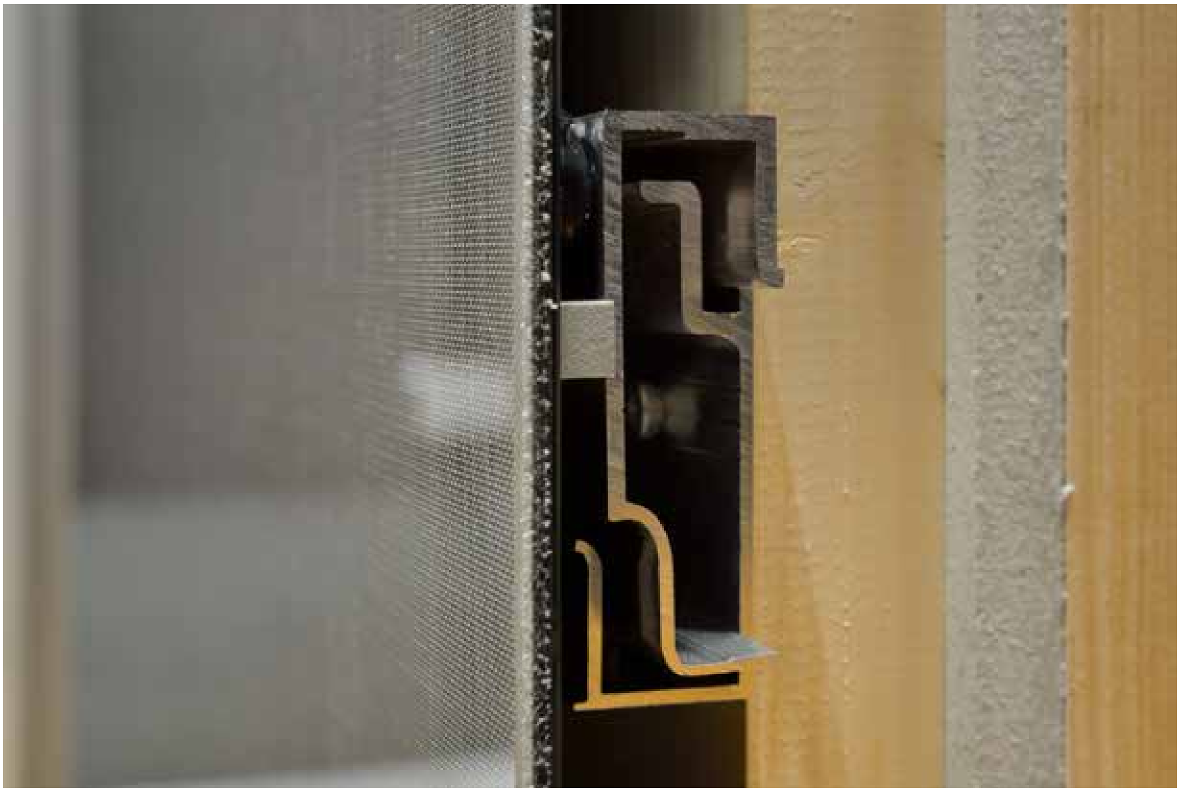
The AAF demonstrator displays the latest BIPV modules produced by CSEM, which are innovative regarding BIPV's architectural expression. This interaction, as defined in the introduction of this chapter, has put in contact the object of the research – Low embodied impact BIPV façades: the AAF – with construction professionals who have provided the research with various optimisation suggestions. The feedback gathered from the different façade construction professionals involved in the design and construction of the AAF demonstrator identify the construction process optimisation potential. At the same time, analysing these feedbacks serves as a first assessment of the AAF transfer potential towards architectural practice.

Regarding the fastening system modification proposed by SIKA, it has been integrated as illustrated in the AAF construction system presented in Chapter 4. This modification increases the final material amount of the construction system but is considered necessary to optimise the durability of the active façade cladding.

The timber construction company suggests the simplification of the double-layer insulation to reduce construction costs and times. However, this modification entails three main disadvantages. The first one is a decrease in the acoustic performance of the façade system, which is based on the different acoustic resistances of the 3 different boards (plasterboard, OSB and wood-fibre cement board), as well as on the sound resistance qualities of the different thermal insulators (wood-fibre and cellulose) [Herzog *et al.* 2004]. The second disadvantage is the reduction of the interior use flexibility. By removing the wood-fibre insulation layer, electric and plumbing facilities are integrated into the cellulose sealed container, as they would be in a concrete wall, and therefore cannot be modified. This makes it difficult to adapt if the building user changes or interior spaces are redistributed. As presented in Chapter 3, sustainable building design must enhance flexibility to extend its lifecycle. Finally, the third disadvantage of adopting the suggestion mentioned above is the increase of the thermal bridges generated by the wood façade vertical substructure. Thermal bridges are minimised in the current AAF construction system thanks to the non-coinciding primary and secondary vertical façade substructure. For these three reasons, the initial design has been maintained. Nevertheless, this suggestion can be studied in office buildings where building services flexibility is usually guaranteed through the installation of technical ceilings or floors, although acoustic requirements remain similar to those of residential spaces [SIA 181 2006]. Eventually, the acoustic performance of the AAF must be tested and adapted to each urban context where an AAF building is designed.

Ultimately, the façade construction experts state that the construction system developed within this thesis could be incorporated into professional practices with no further complication. However, Cuiller remarks the economic factor as a potential barrier due to longer construction times and specialised workforce needed for the BIPV panels electrical connections [Interview with V. Cuiller, 2018]. As presented in Chapter 5, a long-term economic analysis must be performed to justify and find the economic advantages of designing and constructing an energy-efficient façade.





6.3. Presenting the AAF

The second interaction designed to investigate the transfer potential of the AAF towards architectural practices consists of the presentation of the AAF to different publics. The objective is to assess professional and non-professional acceptance, that is to say, their willingness to integrate BIPV and low embodied impact principles in architectural practices. This acceptance has been taken as an indicator of the AAF's transfer potential towards professional practices.

Three stakeholders' groups are selected to perform the AAF acceptance assessment. First, architecture practitioners are addressed and invited to visit the AAF demonstrator. Second, architecture experts are interviewed regarding BIPV integration and the developed AAF building scenarios. Third, a partnership with the ZHAW enables the social acceptance evaluation of the AAF building scenarios through a national online survey. We explain here the interactions with the three stakeholders' groups and present the results showing their different levels of acceptance. Afterwards, a discussion of the results brought by these three interactions is performed to measure the professional and non-professional acceptance, that is the willingness to adopt AAF design and construction practices, indicating this way its transfer potential.

6.3.1 Practitioners acceptance

The first stakeholder›s group includes architecture practitioners. As a reminder, to investigate the practitioners' acceptance, architects and other construction professionals are invited to a guided visit of the AAF demonstrator. They are subsequently asked to respond to an online survey to register their comments and opinions about the AAF. The sequence of the visits is here explained, as well as the survey methodology, followed by the presentation of the results.

AAF demonstrator visits

The visits of the AAF demonstrator are organised in two ways. First, a presentation of the AAF construction system and AAF demonstrator is carried out at the 9th edition of the Ecoparc Forum in Neuchâtel, Switzerland, which took place on September 8th, 2017. Second, individual visits are organised at EPFL, where the façade demonstrator is installed most of the time.

Figure 6.9
Forum Ecoparc 2017. Attendees visiting the AAF demonstrator.

The façade demonstrator previously presented in Section 6.2 is mounted for the first time in Neuchâtel, at the venue of the 9th Swiss Sustainable Forum: Ecoparc 2017 [Ecoparc 2017]. This edition proposes discussion topics around the solar potential of the urban context and gathers around 250 attendees [Clúa Longás *et al.* 2017; Rey *et al.* 2017]. During one whole day, forum attendees, which are mostly professionals of the building and energy industries, are guided through the design process of the façade demonstrator, as well as through its expected energy performance (Figure 6.9).

After the forum, the demonstrator is moved to Lausanne and installed in the LE building's hall, at EPFL. During the year 2018, visits are organised with different architecture practitioners who voluntary collaborate in this research step. The architecture practitioners invited to visit the façade demonstrator at the EPFL are mostly Lausanne or Geneva residents with at least five years of professional experience in building construction.

The demonstrator is shown to the practitioners, and its composition and energy performance is explained during their visit. The latter is designed to last 45 minutes, although the multiple questions and comments prolong the sessions up to one hour.

Survey

Surveys are an extended research method which is mainly used for data collection [Harrison, 2009]. In this case, the objective of the survey is to provide information, in a statistical format, about the acceptance and willingness to adopt the AAF in Swiss professional architecture practices. The way to collect this information is by asking questions of a determined number of subjects, through a survey. For that, it must include three steps: sampling, question design and data collection [Floyd *et al.* 2009].

- The *Sampling* step defines the sample frame and size. The sample frame is the set of people addressed. In this case, subjects must comply with the requirements of being a construction sector professional.

  The sample size initially integrates all the Ecoparc forum attendees. However, due to data protection regulation, only 140 attendees were contacted by email. The low response rate of the first survey (10%), provides the research with 13 completed and valid answers.

  To achieve a larger number of valid completed answers, the EPFL visits are organised, targeting a total of 50 complete and valid answers.

- The *Question Design* step defines the questions, as well as how it is administered. In this case, the survey is designed as a self-administered questionnaire sent by email. The questionnaire is designed with Google forms, and it is composed of fifteen discrete[2] and closed-end questions in French, which are translated and gathered in Table 6.1

- The *Data Collection* is computer-assisted, thanks to the survey design with Google forms that is programmed to produce statistics. This computer-assisted method enables data erasing if respondents are not included in the defined sample frame.

2
A discrete type of question is a variant of a closed end question which is anwered by yes or no [Harrison, 2009].

AAF DEMONSTRATOR'S FEEDBACK SURVEY

1 OCCUPATION

. Architect | . Urban planer
. Building engineer | . Building energy professional | . Other

. Architect	. Urban planer	
. Building engineer	. Building energy professional	. Other

2 WHERE DO YOU WORK?

. Switzerland	. Germany	
. France		. Other

3 HAVE YOU ALREADY DESIGNED / WORKED WITH BIPV FAÇADES

. Yes	. No	

4 IF NOT, ARE YOU WILLING TO?

. Yes	. No	. I don't know

5 DO YOU THINK IT IS EASY TO DESIGN / WORK WITH BIPV FAÇADES?

. Yes	. No	

6 HAVE YOU ALREADY DESIGNED / WORKED WITH LOW-EMBODIED-CARBON FAÇADES?

. Yes	. No	

7 IF NOT, ARE YOU WILLING TO?

. Yes	. No	. I don't know

8 DO YOU THINK IT IS EASY TO DESIGN / WORK WITH LOW-EMBODIED-CARBON FAÇADES?

. Yes	. No	

9 DO YOU THINK THE AAF CONSTRUCTION SYSTEM IS SIMPLE?

. Yes	. No	

10 DO YOU THINK THE AAF CONSTRUCTION SYTEM CAN BE USED IN A LARGE VARIETY OF FAÇADE PROJECTS?

. Yes	. No	

11 WHICH OF THE FOLLOWING ARCHITECTURAL REQUIREMENTS THE AAF FULLFILS SUCCESSFULLY?

. Energy efficiency	. Façade design flexibility	. Project adaptability
. Energy production	. Construction simplicity	. Urban context adaptability
. Low carbon design	. Reciclability of façade elements	. Expressive coherence

12 WOULD YOU CONSIDER INCREASING THE INITIAN INVESTMENT FOR INTEGRATING THE AAF IN A BUILDING, CONSIDERING THAT IT CAN PROVIDE 40% ENERGY ECONOMY COMPARED TO COMON PRACTICES? IF YES, HOW MUCH?

. Yes	. No	. I don't know

13 DO YOU THINK THE AAF DEMONSTRATOR VISIT HAS RAISED YOUR AWARENESS AND INTEREST ON BIPV FAÇADES?

. Yes	. No	

14 DO YOU THINK THE AAF DEMONSTRATOR VISIT HAS MOTIVATED YOU TO CONSIDER WORKING WITH BIPV IN FUTURE PROJECTS?

. Yes	. No	

15 WHICH OF THE FOLLOWING ASPECTS OF THE AAF CONSTRUCTION SYSTEM SHALL BE IMPROVED?

. Panel fixing system	. Dimensional tolerances	. Surface treatment
. Thermal insulation	. Façade statics	. Exterior aspect
. Humidity insulation	. Water tightness	. Security
. Noise insulation	. Façade total thickness	. Cost perception

Table 6.1
Set of questions of the AAF demonstrator's feed-back.

After visiting the AAF demonstrator at the Ecoparc Forum or EPFL, each practitioner receives a questionnaire, which is called *AAF demonstrator's feedback* (Table 6.1). The questionnaire is sent by email to register their comments and suggestions to optimise the construction system and to register their acceptance of the AAF. This feedback is the base to evaluate its transferring potential towards professional practice.

Results

The results of the survey *AAF demonstrator's feedback* gather the answers of a total of 50 subjects. Questions 1 and 2 have a classification purpose and ask the subjects occupation and the location of their professional practice. The occupation question (Question 1) determines if the subject is part of the sample frame or not, which resulted in all 50 valid answers gathering construction and energy professionals exclusively, with a majority of architects. The location question (Question 2) shows that 100% of the subjects develop their professional practice in Switzerland.

Question 3 to Question 8 are discrete questions. Questions 3 and 6 allow to determine that 32 out of 50 subjects have never worked or designed a BIPV façade, and 34 out of 50 subjects have never worked or designed a low embodied impact façade. Among those subjects who have never designed or worked on BIPV façades, 60% of them are willing to do so in the near future (Question 4). Regarding those subjects who have never designed or worked on low embodied impact façades, 50% of them are willing to do so in the near future (Question 7). In addition, 53% and 55% of the subjects find that it is not complicated to design either BIPV façades or low-embodied-impact façades, respectively (Questions 5 and 8).

Questions 9 and 10 refer to the construction system presented on the AAF demonstrator. Among the subjects, 86% find that it is a simple façade construction system (Question 9). 86% of the total respondents also believe that the AAF can be integrated into a large variety of façade projects (Question 10).

In Question 11 of the questionnaire, a list of façade requirements is provided to the subjects, who are asked to indicate which requirements among the list are successfully met by the AAF (Figure 6.10).

The energy production requirement is successfully met according to 92% of the subjects. Similarly, 80% of the subjects affirm that the energy efficiency requirement is also successfully met. Concerning the embodied energy of the system, 68% of the subjects appreciate its low embodied carbon design, and 56% finds that the façade components can be reused or recycled. Regarding façade design concerns, 70% of the subjects approve the expressive coherence of the façade design proposed on the AAF demonstrator, and 64% believe that its construction system can be integrated into different building projects. However, only 38% believe that it has a flexible construction system which allows the design of different façades, and only 44% believe that the AAF can be integrated into different urban contexts.

Question 12 refers to the cost of the AAF and asks the subjects if they would consider an increase of the façade's initial investment, knowing that the upgrade entails an energy economy of around 40% if compared to common practices. 66% of the subjects would accept a higher price for the AAF, 5% would not accept an increase, and the rest (29%) does not know whether they would accept or not. Those subjects who accept a higher price for the new façade are

FAÇADE ACHIEVEMENTS

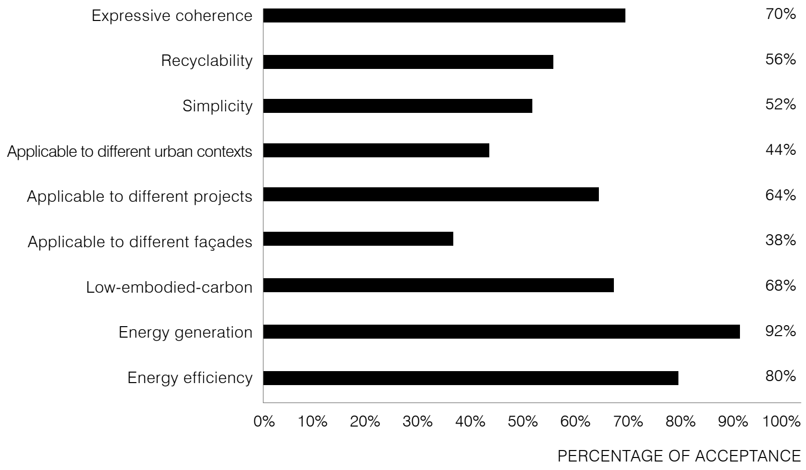


Figure 6.10
Façade requirements successfully met by the AAF.

FAÇADE COST INCREASE

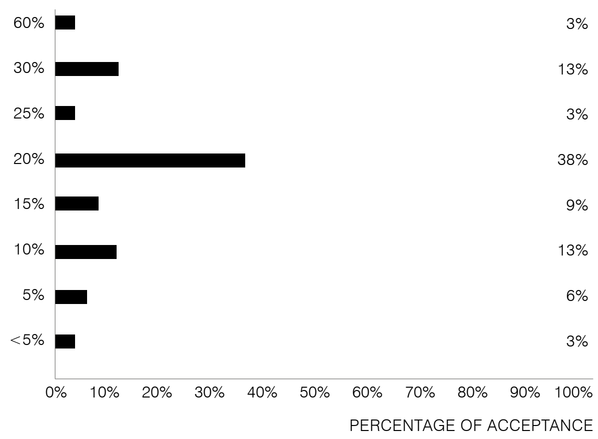


Figure 6.11
AAF price increase acceptance, compared to common practices.

FAÇADE IMPROVEMENTS

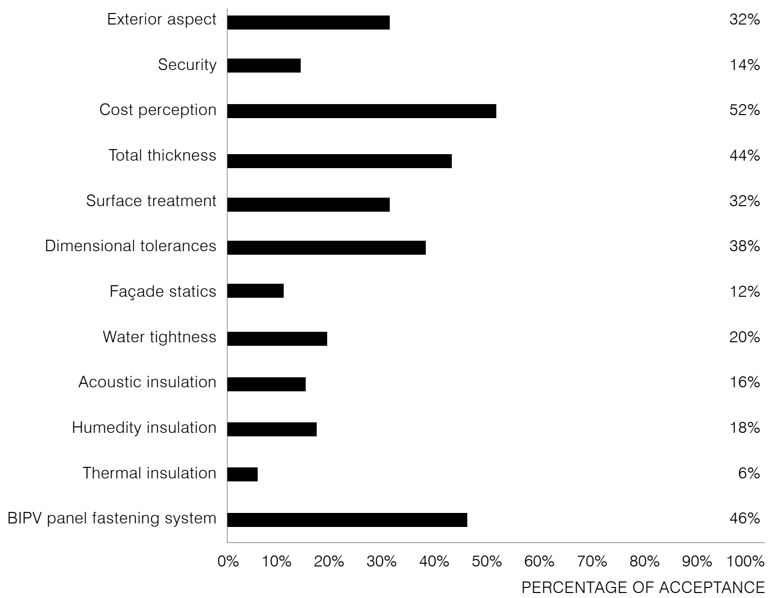


Figure 6.12
AAF construction aspects to be improved.

then asked what would be an acceptable price increase. The range of different price increase acceptance is displayed in Figure 6.11. It shows that 19% would accept a cost increase higher than 20%, 38% would accept a cost increase of 20%, and 28% would accept between 5% and 20% cost increase. The rest of the respondents accepts less than 5% cost increase.

Questions 13 and 14 ask the subject to evaluate the impact of the AAF demonstrator visit on his or her acceptance and willingness to adopt the AAF and work with BIPV façades. 94% of the subjects affirm that the AAF demonstrator visit has increased their interest in BIPV façades. Similarly, 94% affirm that the visit has motivated them to consider working with BIPV façades in future projects.

Question 15 asks subjects to indicate on a list of façade design and construction issues those to be further developed an improved. This question is very similar to Question 11 but is formulated in the opposite way. While Question 11 asks which requirements are met, Question 15 asks which issues need to be improved. It has been designed as such to maximise the AAF optimisation potential. The answers are presented in Figure 6.12 and show that 46% of the subjects consider that the panel fixing system must be improved. Half of the respondents (52%) also believes that the façade cost perception is too high. 44% considers that there is room for improvement in the total façade thickness, which has been recurrently commented to be too thick during the practitioner's visits.

Regarding insulation, only 6% of the respondents feel that thermal insulation must be improved, 16% suggest an improvement of the acoustic insulation, 18% suggest an improvement of the humidity insulation and 20% suggest an improvement of the façade's water tightness. Concerning dimensional tolerances, 38% of the subjects consider that they are not optimal. Façade statics and security aspects have received 12% and 14% of the participant's critics, respectively. Ultimately, 32% of the subjects consider that both the AAF's surface treatment and the AAF exterior aspect can be improved to achieve an optimisation of the AAF.

At the end of the questionnaire, subjects are asked to leave their comments for the optimisation of the AAF. Most comments concerned the façade's price and proposed a financial study regarding the energy output of the BIPV panels to justify a higher initial investment.

The BIPV panel fixing system has also been discussed in the comments section. Some practitioners are concerned about the compatibility of the proposed system with fire regulations and proposed to substitute the adhered solution for a mechanical one. It was also proposed that regarding the fastening system, low embodied impact principles shall be left aside in order to optimise the construction process. This implies incorporating long sections of metal profiles instead of punctual ones, which facilitates the installation but increases the carbon footprint of the system.

Regarding the proposed insulation, most practitioners are concerned about its consequent façade thickness. It is proposed to continue studying different low embodied impact alternatives to minimise the insulation layer thickness.

The comments showed a general interest in studying the application of the AAF to façade renovation projects. Indeed, AAF demonstrator visitors saw great potential in incorporating the AAF to old buildings to improve their energy efficiency. Such an option would involve the adjustment of the prefabricated module dimensions to each particular renovation project.

In addition, several remarks and suggestions were made about the BIPV panels. They are gathered here under their main concern:

Scale: The copper filtered BIPV panels have the smallest metal mesh, which seems too small to most of the demonstrator visitors. They stated that the mesh scale might be appropriate for a BIPV panel sample, but at the demonstrator scale, it looks too dense. Consequently, the texture cannot be appreciated from about 5 meters away, losing much of the expressive quality of the material itself, the brightness and reflections. The grey metal mesh scale has been considered appropriate for the demonstrator scale, although many respondents proposed to study a larger scale and to analyse its expressive quality from 20 meters away, which would better correspond to the relationship with façades in an urban context.

Transparency: It was suggested to eliminate the black rear sheet to allow a certain translucency of the panel. This would show the different façade panes highlighting the façade depth, augmenting the design possibilities of an active façade cladding.

Integration: Some practitioners expressed their interest to see examples where traditional façade claddings and the AAF cladding are combined. This would enable the study of partial active integrations, which would lower the initial investment.

Variety: Without exception, the practitioners found the proposed texture solutions very interesting, and most of them asked to develop the filtered layer further to enlarge the variety and expressive possibilities of BIPV.

Globally, practitioners had positive attitudes towards the presented AAF demonstrator. It is worth mentioning that some of them have requested additional information and details to implement the AAF principles in their architecture competition proposals. The visits and survey results are here discussed and assessed regarding the practitioners' degree of acceptance.

Results in discussion

The practitioners' acceptance is discussed and assessed following the AAF demonstrator visits and the results of the survey.

As it has been registered in the online questionnaire, the survey reflects a high transfer potential of the AAF to professional practices based on the increasing interest of architects on BIPV. However, we notice a lack of experience among practitioners directly related to the lack of knowledge barrier presented in Chapter 3. Besides, some technical concerns need to be improved, tested or better explained to enhance the transfer potential.

Regarding cost concerns, Section 5.4 contains the required information to evaluate the possibility of integrating the AAF into a residential building. This section aims at solving most questions regarding BIPV costs, including both initial investment and economic performance through the system and building's lifespan. It is worth noting that a large majority of practitioners would accept a façade cost increase to integrate BIPV, according to the survey results, of at least 20%.

The BIPV panel fastening system is slightly modified from the façade demonstrator design to the final AAF construction system. Practitioners' comments, as well as the construction process of the AAF demonstrator (Section 6.2), help to improve the final design (presented in Chapter 4) within an iterative design process. The final design has longer metal profiles to optimise the construction process and incorporates additional vertical profiles to minimise the fastening system deterioration due to water stagnation.

The AAF construction system is initially designed for new buildings, although its constructive solutions can easily be adapted to existing buildings to improve their energy performances with active renovation projects. In this case, energy evaluations must be performed, adapting the new building scenario to an existing building scenario. Existing buildings have lower energy performance systems with varied embodied impacts, which notably affects the building's energy balance.

Regarding the different comments about the BIPV panels and their textures, a new grey metal mesh filter on a double scale is proposed to BIPV producers to study the effect from 20 meters distance. A better appreciation of the vibrant reflections and the texture itself is expected. The actual mesh scale has a uniform appearance from a twenty-meters distance, loses the vibrant reflections which characterise the metal mesh filter.

Ultimately, the visit of 50 practitioners has helped to optimise the AAF construction system as well as to assess its transfer potential towards architectural practice. This potential is enhanced by the high level of interest among practitioners. At the same time, this knowledge transfer can be slowed down, mainly due to inexperience and cost concerns.

6.3.2 Experts acceptance

The second stakeholders' group include architectural experts. Their acceptance, that is to say, their willingness to integrate the AAF in their construction practices is a valuable indicator of the architectural quality of this research's output, and by extension of its transfer potential. Furthermore, considering the experts' point of view and suggestions is another occasion to improve the AAF's design. Ultimately, this interaction tests the accordance of the work developed in this thesis with today's design and construction practices in Switzerland. In order to gather all this information, personal interviews with experts have been designed and organised. The selected experts are here presented, followed by the structure of the interviews and the results.

Experts

Interviewing experts as a research method is an efficient tool to explore expert knowledge and to collect data [Bogner *et al.* 2009; Meuser *et al.* 2009]. Defining who can be considered an expert depends on the research focus and is defined by the researcher interests [Meuser *et al.* 2009; Pfadenhauer 2009]. In this case, the criteria established is the architect's professional experience in constructing collective residential buildings, the quality of their work recognised by architecture awards and their publications. A total of five architecture offices are selected to investigate the expert's willingness to integrate the AAF in construction practices (See Appendix A.3 for details).

Interviews

Among the different existing types of interviews, the one performed in this research phase is designed as a *systemizing expert interview* [Bogner *et al.* 2009]. It focuses on obtaining knowledge from experts' experience, derived from practice [Gläser *et al.* 2004]. Experts' work is the object of the research rather than experts themselves, who are considered informants.

Interviews are intended to reconstruct an expert's knowledge [Pfadenhauer 2009] and have been designed as a combination of an unstructured and structured interview [Young *et al.* 2018]:

The first part is an unstructured interview guided by the presentation of the AAF's construction system design process and its implementation into the AAF building scenarios. This part is similar to a project critic session, with a conversational style, more than a question-answer style. The expert is encouraged to critic and comment on the research's design output to register his opinions that are later considered to optimise the AAF design.

The second part is a structured interview based on a fixed set of questions, which are the same for all experts to allow comparison. These questions focus on evaluating the AAF building scenarios presented in the first part of the interview. They also aim at assessing the transfer potential of the AAF towards architectural practices through the expert's acceptance. The latter refers to the accordance of the AAF building scenarios with Swiss contemporary construction design and the experts' willingness to integrate the AAF in their architectural practice.

It is important to note that the results of the Quantitative assessment (Chapter 5) are not presented to the experts in these interviews, because Phase II and Phase III of the research were developed simultaneously.

The questions relating to the AAF building scenarios are:

- Do they represent contemporary collective residential building design practices in Switzerland?
- Do they show that most contemporary collective residential buildings can be designed with active façades, meeting current architectural trends?
- Do they show how BIPV can be incorporated as a real construction material, regarding façade composition?

The questions relating to the transfer potential towards architectural practices are:

- Do you think the AAF can optimise the architectural process of designing an active façade to comply with new energy regulations?
- Do you think that this material can help fill the gap between technology and architecture?
- Has this presentation increased your awareness of and interest in BIPV façades?

The selected offices are contacted to invite their founders or associates to participate in this research process. The interviews are conducted essentially between November 2017 and July 2018. They were conducted either in French, English or Spanish and for reasons of consistency, experts are referred to as Expert A-E. Further information about the experts can be found in Appendix A.3.

All interviews were designed to last around one hour. They were audio-recorded and later transcribed and analysed. The following result section includes the main comments and output of the surveys.

Results

As a reminder, all interviews start with a presentation of the AAF (Chapter 4), which is followed by two sets of three questions. The six questions are answered by the experts and motivate comments and open discussion topics, which are summarised in the following paragraphs.

All experts respond positively to the first question, meaning that they agree that the building scenarios presented in Chapter 4 represent the contemporary collective residential building design practices in Switzerland:

> Expert A adds to his affirmation that the developed building scenarios correspond to a good standard architecture with a large aesthetic potential. He recognises a careful work of façade composition regarding proportions, colours and textures. In his opinion, the current trends of façade construction and its architectural expression approach the concept of skin. This means that only Group 4 of the façade classification presented in Section 4.2.1.1 is truly contemporary, because it defines a building skin as a unified coat, representing the continuity of the insulation system. Expert A states that the other façade composition groups are an aesthetic inheritance of modern architecture, where the expression of horizontality corresponds to a predefined design, rather to the veracity of the façade construction. *Today, Le Corbusier's domino structure is completely coated with insulation, representing the horizontal slabs on the facade is a mere aesthetic intention, although this aesthetic intention is still valid.*
>
> Expert B describes the building scenarios presented in Chapter 4 as *very Swiss*. However, he points out that the sizing of the building proposed can largely vary depending on the location.
>
> Expert C agrees that AAF building scenarios are adapted to the current swiss architectural design trends. However, regarding the proposed façade composition classification presented in Section 4.2.1.1, he suggests a modification: Façade composition groups 1 *(Slab to slab*) and 2 *(Total storey)* could be the same because they both highlight the horizontal slab. Expert C states that the dimension of the slab highlighting element is secondary. He states that architects can design façades defining a monolith, which corresponds to façade group 4 (*Total volume*); they can design a façade highlighting horizontality, which corresponds to group 3 (*Balustrade*); and they can design a façade based on a structural grid, which corresponds to both groups 1 and 2.
>
> Expert D and Expert E also agree to the question, although Expert E specifies that the building scenarios do not represent his work. He states that in his architectural practice, he seeks to avoid falling into generalities to keep away from architectural monotony. In a like manner, he states that the fact that the building scenarios correspond

to a large percentage of the building project has some construction advantages, but they might have many aesthetic disadvantages when considering a monotonous urban context.

Most experts agree with the second question and affirm that the AAF building scenarios show the potential of contemporary dwellings to become active. There are, however, some remarks:

Expert A brings up again the idea of skin: a multifunctional active skin that can gather all the technique with which architects can decide how much of this active skin they want to integrate into their designs.

Expert B calls attention to the fact that even if the building scenarios have active façades, it does not mean that they optimise BIPV efficiency, as it would be on roofs.

Expert E points out two issues: the issue of homogenization of the urban space and the issue of BIPV efficiency in non-optimal orientations. First, he claims that the available BIPV systems on the market are very similar, which means that integrating these systems in all new buildings could have a negative impact on the urban context, defining monotonous spaces, as Expert E claims in the previous question. Second, he is concerned about the reduced energy output of vertical BIPV panels.

The third question refers to the potential of BIPV to be used and incorporated as a real construction material.

Expert C states that that BIPV can be integrated into construction practices as shown in the building scenarios. Although in his opinion, BIPV is a material that has not found its architectural expression yet. That is to say; the proposed strategies incorporate BIPV in a similar way as other existing construction material. However, Expert C proposes to search deeper into the nature of BIPV to find its particular architectural expression. BIPV has properties that other construction materials do not have: it generates energy. This energy generation is directly affected by the way BIPV is integrated into the building and, according to Expert C, this condition should determine its architectural expression.

This discussion with Expert C is further developed to the point that he proposes that active building morphology, active building typology, and even interior housing distribution should be re-thought to adapt its architectural expression to the *Building 2.0* – as he calls it – an active building that optimises the use and generation of energy. He also suggests that new forms of social interactions within a residential building might appear as a consequence of this optimisation of the building's energy balance.

The fourth question refers to the energy transition context and evaluates the potential of the AAF to optimise the architectural process of designing an active façade, complying with new energy regulations. It has been agreed and discussed by the interviewees:

Expert B describes this research design output as a catalogue of ideas showing the design potential of BIPV. He finds it useful to provide architects with an overview of different BIPV systems, their efficiency, and their façade integration potential. In his opinion, integrating the AAF simplifies the design process of an architect who is not experienced in energy-economy building design strategies and can help to comply with new energy regulations.

Expert D states that the AAF itself cannot help to comply with new energy regulations. It needs to be provided with a set of data, including the quantitative energy evaluation as well as information about the different façade orientation's performance. With all these data, the architect can integrate the AAF construction system in his design process, optimising both the costs and the building's energy balance.

Expert E finds that the total thickness of the AAF is a problem regarding the final economic performance of the building, mainly because we are working with residential buildings where costs are controlled, and budgets are usually limited. However, he believes that the AAF shows the potential of BIPV integration.

The fifth question has raised contrary opinions among the respondents, some of them believe this research can help to save the gap between technology and architecture, and others believe that other issues need to be taken care of to achieve this goal:

Expert A states that bridging the gap between technology and architecture is the most significant achievement of this research. He highlights how this research manages to produce good architectural references integrating the latest BIPV technology. He states that the choice of integrating BIPV could become an aesthetic one. According to him, BIPV expressive quality is no longer a restriction but open the door to create new and different building designs, more appropriate to contemporary construction practices.

On the contrary, Expert B says that this research is not enough. He states that every project requires numerous energy efficiency simulations to enable a comparative analysis of the different façade design options. According to Expert B, it is this kind of design processes, which integrates quantitative analyses, that can help bridge the gap between technology and architecture.

Expert C is sceptical about this research contributing to bridging the gap between architecture and technology. For him, the main issue is the high cost of the technology, which he defines as the real gap between architecture and BIPV. He explains that, especially in residential buildings, the high cost of a construction material determines if it can be incorporated into the design or not.

Expert D states that the material presented throughout the interview can help to bridge the gap between technology and architecture. However, he comes back to the need for extra technical information: a complete cost analysis of the different façades as well as the economic savings that entails the BIPV energy generation.

Expert E states that this research, through architectural design, has turned BIPV from an independent technology to integrated construction material. Hence, he agrees that this research has the potential to narrow the gap between technology and architecture.

The last question is directly addressed to the experts and asks if the presentation has increased their awareness of and interests in BIPV façades. Answers are varied, but mostly positive:

> Expert A, C D and E affirm that their interests and motivation to integrate BIPV in future projects have increased through the study of the AAF. However, they state that the lack of clients willing to pay for it is the main barrier blocking their willingness.
>
> Expert B explains that he has already worked with BIPV façades, and in most cases, the high cost of the technology is the reason why the client rejects the proposal of designing an active façade.

Globally, the expert's interviews brought constructive feedbacks about the AAF in general and, more specifically, about their willingness to integrate the AAF in their construction practices. In parallel, some concerns were highlighted, such as BIPV costs and design possibilities. The interview results are discussed more in detail in the following paragraphs and assessed regarding experts' acceptance.

Results in discussion

The experts' acceptance is discussed and assessed following the results of the interview.

Different professional profiles can be distinguished from the analysis of the various responses, from Expert B who has already experience with constructing BIPV façades to Expert D, who is more interested in achieving passive energy savings rather than integrating active energy generating systems in his designs.

There are four points to be highlighted and discussed from the results of the expert's interviews. First, the topic of monotonous architecture, which has been brought up twice by Expert E; second, the AAF energy performances, which has been referred to by Experts B, C and D; third, BIPV costs, which concern specially Experts B, C and D; and fourth, BIPV expression as a construction material which has been deeply discussed by Expert C.

Monotonous architecture. Expert E states that architectural uniformity can lead to monotonous urban space. He adds that the use of the same or similar materials can have a negative impact on urban space. However, different points of view can be found. Many urban regulations are precisely focused on maintaining a certain degree of architectural uniformity in the urban space: building alignments, material uniformity, windows dimension, even some roof shapes can be pre-determined by some regulations, and the resulting urban spaces have an indisputable architectural quality [Ayuntamiento de Madrid 1996; Commune de Val-d'Illiez 2018; Conseil de Paris 2018].

AAF energy performance. BIPV's energy performance issue is addressed from two different perspectives: first, Expert B affirms that the energy efficiency of BIPV is not optimised when integrated into a façade. However, as discussed in Chapter 5, current practice buildings cannot reach SIA2040's limit values by integrating PV exclusively on the roof. For this reason, even if BIPV efficiency is lower when integrated vertically, BIPV façades must be considered when targeting SIA2040 energy efficiency limit values. In addition, façade integrated BIPV is not determined to be always vertical; architects must define both BIPV system orientation and inclination throughout the architectural design process of the building and specifically of the façade.

Second, Experts C and D refer to the need to provide a quantitative assessment of the BIPV's energy performances, to prove the applicability of the AAF and to increase interest among architects. This information, although not presented to the experts because of its simultaneous development, has been presented in Chapter 5. The quantitative assessment results should be presented in order to judge their relevance in proving and fostering the applicability of energy-efficient façade design into professional architectural practices.

BIPV costs. The costs of BIPV have been largely discussed during the different interviews. Expert B states that he has developed BIPV façades that were finally rejected due to the extra costs they entail. Expert C believes that until BIPV prices go down, the gap between technology and architecture cannot be bridged. For his part, Expert D states that even if he is very motivated to integrate BIPV, he needs a client who is ready to pay a higher price for a residential building. This financial concern is widespread among architects and highlights the main objective where BIPV industry should focus: lowering BIPV systems costs. Recent researches have demonstrated that the payback time of a BIPV system is getting shorter every year [Biyik *et al.* 2017]. In addition, Section 5.4 presents an economic evaluation of the AAF building scenarios where all of them result to be more profitable than current practices by the end of the building's lifespan. However, a significant initial investment seems to be the highest barrier to the widespread use of BIPV.

BIPV expression. Expert C has opened a very interesting topic that is explored in the last section of this thesis as the perspectives of the integration of BIPV in façades (Section 7.2). It deepens the architectural expression of BIPV as a construction material.

Five interviews are not sufficient to generalise results. Nevertheless, they are a good indicator of the transfer potential towards architectural practices. Experts seem more reluctant than practitioners to integrate BIPV, and more particularly, the AAF in their construction practices. Some of them have already studied the integration of active façades in their designs, and they have all encountered the cost barrier, which has been decisive to discard the active façade variant. This implies that more efforts on lowering BIPV costs and improving the façade cost perception are needed to increase the AAF transfer potential.

6.3.3 Social acceptance

The third stakeholders' group include non-experts. The investigation on non-experts BIPV acceptance is performed through a collaboration with the ZHAW. Indeed, ZHAW's team has identified three dimensions of acceptance: the social, the socio-political and the market acceptance [Lobsiger-Kägi *et al.* 2018b]. Throughout their research, the ZHAW's team affirms that widespread use and adoption of BIPV depends in a great manner on its social acceptance, as much as on construction stakeholder's acceptance [Lobsiger-Kägi *et al.* 2018c]. Therefore, the topic of BIPV's social acceptance is studied as a consequence of the *Not In My Backyard* (NIMBY) debate, where non-experts are in favour of renewable technologies but do not accept the installation of renewable energy systems in their neighbourhoods [Lobsiger-Kägi *et al.* 2018a; Smith 2019].

More precisely, the goal of ZHAW's study is to examine the social acceptance of BIPV in Switzerland, focussing in particular on the acceptance by the broad population and local administrations, which refers to the specific acceptance of renewable energy projects [Wüstenhagen *et al.* 2007]. To do this, they have

Figure 6.13
Images of the AAF building scenarios provided to ZHAW's survey.

SOCIAL ACCEPTANCE SURVEY: AAF RELATED QUESTIONS

1 PROTOTYPE RANKING FROM 1 TO 5

. I like it
. I really like the colour
. I really like the design
. Fits in a city center
. Fits in a traditional residential area
. Fits in a new residential area
. Fits in an old town
. It would disturb me in sight of my residence
. Fits in an industrial district
. Increases the reputation of the place
. Its environmentally friendly

2 AESTHETICS_ If the AAF building scenario is built in my neighborhood…

. Color is more important than energy efficiency
. Design is more important than energy efficiency
. Color is more important than electricity production
. Design is more important than electricity production

3 GENERAL ACCEPTANCE

. I generally support the use of BIPV in Switzerland
. I generally support the use of BIPV inmy community
. I generally support the use of BIPV in my neighborhood

4 ATTITUDES : BIPV-ENVIRONMENT

. BIPV can make an important contribution to the Energy Transition
. BIPV can play an important role in climate protection
. BIPV can play an important role on the road to CO2-free energy supply in Switzerland

5 ATTITUDES: MUNICIPALITY IMAGE

. I believe that municipalities with BIPV are perceived as role models as environmentally friendly
. I believe that municipalities with BIPV are perceived as role models for sustainability
. I believe that municipalities with BIPV are perceived as role models for innovation

6 RISK PERCEPTION

. Yes
. No

Table 6.2
ZHAW's survey questions related to AAF building scenarios.

studied the main factors influencing BIPV social acceptance in Switzerland. The most relevant factors are the perceived environmental impact, the perceived risks, the perceived impact on municipality image, the visual impact, the urban aspects, trust and costs.

ZHAW's team also studied how different architectural design propositions can affect the acceptance of BIPV. The latter task is designed in collaboration with the LAST at EPFL and integrates some of the AAF building scenarios to evaluate their social acceptance.

The collaboration between LAST and ZHAW focuses mainly on the impact of BIPV's visual aspect in social acceptance. In order to measure the level of acceptance, an online survey has been conducted with non-expert subjects. We describe here the structure of the survey, followed by the results. The discussion of the results for social acceptance is then developed at the end of this section.

Survey

An online survey is conducted by ZHAW to address BIPV's non-expert's acceptance. The subjects are recruited through an access panel provided by a market research company. The survey is intended for the German-speaking area of Switzerland to the population between 18 and 69 years [Lobsiger-Kägi *et al.* 2018a].

A short definition of BIPV is provided at the beginning of the questionnaire because subjects are not expected to be familiar with the technology. After this, respondents are confronted with five images of different AAF building scenarios (Chapter 4): 1A, 2B, 3C, 4A, and a white version of 4A (Figure 6.13). Respondents are explained that these images incorporate BIPV as part of the façades and are asked about their attitudes towards these building scenarios. Besides, it is worth mentioning that subjects are not provided with technical specifications about the AAF building scenarios' energy performances [Lobsiger-Kägi *et al.* 2018a].

Questions related to the AAF building scenarios are close-ended and have a four-degree Likert scale with labels: *Do not agree at all* (0), *Do rather not agree* (1), *Neutral* (2), *Do rather agree* (3), and *Do perfectly agree* (4) (Table 6.2). The questionnaire also addresses aesthetic-related questions which are included in Table 6.2. Additionally, technology-related regarding risk and politics acceptance questions complete the questionnaire, although they are not referred to in this section for being outside of this research framework. However, the complete questionnaire and its results can be consulted in Appendix 3 of Lobsiger-Kägi et al.'s research report [Lobsiger-Kägi *et al.* 2018a].

Results

A total of 552 subjects have responded to the survey. First, the results highlight the generalised lack of knowledge of Swiss society regarding BIPV. Only 15.4% of the respondents stated that they have heard about BIPV, and only 3.4% have actually seen it. Despite this lack of knowledge about BIPV, ZHAW researchers have detected a high average acceptance level of BIPV (average 3.6 ratings from 0 to 4), which they correlate with the level of education.

Concerning the acceptance results of the AAF building scenarios, respondents have a rather positive impression regarding the architectural expression of all of them, being rated between 2.75 – 1A – and 3.13 – 2B – from a 0 to 4 scale, being 0 the most negative and 4 the most positive. However, these results show that there is not a particular enthusiasm for incorporating this technology in buildings. Respondents seem to accept BIPV due to its *environment-friendliness look*, which was rated with an average of 3.42, although they were not informed about the building's energy performances.

Regarding BIPV colour, and against what was expected, the white variant of the 4A building scenario is less accepted – ranked with 3.08 points – than the original dark design – ranked with 3.30 points.

There is a majority of respondents in favour of the use of BIPV in Switzerland, which was rated with 3.73 points in total. However, most of them prefer that this technology is not integrated into their neighbourhood in sight of their residences – rated 2.89, which brings up the NIMBY debate previously cited. More particularly, answers show that the social acceptance of the presented AAF is higher in new residential areas – rated with an average of 3.87 points – than in historic city centres– rated with an average of 1.94 points.

Regarding risk perception, 86.1% of the respondents do not perceive any particular risk with BIPV. The remaining share (13.9%) identifies aesthetic technology-related risks, affirming that *BIPV can optically disfigure a municipality* and that *BIPV destroys the townscape*. Eventually, those who perceive risks related to BIPV incorporation in buildings are concerned about its embodied energy affirming that *BIPV manufacturing involves embodied energy*.

Globally, this survey has brought interesting feedbacks about social acceptance of BIPV and at the same time, the potential integration of the AAF in the built environment. However, we notice also some reluctance. The survey results are here discussed.

Results in discussion

Active facades' social acceptance is discussed and assessed following the results of the survey performed in collaboration with ZHAW. Globally, the survey results show that BIPV social acceptance, although rather positive, is not generalised. Based on these results, a series of actions can be considered to improve social acceptance.

Due to the critical lack of knowledge of non-experts with regard to BIPV, a first step to improve and stabilise BIPV's social acceptance would be to provide more information to the public by educating on building energy policies. According to the survey results, the most influential factor enhancing BIPV acceptance is the perception of positive environmental impacts, which should be considered in communication strategies focused on increasing BIPV social acceptance.

Results show that there is an aesthetic barrier that needs to be addressed to increase social acceptance. Some existing low-quality integrations of PV may have influenced the social acceptance negatively, making respondents reject BIPV in their own neighbourhood. For this reason, building BIPV demonstrators and BIPV pilot projects must be encouraged as good examples of architectural references with BIPV [Lobsiger-Kägi *et al.* 2018a].

In line with the previous recommendation, good architecture examples are expected to reduce the aesthetic barrier as well as to contribute to changing the NIMBY debate towards a broader acceptance of BIPV. It can be expected that neighbours shall be willing to adopt BIPV technology *in their backyard* if they see quality pilot projects.

The social acceptance results analysis indicates that there is not a generalised preference of light-coloured BIPV panels over dark ones. However, they highlight that there is the perception that BIPV has high embodied impact, which might promote the rejection of this technology.

Overall, BIPV acceptance can be considered high among Swiss citizens. This result is mostly due to its positive environmental impact perception. This factor must be integrated into BIPV communication strategies to enhance social acceptance. In parallel, pilot projects are also expected to increase BIPV acceptance. Finally, further research on BIPV's embodied impact is also required to overcome technology-risk perception.

6.3.4 General acceptance discussion

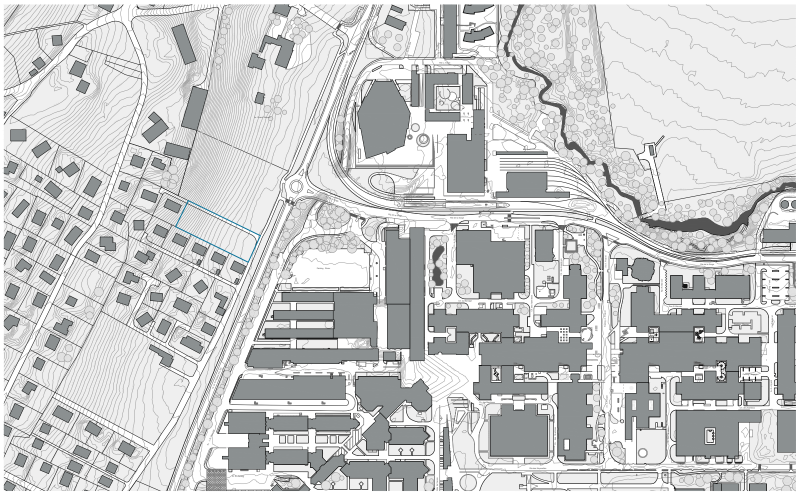
This second step of the transfer potential assessment consists of different interaction with three subject groups: practitioners, experts and non-experts. The main objective is to measure their level of acceptance, that is to say, their willingness to integrate BIPV and low embodied impact principles, more specifically the AAF construction system, in architectural practices. In this sense, this step contributes to the assessment of the transfer potential of BIPV towards architectural practices. This concluding section presents a transversal discussion of all three interactions.

The different interactions here presented reveal a particular willingness to incorporate BIPV and low embodied impact principles in architectural practices, based on the high interest registered from the architecture practitioners and experts' feedback. Similarly, the Swiss society is concerned about the problems associated with climate change and see the integration of BIPV in the built environment as a potential solution to reduce CO_2 emissions associated with the Swiss energy supply.

In contrast, the general lack of knowledge among practitioners and the existence of low-quality architectural examples make the practical integration of active energy strategies into the building context a challenging task. However, this challenge can be overcome with more architecture-oriented information as well as marketing strategies focusing on BIPV's design potential and energy efficiency virtues. For example, integrating BIPV in high-profile public buildings and awareness campaigns. Similarly, the incorporation of energy-efficient design strategies into architecture and non-architecture learning programs would increase both its knowledge and acceptance.

Likewise, the perception of high façade cost, exclusively linked to the initial investment, seems to block both architecture practitioners and experts to accept the AAF. However, most of them refer to their clients' budget as the main reason hindering the development of energy-efficient façades. Long-term economic assessments, like the one performed in Chapter 5, could significantly contribute to overcoming the high-cost perception barrier towards energy-efficient construction practices.

Ultimately, the AAF's general acceptance serves as a second assessment of the AAF transfer potential towards architectural practice. It is, therefore, a complement to the demonstrator construction step (Section 6.2) and is further discussed in the Synthesis of this chapter (Section 6.5).



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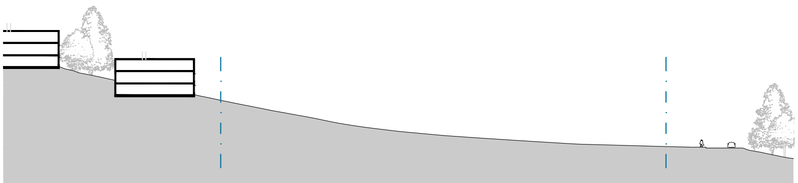

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Figure 6.14
Plans and section of the site and its urban context.

6.4. Initiating knowledge transfer through a student competition

The last step of this research's outcome transfer potential analysis consists of transferring knowledge through the organisation of an architecture competition for students. Architecture competitions are often used to generate new ideas and stimulate scientific development in the field of architecture [Lewis *et al.* 1991; van Den Berg *et al.* 2009]. According to Ebner et al. *An ideas competition is the invitation of a private or public organiser to the general public or a targeted group to submit contributions to a certain topic within a timeline. An idea reviewers committee evaluates these contributions and selects the rewarded winner(s)* [Ebner *et al.* 2009].

The organised competition is called *Active Housing* and demands for the integration of the AAF construction system into a collective residential building in Lausanne. This objective allows studying the applicability of the research outcome into collective residential building design practice. This applicability is measured through the analysis of the architectural quality and energy performance of the entries as well as through the feedback of participants and jury members.

Hence, this section presents an overview of the *Active Housing* competition design. Then, it presents the evaluation of the competition entries regarding their architectural quality, the general energy efficiency and the specific integration of the AAF. After that, the feedback of the winners and an interview with a jury member allow to further develop the analysis of the transfer potential of the AAF as well as its design limitations. Ultimately, all results are discussed in Section 6.4.4.

6.4.1 Competition design

The competition for students *Active Housing* is organized as part of the Sustainable is Beautiful student competition series organized by the Laboratory of Architecture and Sustainable Technologies (LAST) at EPFL with the support from the Swiss National Science Foundation (National research program 70), the Swiss Federal Office of Energy (SFOE), Swissolar, and the City of Ecublens [LAST 2019]. Essentially, the competition is conceived as a knowledge transfer step that aims at testing the design potential of the AAF. To this end, it focuses on energy-efficient residential building design. By doing so, the competition entries are expected to enlarge the previously presented sample of AAF building scenarios (Chapter 4).

The competition design involves defining the context, the program, and the timeline. Then, the organisers must specify the participation conditions as well as the evaluation criteria. In addition, an incentive is defined, which is, in this case, a specific prize for the winner(s).

The proposed site is part of the municipal territory of the City of Ecublens, which is suitable for the establishment of one or multiple housing buildings. The plot has a total area of 3.402 m^2 with an irregular slope. As illustrated in Figure 6.14 and Figure 6.16, it is located between an existing residential area and a large unbuilt plot, dedicated to future public utility buildings, near the EPFL campus.

The projects are required to propose a coherent and harmonious integration with the characteristics of the site and the surrounding buildings. The

Figure 6.16
Photographs of the site.

participants are asked to design one or more collective residential buildings integrating sustainable construction principles as well as proposing quality spaces. The main design requirement is that the housing project must integrate the AAF to enhance the building's energy efficiency.

In terms of architectural features, the building design process must include the following objectives:

- Integration: Development of a building volume which is adapted to the characteristics of the site
- Quality of life: Design of an inventive typology that enhances user's well-being
- Expression: Propose a concept that induces quality and coherence of architectural expression.
- Efficiency: Reduce building energy needs and its carbon footprint
- Production: Maximize the building's energy generation through the integration of BIPV into the façades

In addition, a typological diversity is desired with a majority of apartments with 2.5 and 3.5 rooms to account for the reduction in household size observed in the demographic statistics [Kohli 2008, 2017]. Ideally, each apartment benefits from a favourably oriented outdoor area (loggia, balcony, terrace or garden).

The competition development timeline is illustrated in Figure 6.15 and shows the different events organised throughout the competition period: competition design, AAF demonstrator visit, jury and award ceremony, among others.

Figure 6.15
Active Housing Competition timeline.

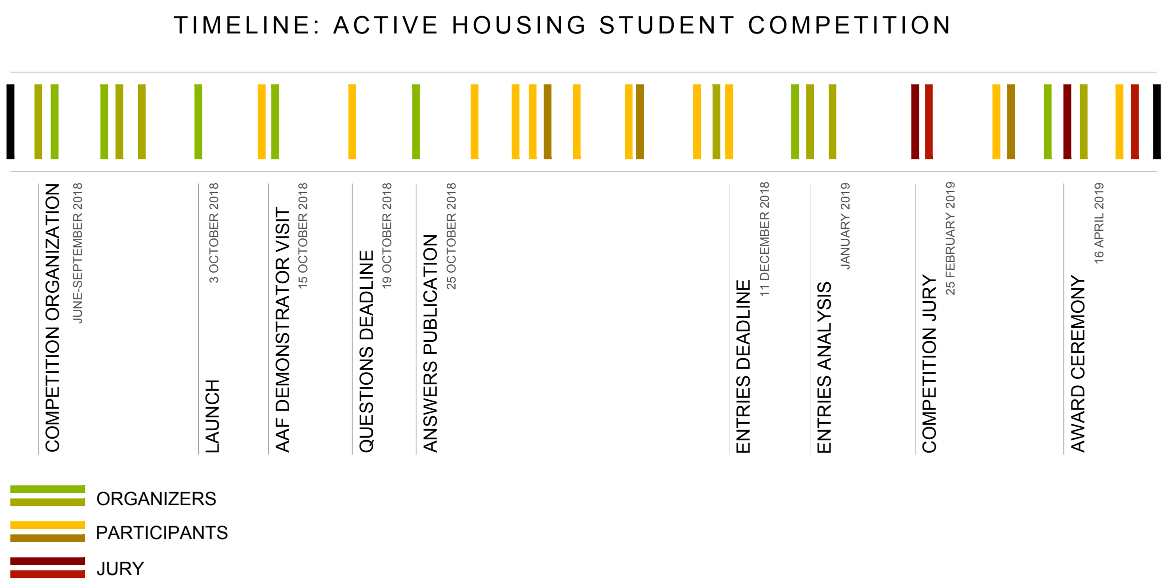
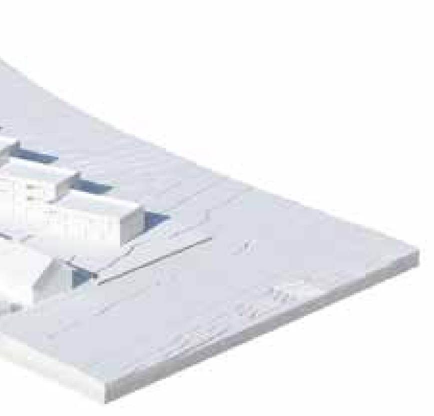


Figure 6.17
Base scale model and 11 entries.



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6.4.2 Competition entries evaluation

Initially, 61 students grouped in 22 teams signed up to participate in the *Active Housing* student competition. Eventually, a total of 39 students grouped in 13 teams delivered a project proposal[3]. Among the 13 entries, 11 include a building scale model of the proposal, shown in Figure 6.17. All entries are accepted to be evaluated by the competition jury following the objectives mentioned above.

Entries analysis

Prior to the jury's evaluation, the organisation team analyses the entries regarding energy efficiency and how it is affected by the building design as well as regarding the AAF incorporation.

Regarding the different building design and as illustrated in Figure 6.18, three different building shapes are identified: 1) the *Bar* –Projects 04, 07, 09, 11, 14, and 17; 2) the *Islets* – Projects 01, 06, 16, 18, and 19; and 3) the *Monolith* – Projects 11 and 12. Project 11 presents a combination of the *Bar* and the *Monolith* shapes and has been included in both typology classification due to the significant urban impact of the monolithic part of the building.

Most of the *Bar* projects are fractioned into two or more sections to improve the integration of the building into the urban context and the slope. The *Islets* typology propose a repetition of the same element, or a variation of it, within the proposed plot. Ultimately, the *Monolith* typology concentrates all the functional program in a unique and high building.

Regarding the building energy efficiency, Figure 6.19 displays the results of the energy efficiency analysis of the 13 entries, normalised per building ERA. This graphic displays the final energy needs of each building, the PV production and the resulting energy balance. It also displays the energy import and export as well as the building's self-sufficiency ratio.

All entries have a similar energy demand per ERA, between 53 (Pr.16) and 46 (Pr. 12) kWh/ m^2 year. The energy demand is directly related to the building compactness – expressed by the building's shape factor – which is illustrated in Table 6.3 and varies between 2.01 (Pr. 16) and 0.91 (Pr. 12).

The different entries have different PV generation which depends on the façade design of each project. The energy balance, expressed in black in Figure 6.19, represents the sum of the building's energy demand – negative value – and the PV generation – positive value. Projects with positive energy balance (4,

3
The registered rate of non-submission coincides with other ideas competitions. [Ebner *et al.* 2009] *state that on average, 68% of registered users do not submit any idea. However, most of the registered students who did not deliver state that the proximity of the competition deadline with the semester exams has resulted in a non-manageable load of work. This is the reason why the number of participants in almost half of the number of registered students.*

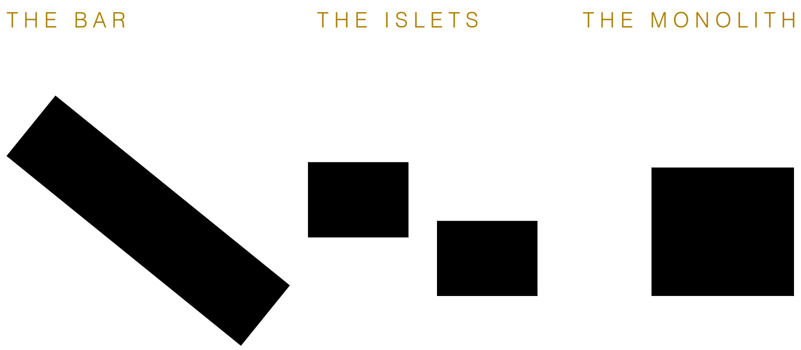

Figure 6.18
Active Housing entries: building shapes classification.

Table 6.3
Project analysis: Shape Factor.

PROJECT N°	SHAPE FACTOR
1	1,27
4	1,85
5	1,37
6	1,33
7	1,90
9	1,40
11	1,59
12	0,91
14	1,26
16	2,01
17	1,52
18	1,15
19	1,84

6, 12 and 14) are considered as positive energy buildings, that is to say, they generate more energy than what they need. However, it is worth remembering that a positive energy balance does not directly entail a 100% self-sufficiency. The incorporation of EMS can help to reach higher rates of self-sufficiency, especially in buildings with a positive energy balance, because they have large energy export values.

Through this analysis, the organisation team noticed that the AAF integration has resulted in a variety of building designs regarding façade composition, façade morphology and overall building design. This speaks of the design flexibility of the system, which is not related to a specific façade design. Most projects integrate the AAF as a uniform façade solution of façade cladding into all the building façades. However, some of the projects select only the most performant façades to integrate active surfaces, while others also add active façade accessories (balustrade railing). Moreover, two projects – projects 12 and 14 in Figure 6.17 – have further explored the design potential of the AAF by modifying the inclination of the active surfaces. The former modifies the AAF construction system by tilting each BIPV panel to 80°, adapting the panel fastening system (Figure 6.20). The second modifies the façade inclination on the upper floor, defining a 70° active surface along the whole south façade.

Entries evaluation: the jury

A multidisciplinary jury is gathered for the evaluation of the *Active Housing* Student Competition entries. This jury is composed of architects, solar architecture experts, a BIPV developer, a sustainable development expert and a representative of the City of Ecublens[4]. The meeting was held on February 25th, 2019, at the EPFL. At the beginning of the session, the jury is reminded of the design competition objectives and is illustrated with the energy efficiency

Figure 6.19
Energy analysis: Building energy needs, PV production, Energy balance, Energy export, Energy import and Self-sufficiency rate.

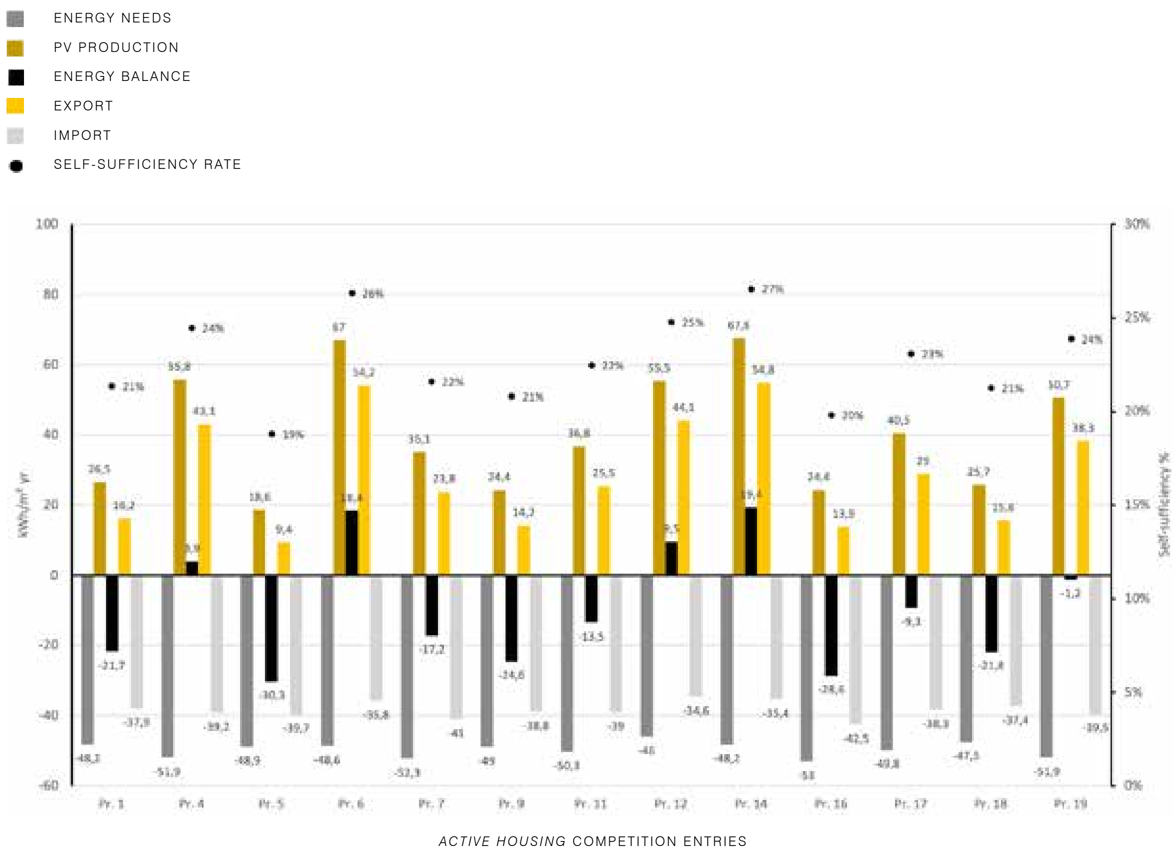

Figure 6.20
Active Housing jury: evaluation rounds and discussion.

analysis. In the first instance, the jury has to evaluate the entries according to their appropriate integration into the site and the apartment typology, then the AAF integration must be evaluated.

Each jury member has the opportunity to view the 13 entries individually. Then, the jury members collectively take an attentive tour through the exhibition hall past all the entries (Figure 6.20). At this time, six projects are discarded due to an inefficient distribution of the building program or an inadequate integration in the site and the urban context.

During the second tour, three projects are discarded due to the lack of space flexibility or the non-optimal integration of the AAF construction system. This second qualifying round brings out four projects, which are selected for the distribution of the awards. Before advancing in the process of award distribution, the jury proceeds to one round of repechage. However, no project is considered from the two previous qualifying rounds.

The jury awards unanimously project number 12 with the first prize. Three more prices are largely discussed for the other three entries: projects number 11, 17 and 18. Ultimately, the three entries are awarded 2nd ex-aequo prices – project 11, 17 and 18 –and the additional Special Prize City of Ecublens – project 18. The following paragraphs describe the first prize awarded project. Further detail on the other awarded projects and the jury's project critics can be found in Appendix A.6.

Project 12 – 1st prize

The featured awarded Project 12, represented in Figure 6.20, has a clear architectural strategy of concentrating all the program in a single monolith. This resulting volume has a shape factor of 0.91, expressing a high degree of compactness. The building volume is defined based on the study of its urban context and a geometric approach that considers the solar trajectory to minimise the north façade orientation. Three active façades are facing south, south-east and south-west and two non-active façades face north orientations. The façade morphologies incorporate loggias providing quality exterior spaces to the apartments whereas remaining consistent with the monolithic character of the building.

As previously mentioned, the BIPV panels are incorporated into the AAF with an inclination of 80°, achieved through the adaptation of the panel-fastening substructure. This inclination increases, according to the energy-efficiency calculations, by 12.4% the building's total energy output, which reaches 142 MWh/year. 21% of this energy output can be directly self-consumed, resulting in a self-sufficiency rate of 25% (Figure 6.19). Ultimately, this building has a positive energy balance, meaning that it is a positive energy building.

6.4.3 Transfer potential feedback

Following the completion of the competition, the jury and the participants are contacted in order to register their feedback regarding the transfer potential of the AAF towards professional practices. First, the four students composing the winning team (project 12) are interviewed to register their feedback on the use and integration of the AAF in their architectural design process. Second, a member of the jury, who is an architect, is contacted and interviewed to

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The jury is composed of the following experts in the field of architecture, BIPV technology and sustainable development:

Prof. Emmanuel Rey, head of the LAST Laboratory, EPFL

M. Cyril Besson, urbanist, City of Ecublens

Ms Angela Clúa Longás, PhD candidate and assistant of the LAST Laboratory, EPFL

Ms Astrid Dettling, architect, represents SIA (Swiss Engineers and Architects Association)

M. Raffael Graf, architect, represents Swissolar

Dr Maria Cristina Munari Probst, solar architecture expert, EPFL

Ms Sandra Maccagan, architect

Dr Laure-Emmanuelle Perret-Aebi, BIPV expert, CSEM

M. Philippe Vollichard, head of the Sustainable Campus unit at EPFL.

register her feedback on the AAF design results and its potential integration into professional practices.

Participants' feedback

Before getting into the heart of the topic – the AAF construction system – the winning team starts by explaining that they already had some knowledge of BIPV design due to the Solar architecture course that they attended at EPFL.

Regarding the AAF, the winning team states that it is a façade construction system that is simple to understand and flexible enough to be incorporated in the collective residential building design process. According to them, visiting the AAF demonstrator provided a better understanding of the system and its design potential.

The participants argue that the AAF has been smoothly integrated into their design process which started with 1) a building volume study to maximize its compactness, then 2) a work on the building's plan to maximize the south-oriented façade area, avoiding north-oriented façades, and 3) an adaptation of the housing program into the resulting building volume and plan.

The winners state that the most challenging part of the AAF design process is the study of the façade composition. The constraint of integrating BIPV as façade cladding panels has restricted the options of their façade design, which includes two types of BIPV panels of different dimensions. Another issue has been the AAF total thickness, which affects the architectural expression of façade openings. Indeed, openings can be perceived as deep holes in the façade surface.

Figure 6.21
Project number 12. 1st prize.

The idea of tilting the BIPV panels came as a solution to provide the façade with movement and break with the unitarian aspect of the building as a monolith. This strategy is also motivated by the fact that the inclination of the BIPV panels increases its energy output.

The participants recognise that the AAF simplifies the architectural design process when the objective is an energy-efficient façade which incorporates BIPV. More specifically, it contributes to articulate BIPV with other façade elements such as windows. They also note that the AAF construction system can be very flexible. For instance, the basic form can be modified, as they did by tilting the BIPV panels, opening a wide range of design possibilities. Ultimately, they state that the AAF notably simplifies the façade design process, contributing this way to dissolve the initial impression that designing with BIPV might be complicated [Interview with Team 12, 2019].

Jury's feedback

An architect, member of the jury, is interviewed to register her opinion of the AAF transfer potential in sight of the competition entries and their evaluation. As a first comment, she states that the AAF can be taken as an architectural reference to inspire energy-efficient façade design. However, she points out that the integration of BIPV is limited by the nature of its panels: glass. Integrating glass as a façade cladding is not always an adequate architectural solution (e.g. façades with a high risk of impacts such as schools' ground and first floors). Because of BIPV's fragile nature, a building that incorporates the AAF with BIPV as a façade cladding might be designed with a plinth. This solution, which solves at the same time the integration of the building into the irregular slope of the site, characterises many of the proposed building projects developed by the student competition participants.

Regarding the AAF design flexibility, she states that the aesthetic potential relies, like any other panel-format material, on the study of the façade modulation, the design of the panel joints, and the work of the façade details. According to the jury expert, these aspects provide the façade with high aesthetic potential, rather than choosing one construction material over another one. This means that BIPV façade design leads to a wide range of façade compositions.

Ultimately, she stated that participating in the *Active Housing* competition for students as member of the jury has raised her awareness and interest on BIPV and low embodied impact façades and motivated her to incorporate energy-efficient façades such as the AAF in her professional practice [Interview with A. Dettling, 2019].

6.4.4 *Active Housing* outline

As introduced in the previous section, the third step of the *Transfer potential assessment* consists of the organisation of an architecture student competition. The latter aims to create an opportunity to stimulate research by design and to encourage creativity among the younger generation of designers. Through this interaction, the developed research knowledge is transferred into an architecture learning process to study the applicability of the research outcome – the AAF – into architectural practices.

The competition requires the design of a collective residential building that integrates the AAF construction system. After the competition deadline, 13 projects are received and accepted for their evaluation. These 13 collective residential projects highlight the diversity of building shapes, façade morphologies and façade designs that can integrate the AAF as a façade construction system. These collective residential projects enlarge the AAF building scenario sample presented in Chapter 4 to illustrate the applicability of energy-efficient façades into architecture.

The entries propose various building shapes classified as *Bar, Islets* and *Monolith*. The project variety indicates that the AAF does not affect the building at the volume level, allowing a flexible building design. However, the feedback of the jury member brings to attention that because of the BIPV's fragile nature – glass panels – the design of a plinth or the change of façade cladding material in the ground floor is recommended. This strategy has been used by many of the competition participants. In particular, Projects 06, 07, 12, 14 and 16 display a plinth in their scale model presented in Figure 6.17, which has a different façade cladding than the rest of the façade.

The interviewed jury member also notes that, like any other panel-format material (glass, metal panels, eternit, or similar), the aesthetic potential of the façade relies in a great manner on the façade design details and not only on the construction material itself. This potential has been explored by Project 12 (winner) who has integrated the active façade cladding as façade scales providing the building with movement and additional texture.

Due to the consideration of an adequate site integration and typology over the design of an energy-efficient façade, the energy efficiency of the different entries has not affected notably the final decision regarding the attribution of the prices. However, the fact that Project 12 is a positive energy building has contributed favourably to the jury's decision to award it with the first price.

Regarding the energy-efficient façade design process, the participants' feedback highlights that the integration of the AAF into design practices simplifies the task of designing an energy-efficient façade. However, they state that visiting the AAF demonstrator helped them understand the composition of the construction system better. According to the competition participants, this visit illustrated them with the potential and limitations of designing a low-embodied-impact façade incorporating BIPV systems.

According to the participants, the façade design is in a way conditioned by the thickness of the construction system, which affects the architectural expression of the façade openings, defined as deep holes in the building skin. To solve this issue, specific façade opening details can be designed to provide the façade with a particular architectural expression. This can prevent the AAF construction system thickness from being an element hindering the façade design potential.

Ultimately, the competition aims at using critical reflection and debate – encouraged by the jury – as a means of scientific stimulation development in the field. The outcome of the student competition organisation reveals a high transfer potential of the AAF towards professional practices. This potential is based on the diversity of façade designs proposed by the students and the simplicity of the AAF building integration process, as stated by the competition winners. Although the number of entries is not large enough to affirm that the AAF can be transferred into professional practices, it illustrates the easiness of the process and the willingness of the future young professionals to adopt energy-efficient design practices.

6.5. Synthesis

The assessment of the applicability and transferring potential of the AAF towards architectural practices is designed as multiple interdisciplinary interactions of the research outcome with professional and non-professional subjects. These interactions are successive research steps that confront the AAF to various target audiences: façade construction experts, architecture practitioners, architecture experts, non-professional stakeholders and architecture students. The collective of these subjects represent the main agents blocking the BIPV widespread use due to its architectural expression issues and generalised lack of knowledge and interest barriers (Chapter 3). These stakeholders are addressed through three types of interactions: the construction of the AAF demonstrator, the presentation of the AAF and the organisation of an architecture competition for students.

The set of interactions is part of the iterative process focused on optimising the AAF design and targets as well a knowledge transfer objective. The latter entails the presentation of the knowledge developed through the research by design process to the subjects. This aims at contributing to overcome the BIPV lack of knowledge and lack of interest barriers identified in Chapter 3.

The first interaction consists of the construction of the AAF demonstrator, which confronts the research outcome with façade design experts, façade construction professionals and façade component producers. In a like manner, this interaction provides the research team with the experience of constructing the AAF and the means to evaluate the construction process, the material compatibility and the system's optimisation potential. These objectives differ from other BIPV façade demonstrators, which are mostly focused on assessing the BIPV system's performance.

The AAF demonstrator results in a real-scale three-dimensional object that can be visited and illustrates every detail of the AAF construction system and its design potential. Within an iterative process, the construction of the demonstrator enables the optimisation of the BIPV panel fastening system and allows the AAF transfer potential assessment, based on the construction practices. The professional feedback highlights that the AAF construction system can be incorporated into professional practices with no further modifications. However, a construction cost increase related to the specialised and additional workforce required to connect each BIPV panel must be considered as a barrier to the transfer towards extended architectural practices.

The second step involves multiple interactions of the AAF with different subjects to measure their level of acceptance of the AAF. The first one is the presentation of the AAF demonstrator to architecture practitioners, the second one is the presentation of the AAF construction system and AAF building scenarios to architecture experts, and the third one is the integration of a sample of the AAF building scenarios in a national survey to evaluate the social acceptance of BIPV among non-experts.

The main outcome of these interactions is the high-interest rate among professionals regarding BIPV and low embodied impact façades – both practitioners and experts. 94% of the addressed professional subjects state that interacting with the AAF has increased their interest and motivation to work with energy-efficient façades. Among their main concerns are the perception of AAF's high initial investment costs and the reduced energy performance of BIPV panels when filtered and vertically incorporated into façades. Another concern is about the social acceptance of BIPV façades that is reduced in traditional residential neighbourhoods and city centres. The latter may be related to the unconvincing architectural expression of existing PV building attached systems. To overcome these concerns, the energy and economic performance assessment presented in the previous chapter (Chapter 5) aims at contributing to improving the acceptance rate. In a like manner, the development of the AAF as a building design architectural reference targets reaching the general public to overcome the existing aesthetic preconceptions of BIPV's architectural expression.

As a limitation of this interaction, it must be noted that professionals and non-professionals have not been provided with detailed information on the energy and economic assessment of the AAF because of the simultaneous development of Phase II and Phase III of the research process.

The third interaction has been designed to confront architecture students with the AAF within the context of a building design competition. Through this interaction, the applicability of the AAF into collective residential architecture can be studied and transferred into the academic architectural practice. The knowledge transfer objective is present in all three interactions but specifically in the interaction with the architecture students for introducing the research output into an architecture learning program, fostering the knowledge transfer process.

The outcome of this interaction highlights the variety of façade designs achieved, all of them incorporating the AAF. However, some design constraints are remarked. These are the design limitations of a glass and panel-format façade cladding, which refer mostly to the fragility of the material and the need for a careful design of the façade details regarding joints and panel arrangement.

Regarding the façade design process, the competition participants remark the energy-efficient façade design simplification provided by the AAF construction system. Similarly, they praise how the AAF demonstrator can illustrate the AAF expressive quality potential.

To conclude, the above-described research steps involve interdisciplinary interactions that evaluate the technical possibility of integrating energy-efficient façade design in construction practices, its acceptance by professional and non-professional subjects, and the design complexity of the process. This evaluation result indicates a high constructive integration potential, a notable energy-efficient façade acceptance, despite its high-cost perception, especially among professionals and significant design flexibility regarding building design and façade composition.

7. Conclusion

Within an architectural approach, a thorough and original research methodology has been developed to set a solid base for energy-efficient façade design incorporating active surfaces. This methodology defines an iterative process specifically elaborated for the adopted research by design approach. It guides architects through the design of an innovative façade construction system, its performance assessment and its transfer potential evaluation towards architectural practices. Throughout this methodology, a new architectural façade has been produced with the potential of significantly contributing to bridging the gap between energy-efficient technologies and architectural practices, hence contributing to face the energy transition challenges.

The research process and outcome of the design, assessment and transfer phases motivate reflections regarding energy-efficient façade design, in particular its performances, costs and acceptance potential. Three sections structure this concluding chapter, synthesising these reflections and analysing the outcome of the different research phases. First, the research process and outcome provide a consistent and structured review of the research question, which initially motivates the current research project. In a second step, the design of energy-efficient façades is discussed to lead building construction towards achieving the energy transition objectives. Finally, general recommendations and perspectives are presented to enrich future research that might be developed in the current research context and potential follow-ups for this specific research work.

7.1 Looking back at the research question

Today, the reduction of GHG emissions is a prevailing priority to mitigate the pervasive and irreversible impacts of climate change for people and ecosystems. This challenge is addressed from all energy-consuming sectors setting the framework of the energy transition. Among energy-consumers, the construction sector is the largest in Europe, and therefore, its energy performance improvement has a significant potential to reduce harmful emissions. New and highly demanding building energy performance directives urge for profound changes in current construction practices which are currently unaddressed due to a gap identified between energy-efficient technologies and architecture practices.

Based on these initial reflections, Chapter 2 presents the research question that motivates this research, which is: *How can the architectural design of collective residential façades contribute to the energy transition?* The research by design methodology developed to answer this question involved the analysis of contemporary collective residential façades, BIPV design practices and low embodied impact construction principles. This analysis outcome defines a base for the energy efficient façade design and has led to designing the Advanced Active Façade (AAF). The latter has the potential of improving the building's energy efficiency, contributing this way to the energy transition.

The analysis of this façade's energy performance, when implemented into different building scenarios, highlighted that the potential of an energy-efficient façade relies significantly on its architectural design. To reach the energy transition objectives, advancements in energy-efficient technologies are as important as façade design regarding its composition and morphology. Looking back to the research question, it can be confirmed that architectural design has the potential to lead the development of the collective residential construction sector towards the energy transition through the integration of passive and active energy design strategies into energy-efficient façade design.

This answer relies on the façade design, its energy and economy efficiency and its transfer potential towards professional practices. The transversal analysis of these elements, which have guided the research by design workflow, allows defining the main achievements and contributions of this research as well as the remaining limitations.

7.1.1 Achievements and contributions

To bridge the gap identified between energy-efficient technologies and architecture practices, this doctoral thesis studies the state-of-the-art of passive and active energy design strategies. On the one hand, passive energy-efficient construction practices are investigated to highlight a set of low embodied impact construction principles with the potential of lowering the building's embodied and operational energy. On the other hand, current BIPV research is investigated in search of architectural approaches of BIPV façade design that can improve the building's energy efficiency when combined with low embodied impact construction principles. Ultimately, this study identifies several barriers hindering energy-efficient technologies' potential in various interdisciplinary fields: design, energy, costs, information, interest and professional experience. To overcome these barriers and enhance the building's energy efficiency through façades, a holistic architectural approach is designed: it takes a research by design methodology to produce an architectural reference that motivates energy-efficient façade design.

This holistic architectural approach is a major contribution of this work for its complex and interdisciplinary methodology that can guide architects through energy-efficient façade design. This approach presents the complete architectural process of façade design that results in the AAF development by integrating energy-efficient construction principles. Similarly, it presents a step by step analysis of its energy and economic performances. Ultimately, this holistic approach presents several interactions with multiple contexts and subjects to evaluate the AAF acceptance and transfer potential towards professional practices. This methodology can guide architects through energy-efficient design practices and may motivate them to develop new alternative energy-efficient constructive solutions.

The following paragraphs provide an overview of further achievements and contributions of this research. They are gathered under four main topics highlighting four reflections on the present research work: 1) the potential of façade design to contribute to the energy transition, 2) the need to upgrade common construction practices to reach the energy transition's objectives, 3) energy-efficient building development as a long-term economic investment and 4) the increasing willingness to adopt energy-efficient design strategies.

The potential of façade design to contribute to the energy transition

The outcome of this research highlights the significant potential of collective residential façade design to improve building energy efficiency by integrating passive and active energy design strategies.

Regarding passive energy strategies, existing researches show how reducing the thermal transmittance of the building envelope has the most significant impact on reducing the building's operational energy demand. This reduction is mostly achieved through increasing the thickness and the performance of the façade's insulating layer [Richarz *et al.* 2008; Zeng *et al.* 2017]. Due to the undesired additional embodied impacts associated with the increase of construction insulating material quantity, the present thesis has studied different low embodied impact construction principles with the potential of lowering the embodied impacts of the whole façade. These construction principles aim at compensating the additional embodied impacts associated with augmented insulating material layers or the incorporation of energy-efficient technologies into the façade like BIPV systems. Among the low embodied impact construction principles described in Chapter 3, the following are highlighted due to their relevant integration in the energy-efficient façade design process: use of natural and local construction materials, design for lightweight prefabrication, design for durability and flexible use, and design for deconstruction, reuse and recycle.

Regarding active energy strategies, the integration of solar energy systems into the building envelope has the highest potential to generate on-site renewable energy. In particular the incorporation of BIPV systems, which transform solar energy into electricity while fulfilling one or several façade functions as an integral part of it [Jelle *et al.* 2012; Reijenga *et al.* 2012; Perlin 2013]. As mentioned above, these systems entail a high embodied impact; however, the combination with low embodied impact construction principles and the consideration of its energy generation largely compensates for its embodied impacts.

Façade design affects the building's energy balance because it determines the passive design strategies to be implemented (e.g. insulation and low embodied impact), as well as the active energy strategies regarding its technology and integration. The present work has identified different contemporary façade and BIPV design aspects that affect energy-efficient façade design when incorporating BIPV systems. These are the façade composition and the façade morphology that affect the visual and functional features of a BIPV façade installation. Ultimately, architectural façade design can determine the potential of a building to reach the energy efficiency targets.

Throughout the research process, recurrent patterns of façade design have been identified when analysing the façade dimensional composition of contemporary Swiss collective residential buildings. The dimensional composition directly affects the façade surfaces available for PV integration. Likewise, the façade morphology defines specific façade areas where BIPV modules can receive better solar irradiation and avoid self-shading. Furthermore, the BIPV design practice analysis identifies that BIPV systems can be classified according to their visual features: opaque, translucent or transparent. These visual features are directly related to architectural functions that BIPV systems uptake as an integral part of the façade, which are: façade cladding, façade glazing, façade security and façade solar control.

Based on these contemporary façade and BIPV design aspects, an energy-efficient façade construction system, entitled Advanced Active Façade (AAF), has been developed, integrating both passive and active energy design strategies. The development of the AAF construction system shows that BIPV can be integrated as a real façade construction material in a low embodied impact façade substructure, fostering the building's energy efficiency.

To illustrate the potential of façade design to improve building's energy efficiency, the following paragraphs explore both the design and the energy efficiency potential of the AAF. In a first step, the design potential is explored and assessed through a critical architectural approach (Section 4.4) as well as through interactions with architecture professionals (Section 6.3). In a second step, the energy efficiency potential of the façade is explored and assessed through an energy simulation process (Section 5.3). In this step, the active façade building energy simulation results are compared to non-active façade building simulation results to judge the range of energy efficiency improvements.

To explore the design potential of this energy-efficient façade, the AAF has been implemented into a representative collective residential building project based on the contemporary façade, and BIPV design aspects previously mentioned, resulting in twelve distinct active building scenarios (Section 4.4.1). These AAF building scenarios have been presented to architecture practitioners and experts who stated that the proposed energy-efficient façades are compatible with contemporary architectural trends regarding façade design. According to their comments, it is remarked that the presented energy-efficient building scenarios correspond to *good Swiss representative architecture* with significant aesthetic potential. Likewise, the proposed energy-efficient façade solution is found to be flexible enough to be integrated into different types of façade designs, improving the building's energy efficiency (Section 6.3). To further explore the design potential of energy-efficient façades, the AAF construction system has been integrated into an architectural educational process through the organisation of an architecture competition for students (Section 6.4). The different entries propose a large diversity of façade designs which incorporate the AAF as the primary façade construction system.

To explore the energy efficiency potential of façade design, the energy performance of all AAF active building scenarios has been calculated with an energy simulation tool, enabling their energy efficiency analysis (Section 5.3). Likewise, the energy performance of the current practice variant of the same building scenarios integrating common (CP) and best-practice (BP) has also been simulated. The comparative assessment of the different building scenarios shows notable differences among their energy performances, depending exclusively on their façade design and specifically on the size of the BIPV installation that it incorporates. The incorporation of the AAF façades provides the building with minimum energy savings of 14% when compared to current-practice building scenarios. These energy savings can reach 100% depending on the façade design, transforming the building into a zero or positive energy building. The energy efficiency assessment of the different building scenarios shows that the most energy performing façade designs integrates a large BIPV installation which incorporates *High-Performance* PV technology – Tandem Perovskite – in opaque BIPV panels as façade cladding. Otherwise, the least energy performing façade designs correspond to the integration of small BIPV installations which incorporate *Market-Ready* PV technology – Thin-Film – in transparent BIPV panels as façade glazing or façade security accessories.

To conclude, the present research work has explored the potential of the façade design to contribute to the energy transition through an architectural approach. This process has highlighted that the façade has a high potential to improve collective residential building's energy efficiency through architectural design.

To do so, energy-efficient constructive solutions must be adopted among contemporary façade design practices. These solutions refer to passive and active energy design strategies which must be integrated into the architectural design process. More particularly, this research work has studied and analysed the potential of a highly-insulated, low embodied impact façade which incorporates BIPV. The combination of these energy strategies in the analysed scenarios has resulted in a notable contribution to reach the energy transition's objectives. However, this contribution strongly depends on the façade design and the active technology integrated into the BIPV system. The later highlights the weight of the architectural design process towards the energy transition of the construction sector.

The need to upgrade common construction practices to reach energy transition's objectives

The energy transition is driven by an environmental concern that directly relates energy consumption with global warming and its negative environmental impacts [Akadiri *et al.* 2012]. As a reminder, its objectives focus on improving the energy efficiency of all energy-consuming sectors focusing on the consistent use of renewable energy sources [SFOE 2014; OFEN 2018]. Regarding building's energy efficiency, the norm SIA 2040 gathers the established building efficiency targets for the year 2050 [SIA 2040 2017].

The energy performance assessment (Section 5.3) of the different building scenarios (active and non-active) underlines that contemporary non-active construction practices (CP and BP) cannot fully meet the energy efficiency targets established to reach the energy transition's objectives. The energy simulation results show that to meet SIA operational energy efficiency targets (NRPE), common buildings must further reduce their operational energy demand by approximately 50% to have a final annual operational energy demand of 23.8 kWh/m^2. This value is the energy efficiency target expressed in final energy for the Swiss context [KBOB 2016]. Regarding embodied energy, non-active buildings constructed with CP façades equally fail to reach energy transition's target values (NRPE), mainly due to the use of polystyrene as the primary insulator, which has a very high embodied impact. Buildings with BP façades, defined as timber frame façades with rock wool insulation, do reach embodied energy efficiency targets due to the low embodied impacts associated with wood. However, as mentioned above, the combined energy efficiency assessment outlines that neither CP façades nor BP façades fully reach energy efficiency target values. This finding highlights the need for further research and work on the field of energy-efficient buildings to reduce both operational and embodied energy, as it has been done throughout this research.

On the one hand, operational energy demand reduction can be achieved through the improvement of building services and building envelope's thermal performances, the control of solar gains, the regulation of the building's ventilation or the incorporation of on-site renewable energy generation systems, among others. On the other hand, the embodied energy demand reduction consists mainly of following low embodied impact construction principles for the design of each building element, such as the use of natural and local construction materials, the design for lightweight prefabrication, the design for durability and flexible use and the design for deconstruction, as previously indicated .

This research focuses on the potential of façade design to improve the building's energy efficiency. However, as contemporary building construction practices establish, the incorporation of a Building-attached photovoltaic (BAPV) roof has been simulated and assessed. The simulation results show that energy efficiency target values can be fully reached by neither CP nor BP buildings with BAPV roofs, simply because BAPV roofs do not generate enough energy to fulfil the energy demand of a multi-storey collective residential building [Verberne *et al*. 2014; SUPSI *et al*. 2015].

Aiming at finding an energy-efficient alternative to the low energy performing current façade solutions, this research proposes the AAF as a façade upgrade to contribute to reaching the energy transition targets. The combined energy efficiency assessment demonstrates that AAF building scenarios have significantly better energy performance than common practices. Regarding NRPE, an energy-efficient façade can improve the building's energy performances between 15% and 105% compared to CP. Regarding GWP, the improvement is between 19% and 52%[1]. Even though a façade upgrade can provide the building with these significant energy efficiency improvements, reaching the energy transition targets is only achieved by those building scenarios that incorporate large BIPV installations with opaque BIPV panels. Nevertheless, when assessing AAF building scenarios with BAPV roofs, all of them can reach the energy efficiency targets defined for the energy transition. The latter implies that energy-efficient façades, in particular the AAF, can be an energy performing solution to upgrade common practices and contribute to the energy transition.

To shift energy-efficient façade design towards professional practices and achieve its potential, a knowledge transfer action is required. Throughout the transfer potential evaluation, architecture practitioners and experts have been confronted with the energy-efficient façades in the context of the AAF demonstrator visit or personal interviews (Chapter 6). The outcome of these interactions confirms the lack of professional experience on low embodied impact and active façade design. This lack of experience is a barrier blocking the process of upgrading common façade design and construction practices towards the energy transition.

Furthermore, as above-mentioned, the best energy-performant building scenarios are those that incorporate opaque BIPV systems, mostly into large façade areas as exterior cladding. The façade cladding design is an integral part of the façade composition process, which is prioritarly conducted by architects. This entails that, in contrast to some façade components, such as balustrades, which can be subject of an external design by a PV expert, the design and transformation of the façade cladding into an active surface relies strongly on the architects' knowledge and expertise on BIPV technology. This BIPV knowledge, being observed as limited, defines a barrier hindering the potential of residential façades to reach the energy transition's objectives.

To overcome this barrier, architecture-oriented information, as well as didactic actions and presentations, are needed. Similarly, simplified energy simulation tools should be of great help to make architects discover the potential of active façade design.

To conclude, common practice façades require a fundamental upgrade of their energy performances to contribute to the building's energy efficiency. BAPV roofs have been demonstrated not always to be sufficient to contribute to reaching the energy transition objectives. The AAF's design and assessment show that highly insulated, low embodied impact active façades have the

1
Results for High-Performance AAF building scenarios simulation

potential to provide the building with an effective solution to reach the energy transition objectives, although in some cases, BAPV roofs are also needed. These cases are those with small BIPV installations implemented as transparent or translucent façade elements. However, due to the generalised lack of knowledge and experience among architects, further actions must be taken to foster façade construction practices upgrades towards the energy transition. In the context of energy transition, the present research shows that new approaches for integrating photovoltaic systems into the building skin open a broad range of options for combining architectural quality with the necessity to generate energy in a sustainable manner.

The energy-efficient building development as a long-term economic investment

The state-of-the-art of BIPV façade research has highlighted that, aside from the aesthetic barrier, BIPV potential is often hindered by high initial investment costs. To illustrate this, half of the architecture practitioners who have visited the AAF demonstrator (52%) are concerned about the high-cost perception of energy-efficient façades. These architecture practitioners state that a façade cost increase of up to 20% could be accepted by their clients when this increase entails significant energy savings (40%). However, the economic efficiency analysis shows that energy-efficient façades can cost up to 100% more than a current practice façade when it incorporates BIPV as façade cladding. This fact can hinder the development of active façades if the economic efficiency analysis does not go further.

The economic efficiency assessment shows that the costs of a current practice façade represent between 5% and 9% of the total construction costs (land not included). The incorporation of BIPV increases the façade's initial investment, which varies between 7% and 12% of the total construction costs, depending on the façade design. A larger investment is associated with larger BIPV installations and a larger façade surface, which relates to the building's shape factor.

According to real estate experts, investments fostering the building's energy efficiency must be analysed over the long-term because, based on the current energy distribution system, energy savings lead to economic savings with the potential of offsetting the initial investment through higher investment revenue [Rütter-Fischbacher *et al.* 2010].

Energy-efficient building's investment revenue is mostly associated with higher rental revenue, which is possible through the reduction of the building operation charges. The higher rental price plus the lower electric and heating building charges must result in an equal monthly payment for the tenant [DAEC 2015]. If the building integrates a renewable energy generation installation, as is the case of AAF building scenarios, an additional source of revenue is considered: the sale of electricity to the tenant. Throughout this research, it has been assumed that the building owner sells BIPV electricity to building tenants at the same price as they can import it from the grid.

To this end, the economic efficiency analysis shows that the internal rate of return (IRR) associated with energy-efficient building scenarios is up to 2.8% higher than the IRR associated with common practice building scenarios. Energy-efficient building's IRR can reach 8.9% when calculated over an investment period of 30 years and 14.8% when calculated over an investment period of 10 years.

This long-term economic efficiency analysis outlines that incorporating energy-efficient façades into contemporary construction practices can be more profitable, despite a higher initial investment. For this reason, long-term analyses are required when incorporating expensive energy efficiency strategies into buildings. This assessment aims to contribute to overcoming the BIPV high-cost perception barrier and motivate building developers to explore the AAF, or other energy-efficient façade solutions, as a means to increase their investment revenues.

The increasing willingness to adopt energy-efficient design strategies

Several barriers blocking the widespread use of BIPV have been studied throughout the research framework analysis (Chapter 3). Among them, this section has already discussed aesthetics and costs barriers. As a reminder, BIPV research has also identified the lack of knowledge on and interest in BIPV as a barrier blocking its transfer towards professional practices.

Numerous and interdisciplinary construction professionals and non-professionals have been involved in the present research process. In preliminary stages, their professional expertise and opinions have been requested for the design and optimisation of the main research outcome, the AAF. Further in the research progress, interactions with external stakeholders have been mainly focused on assessing their acceptance and willingness to adopt energy-efficient façade design strategies. These interactions have been designed as the AAF demonstrator visit, the expert's interviews, the social-acceptance survey and the organisation of an architecture competition for students. The latter involved architecture students appropriating the AAF construction system in their own design process and an expert jury evaluating the architectural quality of the energy-efficient façade designs of a collective residential building.

These interdisciplinary interactions have provided the means to measure the above-mentioned barrier: *the lack of knowledge and interest on BIPV*. They highlight a generalised lack of knowledge among professionals and non-professionals regarding energy-efficient design strategies. However, the vast majority of the addressed professionals state that after interacting with the AAF, their interest and motivation to integrate energy efficiency design strategies into their professional practice has substantially increased. Regarding non-professional BIPV acceptance, there is still a significant rate of rejection within city centres, although BIPV seems mostly accepted in new residential neighbourhoods. The interaction results analysis highlights that the low acceptance rates among non-professionals might be due to the negative influence of existing PV building attached systems with a weak architectural expression that set a negative preconception.

Ultimately, the interactions designed within the context of this research can contribute to overcoming the lack of knowledge and interest barrier and have significantly increased the professional willingness to adopt energy-efficient design strategies, as shown in the AAF demonstrators feedback (Section 6.3.1), the architecture expert interviews (Section 6.3.2), and the competition for students feedback (Section 6.4.3) . Regarding non-professional willingness to adopt these design strategies, more work is required to increase acceptance rates in all urban contexts. To overcome the negative preconceptions, existing research recommends energy-efficient marketing strategies such as integrating BIPV in high-profile public buildings, BIPV endorsement by well-connected people and awareness campaigns, among others [ACTIVE INTERFACES *et al.* 2019].

The discussion of these four points summarises the main achievements and contributions of the present research work through the development of the AAF, its quantitative assessment and its transfer potential evaluation towards professional practices. However, the research process has identified several limitations related to energy-efficient façade design that are here presented and discussed.

7.1.2 Limitations and opportunities

The energy-efficient façade design, implementation and assessment processes have revealed several issues that are identified here as remaining limitations for energy-efficient façade design. The latter, in turn, generate a series of opportunities for further work and foster energy-efficient façade design.

Energy Management Strategies

Throughout the design process, this research takes an *innovative* approach. As a reminder, the *innovative* approach focuses on maximising the total active surfaces within a coherence with the façade design. This approach relies on the development of novel energy management strategies (EMS), which enable a maximised self-consumption of the on-site generated renewable energy and therefore have the potential to foster the integration of active energy design strategies into architectural practices. However, these EMS are today at an early stage development and have not yet come into widespread use. For this reason, this point is discussed as a *remaining limitation* due to the further research and development on EMS required. Further development of EMS can significantly foster residential building's energy efficiency.

Low embodied impact materials

The development of a construction system following low embodied impact construction principles has found three challenges. The first one refers to the high embodied impacts of BIPV panels, the second one refers to the lack of information on the embodied impacts of the different construction materials, and the third one refers to the high embodied impacts of fire-resistant materials.

When designing a BIPV façade, the high embodied impacts of the BIPV system must be considered. The AAF's substructure is designed to minimise its embodied impacts to contribute compensating the high embodied impacts of the BIPV system. Despite this design effort, the AAF has embodied impacts five times higher than the embodied impacts of a CP façade. These embodied impacts are compensated by the renewable energy generation provided by the BIPV system. However, it should be studied whether, in non-optimal orientations with reduced performance BIPV panels (e.g. filtered panels) and a low range of direct insulation, the BIPV's embodied impacts are still compensated. This calculation has not been performed in the context of this research, which has focused on an average and representative BIPV integration in all four façades with some shadowing from nearby buildings and considering different ranges of BIPV panel performance. Further research on this topic is recommended to explore the limits of BIPV's integration conditions to foster the building's energy efficiency.

The KBOB database contains an extensive list of the most common construction materials and their environmental impacts [KBOB 2016]. However, when studying the incorporation of a specific material that is not on the list, information on its embodied impacts is hardly found among the technical information provided by the product producer. Some producers do provide this information, although in most cases the LCA system boundaries are not clear or vary among products, impeding the incorporation of this data into the façade's embodied impacts calculation. For this reason, the research process had to limit the material selection to the KBOB list or perform approximative calculations based on the combination of materials from the KBOB list. The remaining limitation that must be highlighted here is the need for more information on the embodied impacts of construction materials – provided by material's producers. Moreover, this information should provide information on the LCA's system boundaries and be published for the use of architects and other construction professionals. Recent regulation is fostering these practices among producers, although it is still not mandatory to provide the LCA results of every construction product.

Regarding the performance of low embodied impact materials, this research has encounter limitations regarding its fire resistance performance. The design of a ventilated façade involves specific fire resistance requirements defined by the Swiss norm AEAI. According to this norm, if the insulation is a non-fire-resistant material – RF2 or RF3 – such as cellulose and wood-fibre, the materials defining the façade's ventilated cavity must be fire resistant – RF1 [AEAI 2015]. Throughout the façade design process, it has been found that RF1 materials have a significantly higher embodied carbon than other non-fire-resistant alternatives. This fact is found as a limitation to lower further the embodied impacts of the energy-efficient façade, which would be possible at the theoretical design level, but impossible regarding the compliance with fire resistance standards. For this reason, further research is recommended in the field of low embodied impact and fire-resistant materials to enable a further reduction of the façade's embodied impacts.

Architectural expression issues

The architectural design process of the AAF aims at enhancing the architectural expression of BIPV while providing it with a flexible design that can be adapted to multiple projects in multiple contexts. However, the transfer potential evaluation phase has highlighted that this target finds some limitations regarding the nature of the BIPV panels and the total thickness of an energy-efficient façade, both affecting its architectural expression.

The design flexibility of the AAF is limited by the fact that it incorporates a BIPV system composed of glass panels. This fact involves two restrictions: on the one hand, composing a façade with panel-format construction materials requires the specific design of the panel joints regarding rhythm and details. In addition, its architectural expression is different and cannot be the same as a façade with continuous materials, melted or applied in mass such as roughcast where joints are inexistent (apart from the required expansion and work joints). On the other hand, the fragile nature of glass limits the design of a BIPV façade. Meaning that BIPV panels should not be incorporated in façades or façade areas where there is a high risk of impact as it is, for example, the façade of a schoolyard.

This research proposes a highly insulated façade with a total of 40 cm of insulation. In addition, the required ventilation of the rear face of the BIPV panels adds a minimum of 8 cm to the total façade thickness. Including the different façade panel components, the façade thickness results in a total dimension of 53.5 cm. This dimension has been found as an architectural expression constraint, e.g. by the winners of the architectural student competition. They stated that the openings' depth of their façade project conditioned the global architectural expression of their proposal. To overcome this limitation, more façade opening details must be designed, solving the potential thermal bridges if the windowpane is advanced towards the exterior of the façade. Similarly, further study of low embodied impact insulation could foster its performance and enable a decrease in the insulating layer thickness.

High-cost perception

A high initial investment associated with energy-efficient façade design has been argued in previous sections to no longer be a barrier due to the energy savings that it entails. However, the perception of initial high costs is still the fact that worries most architecture practitioners. To overcome this remaining limitation, more architecture-oriented information about the potential economies achieved through energy-efficient design must be provided. Similarly, BIPV producers should display the full price of the BIPV system, including the cost of the whole electrical system, and not only the price of the BIPV panels.

Specialised workforce required

Throughout the collaboration with a façade construction company for the façade prototype design and construction, it has been remarked that a specialised workforce is needed to connect the BIPV panels. In addition, this process increases by around 50% of the on-site façade mounting process. The need for a specialised workforce and a longer mounting process leads to higher façade construction costs. To avoid a significant price increase, we propose interdisciplinary façade mounting teams who can take care of the whole mounting process without subcontracting specialised external workforce.

Similarly, a new professional figure of the building design and construction process might be needed. His/her profile would be that of an architecture professional who is specialised in energy-efficient design. His/her job would consist of coordinating the integration of energy-efficient technologies into the architectural design process, avoiding technical incompatibilities as well as ensuring the architectural quality of the result.

Limited energy simulation tools

The research's quantitative results presented throughout this thesis are based on the energy simulations results of a digital energy simulation tool: Design-Builder. This simulation tool takes the weather data of the year 2002 and templates for representative energy consumption schedules according to the building use, building components and building services, among others. These templates can provide accurate results regarding the building's energy demand. However, regarding the building's energy generation, Design-Builder only accepts the panel's performance as an input to simulate the BIPV's output. This program does not consider the type of PV technology, which affects the energy output under different irradiation intensity, or the potential for bifacial energy generation, which can increase by 30% the BIPV panel's performance. Further development of energy simulation technology can provide architects with an accurate tool to help decide which PV technology can better improve the building's energy performance.

Unreached energy transition targets

Ultimately, the last remaining limitation discussed here is the fact that not all the AAF building scenarios developed within this research meet the energy transition targets. Only the scenarios with opaque BIPV façade cladding systems reach the SIA 2040's targets without the support of a BAPV roof. The opaque BIPV systems incorporated in the different AAF building scenarios have the highest performances among all the BIPV systems used in this research, which vary from 21% for the opaque Monocrystalline filtered panel to 28% for the Tandem-Perovskite BIPV panel. This means that, even though they improve the building's energy efficiency, the use of low-performance BIPV systems – Thin-Film, translucent and transparent BIPV systems –do not provide enough renewable energy to help the building reach the highly-demanding energy transition's targets. The use of low-performance BIPV panels is therefore considered a limitation that diminishes the building's potential to reach the energy transition targets.

A remarkable difference has been noticed between the scenarios that integrate *High-Performance* PV technology and the scenarios that integrate *Market-Ready* PV technology. This implies that further research and development of PV cells to reach higher energy performance rates can provide architects with better tools to reach energy-efficient targets in the building sector.

7.2 Recommendations

An active, energy-efficient façade design has been developed throughout the present research process to propose a possible solution to answer the research question motivating this work and to contribute to the energy transition. The research process has identified several limitations and opportunities, which have been discussed in Section 7.1.2, and new opportunities for further investigation and practice. The latter are here discussed to promote actions towards energy-efficient façades in both academic and professional practice.

Maximise the potential of energy-efficient façades to contribute to the energy transition

The collective residential façade's potential to contribute to the energy transition has been discussed in this concluding chapter to be notably affected by the architectural design process. The latter is carried out by architects who, as previously mentioned, are mostly unaware of the design and energy potential of BIPV and other energy-efficient design strategies. As a recommendation, the potential of energy-efficient façades can be maximised through design and education.

Regarding BIPV façade design, the energy assessment process of this research has demonstrated that the use of *High-Performance* PV technology entails a significant improvement of the building's energy balance. For this reason, it is recommended to use this type of technology when possible.

Another strategy to maximise the façade's energy output through design is to optimise the BIPV panel's orientation. This strategy opened a new field of research that was presented in the IEA SHC Task 16 where different active façade morphologies are proposed to maximise the energy output of a BIPV façade [Sick *et al.* 1996]. BIPV orientation optimisation has been considered by the winners of the Active Housing competition, which by the inclination of the active panels (80°) achieve a 12.4% energy output increase. This topic has also been discussed during an architecture expert interview – Expert C – who proposes the design of the *Building 2.0* where façade morphology, building typology and even interior distribution are at the service of energy efficiency, optimising the use of energy and maximising the building envelope's energy output. To achieve this, architects are required to incorporate passive and active energy design strategies at the very beginning of the design process to reach a harmonious energy-efficient architectural expression.

To take advantage of the available solar energy and maximise the building's energy efficiency, urban design should also be considered. Urban designers can acknowledge the potential of the building envelope, and the potential of façades to provide neighbourhoods with on-site renewable energy. This involves urban plans that enable a variety of façade morphologies, maximise south-oriented façades and study building heights and proximity to minimise casted shadows. This urban design potential has been studied in numerous researches and must be considered when fostering the design potential of energy-efficient façades [Amado *et al.* 2012; Nault 2016].

Regarding education, energy-efficient façade design is recommended to be introduced in architectural learning processes as well as professional training programs. This recommendation is based on the high rates of interest as well as of the generalised lack of knowledge registered among architecture practitioners who have visited the AAF demonstrator. In a like manner, architecture school learning processes have the potential of motivating creativity among the future generation of professionals and further developing the energy-efficient potential of façade design. Ultimately, education projects can contribute to improving the architect's awareness of energy-efficient design and foster its implementation towards the energy transition of the construction sector.

Encourage interdisciplinary collaborations

Interdisciplinary professional collaborations can significantly upgrade the energy efficiency outcome of the building process. A close collaboration between BIPV producers and architects can significantly improve both professional practices. On the one hand, BIPV producers would produce a product that might be better adapted to the building design and construction processes: standard sizes, dimensional coordination, construction requirements, textures, etc. On the other hand, architects would better know the potential and limitations of BIPV products, allowing for a façade design that maximises the energy output.

Regarding the embodied impact of construction materials and practices, it is recommended to establish interdisciplinary collaborations among architects and specialised engineers. The latter can help the former optimising the façade design as well as the construction process to reduce the embodied impact of the whole building. This collaboration can also bring up some issues or needs regarding the incompatibility of low embodied impact materials with some construction standards, fire resistance for instance, as mentioned in Section 7.1.2, or the need for further development of specific façade elements to optimise their energy-efficient design.

In a like manner, the collaboration of architects with an economy specialist would provide real estate developers with long-term economy performance analysis of energy-efficient building construction. This collaboration would contribute to overcoming the BIPV costs barrier by familiarising architects with the potential economic savings generated by energy-efficient façade design.

At the urban scale, some interdisciplinary researchers and professionals are working on developing the previously-mentioned EMS. These strategies are mostly affected by the user's electricity consumption schedules and by the BIPV's generation schedule. The latter can be affected by the façade design depending on its orientation and type of PV technology integrated. For this reason, interdisciplinary collaboration in this field is recommended to integrate both architecture and EMS towards more energy-efficient neighbourhoods.

Update standards according to the energy transition objectives

The Swiss construction standards currently in force are much less demanding regarding building's energy efficiency [SIA 380/1 2009] than the energy transition targets included in non-mandatory construction recommendations [SIA 2040 2017]. Energy-efficient building construction could be fostered through the integration of the energy transition targets into mandatory energy efficiency standards.

As mentioned in Section 7.1.2, the lack of information regarding the environmental impacts of the different construction products limits the design potential of energy-efficient façade design. To overcome this limitation, standards should require that all technical information on building construction products provide the embodied environmental impacts of their product. The UE is working towards regulating this problem, although LCA is not yet required for all construction products.

7.3 Perspectives

The energy transition has been described as a demanding regulating framework which focuses on energy efficiency. These energy regulations seem unachievable with the practice of current construction systems. However, this research has demonstrated that building façades have the potential to raise a building's energy efficiency towards reaching the energy transition targets through sustainable design.

Every building design project can have as many good design solutions as good architects work on it [Carvajal Ferrer 1997]. This idea can be extended to sustainable building design, where there is no recipe to design an energy-efficient building with architectural quality. However, several energy-efficient construction principles can be combined and integrated into the architectural design process to upgrade the energy efficiency qualities of the design outcome.

The AAF is a façade design solution, among multiple possibilities, that explores the potential of façade design to improve the building's energy efficiency. Ultimately, the implementation of energy-efficient façades demonstrates that reaching the targets of the energy transition is possible through the façade architectural design, which also has the potential of transforming non-active collective residential buildings into positive energy buildings.

This research work, through its methodology, opens up new avenues for designing façades that significantly contribute to the building's energy efficiency towards the energy transition. To this end, this thesis provides architects, PV developers and building developers with a design and assessment methodology to support their decisions concerning the integration of energy-efficient design strategies into building development. Similarly the analysis research phases provide a solid base for the development of energy efficient residential façades. The outcome of this research can foster the adoption of energy-efficient design strategies by practitioners through its architectural approach which focuses on demystifying BIPV as well as illustrating the potential of façades to optimise the building's energy performances. This energy-efficient architectural approach might evolve to define a new professional figure, *the facilitator*, as an interdisciplinary interaction mediator. This professional figure would focus on the practical application of energy-efficient design strategies into architectural practices, contributing to bring closer the different actors involved in this kind of projects.

Ultimately, this thesis highlights that architectural design significantly affects the building sector's energy transition process towards the objectives set for the year 2050. Architectural design can foster the decarbonization of the building sector, which, in the upcoming years, will confront architects and other building stakeholders with the energy efficiency challenges dealt with throughout the present research process.

At the end of this present work, we humbly wish that its results can provide architects with a possible path forward and a design methodology to face the energy transition challenges from an architectural approach. Similarly, we hope that this research can somewhat demystify energy-efficient façade design and can motivate further work in the field to foster the harmonious integration of energy-efficient technology into architectural design.

8. Bibliography

[Abriani 1998] Abriani A., 'Les proportions en architecture. Concepts en détresse'. *Matières*, 1998, 2. ISBN-13: 9782889141814

[Aksoezen *et al.* 2015] Aksoezen M., Daniel M., Hassler U. & Kohler N., 'Building age as an indicator for energy consumption.' *Energy and Buildings*, 2015, 87. DOI: 10.1016/j.enbuild.2014.10.074

[Adjemian Oria 2011] Adjemian Oria A., *La Evolucion de Fachadas Ventiladas, Nuevos Materiales y Sistemas Constructivos.* Universidad Politecnica de Valencia, Escuela Tecnica Superior de Ingenieria de Edificacion, 2011.

[AEAI 2015a] AEAI, *Directive de Protection Incendie. Utilisation Des Matériaux de Construction.*, 2015.

[AEAI 2015b] AEAI, *Norme de Protection Incendie.*, 2015.

[AES 2018] AES, 'Smart Grid.' 2018, www.strom.ch

[AFCS 2018] AFCS, *Loi Sur l'energie.*, 2018.

[AFNOR 2016] AFNOR, EN 13501-2. *Fire Classification of Construction Products and Building Elements - Part 2: Classification Using Data from Fire Resistance Tests, Excluding Ventilation Services.*, 2016.

[Aghajani *et al.* 2107] Aghajani G.R., Shayanfar H.A. & Shayeghi H., 'Demand side management in a smart micro-grid in the presence of renewable generation and demand response.' *Energy*, 2107, 126: 622-637. DOI: 10.1016/j.energy.2017.03.051

[Aguacil 2019] Aguacil S., 'Architectural Design Strategies for Building-Integrated Phovoltaics (BIPV) in Residential Building Renovation.' PhD Thesis, EPFL (Ecole Polytechnique Fédérale de Lausanne), Lausanne, 2019. DOI:10.5075/epfl-thesis-9332

[Akadiri *et al*. 2012] Akadiri P.O., Chinyio E.A. & Olomolaiye P.O., 'Design of a sustainable building: a conceptual framework for implementing sustainability in the building sector.' *Buildings*, 2012, 2 (2): 126-152. DOI: 10.3390/buildings2020126

[ACTIVE INTERFACES *et al*. 2019] ACTIVE INTERFACES, LAST (EPFL), PV-Lab (EPFL), iEnergy (HEIA-FR), iwö (HSG), LIPID (EPFL), ISAAC (SUPSI), IBI (ETHZ), CC-EASE (HSLU), CSEM & ECONCEPT, Active interfaces. 2015. www.activeinterfaces.ch

[Amado *et al*. 2012] Amado M. & Poggi F., 'Towards solar urban planning: A new step for better energy performance.' *Energy Procedia*, 2012, 30:1261-1273. DOI: 10.1016/j.egypro.2012.11.139

[Akinade *et al.* 2017] Akinade O., Oyedele L., Ajayi S.O., Bilal M., Alaka H.A., Owolabi H.A., Sururah A. B., Jaiyeoba B.E. & Kadiri K.O., 'Design for Deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills.' *Waste Management*, 2017, 60: 3-13. DOI: 10.1016/j.wasman.2016.08.017

[Arrigoni *et al.* 2017] Arrigoni A., Pelosato R., Melià P., Ruggieri G., Sabbadini S. & Dotelli G., 'Life cycle assessment of natural building materials: the role of carbonation, mixture components and transport in the environmental impacts hempcrete blocks.' *Journal of Cleaner Production*, 2017, 149: 1051-1061. DOI: 10.1016/j.jclepro.2017.02.161

[ArborCrowd 2017] ArborCrowd, 'Why IRR matters: evaluating real estate investment returns.' 2017. www.arborcrowd.com

[ArchDaily] ArchDaily, 'Architecture Projects.' *ArchDaily*. www.archdaily.com

[ARE 2012] ARE, 'Statistique Suisse de zones à bâtir.' 2012. www.are.admin.ch

[Arnold 2005] Arnold F., *Le Logement Collectif.* Paris : Editions Le Moniteur, 2005.

[Assouline *et al.* 2017] Assouline D., Mohajeri N. & Scartezzini J.-L., 'Quantifying rooftop photovoltaic solar energy potential: A machine learning approach.' *Solar Energy*, 2017, 141: 278-296. DOI: 10.1016/j.solener.2016.11.045

[Ali *et al.* 2018] Ali I.B., Turki M., Belhadj J. & Roboam X., 'Optimized fuzzy rule-based energy management for a battery-less PV/wind-BWRO desalination system.' *Energy*, 2018, 159: 216-228. DOI: 10.1016/j.energy.2018.06.110

[Attoye *et al.* 2017] Attoye D.E., Tabet Aoul K.A. & Hassan A., 'A Review on Building Integrated Photovoltaic Façade Customization Potentials.' *Sustainability*, 2017, 9 (12), 2287. DOI: 10.3390/su9122287

[Ayuntamiento de Madrid 1996] Ayuntamiento de Madrid, *Ordenanza de Rehabilitacion Urbana y Gestion Ambiental*., 1996.

[Azadian *et al.* 2013] Azadian F. & Radzi M.A.M., 'A general approach toward building integrated photovoltaic systems and its implementation barriers: A review.' *Renewable and Sustainable Energy Reviews*, 2013, 22: 527-538. DOI: 10.1016/j.rser.2013.01.056

[Barbato *et al*. 2012] Barbato A. & Carpentieri G., 'Model and algorithms for the real time management of residential electricity demand.' *2nd IEEE ENERGYCON Conference & Exhibition*. Future Energy Grids and Systems Symp, Florence, Italy, 2012. ISBN: 9781467314541

[Biyik *et al.* 2017] Biyik E., Araz M., Hepbasli A., Shahrestani M., Yao R., Shao L., Essah E., Oliveira A.C., del Caño T., Rico E., Lechón J.L., Andrade L., Mendes A. & Atli Y.B., 'A key review of building integrated photovoltaic (BIPV) systems.' *Engineering Science and Technology, an International Journal*, 2017, 20 (3): 833-858. DOI: 10.1016/j.jestch.2017.01.009

[Baker 2019] Baker D.R., 'Battery Reality: There's Nothing Better Than Lithium-Ion Coming Soon'. *Bloomberg*. www.bloomberg.com. Published 2019.

[Ballif 2014] Ballif C., 'Formulaire de requête mySNF: PV2050: Novel PV technologies for optimum space usage and efficient electricity production.' 2014

[Bassand 2005] Bassand N., 'L'epaisseur de la densité ou les qualités revisitées de l'habitat condensé'. *Matières*, 2005, 7. ISBN: 2-88074-621-3

[Binz *et al.* 2014] Binz A., Bichsel J., Geissler A., Hall M., Huber H., Steinke G. & Weickgenannt B., *Energieeffizientes Bauen. Konzepte, Kriterien, Systeme.* Energieschweiz, 2014. ISBN: 978-3-905711-28-8

[Bhandari *et al*. 2015] Bhandari K.P., Collier J.M., Ellingson R.J. & Apul D.S., 'Energy payback time (EPBT) and energy return on energy invested (EROI) of solar photovoltaic systems: A systematic review and meta-analysis.' *Renewable and Sustainable Energy Reviews*, 2015, 47: 133-141. DOI: 10.1016/j.rser.2015.02.057

[Bec Partners SA 2015a] Bec Partners SA, 'Serie de Prix de Marché SPM. Batilog Devis. Base: OFS 2014-10 + Report Des Variantes.', 2015.

[Bec Partners SA 2015b] Bec Partners SA, 'Serie de Prix de Marche SPM. Batilog Devis CTE Catalogue Par Types d'élements. Base CRB EAK. Valeurs Référentielles. Coûts. Classification Par Types d'élements.', 2015.

[Benemann *et al.* 2001] Benemann J., Chehab O. & Schaar-Gabriel E., 'Building-integrated PV modules.' *Solar Energy Materials and Solar Cells*, 2001, 67: 345-354. DOI: 10.1016/S0927-0248(00)00302-0

[de Berardinis *et al.* 2011] de Berardinis P., di Giovanni G. & Bonomo P., 'Technological evolution of photovoltaic envelope. Constructive integration and paradigms of innovation.' *Solar World Congress (SWC)*, Kassel, Germany, 2011. ISBN: 978-3-9814659-0-7

[Birgisdottir *et al.* 2017] Birgisdottir H., Moncaster A., Houlihan Wiberg A., Chae C., Yokoyama K., Balouktsi M., Seo S., Oka T., Lützkendorf T. & Malmqvist T., 'IEA EBC annex 57 'evaluation of embodied energy and CO_{2eq} for building construction.'' *Energy and Buildings*, 2017, 154: 72-80. DOI: 10.1016/j.enbuild.2017.08.030

[Bonomo *et al.* 2015] Bonomo P., Chatzipanagi A. & Frontini F., 'Overview and analysis of current BIPV products: new criteria for supporting the technological transfer in the building sector.' *Vitruvio*, 2015. DOI: 10.4995/vitruvio-ijats.2015.4476

[Bonomo *et al.* 2017] Bonomo P., Frontini F. & Donsante I., 'BIPV: building envelope solutions in a multi-criteria approach. A method for assessing life-cycle costs in the early design phase.' *Advances in Building Energy Research*, 2017, 11 (1):104-129. DOI: 10.1080/17512549.2016.1161544

[Bogner *et al*. 2009] Bogner A. & Menz W., 'The theory-generating expert interview: epistemological interest, forms of knowledge, interaction.' *Interviewing Experts*. Palgrave Macmillan, 2009, 43–80. DOI: 10.1057/9780230244276

[Bouhafs *et al.* 2014] Bouhafs F., Mackay M. & Merabti M., *Communication Challenges and Solutions in the Smart Grid*. Springer, 2014. DOI: 10.1007/978-1-4939-2184-3

[Boswell 2013] Boswell C.K., *Exterior Building Enclosures. Design Process and Composition for Innovative Façades*. John Wiley & Sons, 2013, ISBN: 978-1-118-33279-5

[BP 2017] BP, 'BP Statistical Review of World Energy 2017'. BP, 2017.

[Ballif *et al.* 2018] Ballif C., Perret-Aebi L.-E., Lufkin S. & Rey E., 'Integrated thinking for photovoltaics in buildings.' *Nature Energy*, 2018, 3: 438-442. DOI: 10.1038/s41560-018-0176-2

[BRE 2016] BRE, 'Sustainable refurbishment - how to better understand, measure and reduce the embodied impacts.' 2016, www.bre.co.uk

[Brown 2010] Brown P.A., Passive & Active Design. 2010, www.cisbe.org

[Brinkworth *et al.* 2005] Brinkworth B.J. & Sandberg M., 'Design procedure for cooling ducts to minimise efficiency loss due to temperature rise in PV arrays.' *Solar Energy*, 2005, 80 (1): 89-103. DOI: 10.1016/j.solener.2005.05.020

[Bull 2014] Bull, 'Aluminum.' in Doran D. & Cather B., *Construction Materials Reference Book*. 2nd ed.Routledge, 2014, 5–22. ISBN-13: 978-0750663762

[Bull 2016] Bull J., 'Embodied Carbon of Insulation'. *Greenspec*, 2016. www.greenspec.co.uk, accessed 12th August 2016.

[Cronemberger *et al.* 2014] Cronemberger J., Almagro Corpas M., Cerón I., Caamaño-Martín E. & Vega Sanchez S., 'BIPV technology application: Highlighting advances, tendencies and solutions through Solar Decathlon Europe houses.' *Energy and Buildings , 2014,* 83: 44-56. DOI: 10.1016/j.enbuild.2014.03.079

[Carvajal Ferrer 1997] Carvajal Ferrer F.J., *Curso Abierto: Lecciones Para Arquitectos y No Arquitectos*. Madrid : Colegio Oficial de Arquitectos de Madrid, 1997.

[Crawford *et al*. 2016] Crawford R.H., Bartak E.L., Stephan A. & Jensen C.A., 'Evaluating the life cycle energy benefits of energy efficiency regulations for buildings.' *Renewable and Sustainable Energy Reviews*, 2016, 63: 435-451. DOI: 10.1016/j.rser.2016.05.061

[Cheung *et al.* 2015] Cheung L. & Farnetani M., Whole-life carbon: Façades. *Building*, 2015, www.building.co.uk

[Chatzipanagi *et al.* 2016] Chatzipanagi A., Frontini F. & Virtuani A., 'BIPV-temp: A demonstrative Building Integrated Photovoltaic installation.' *Applied Energy*, 2016, 173: 1-12. DOI: 10.1016/j.apenergy.2016.03.097

[Chamberlain *et al.* 2016] Chamberlain J.P., Hammerschlag R. & Schaber C.P., 'Energy Storage Technologies.' in Goswami D.Y. & Kreith F., *Energy Efficiency and Renewable Energy Handbook*. 2nd ed.Boca Raton : CRC Press, 2016, 939–65. ISBN 9781138749115

[Chau *et al*. 2015] Chau C.K., Leung T.M. & Ng W.Y., 'A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings.' *Applied Energy*, 2015, 143: 395-413. DOI: 10.1016/j.apenergy.2015.01.023

[Christiansen *et al.* 2015] Christiansen C., Murray B. & AECOM, 'Energy Storage Study. A storage market review and recommendations for funding and knowledge sharing priorities.' 2015.

[Chamilothori *et al.* 2016] Chamilothori K., Wienold J. & Andersen M., 'Daylight patterns as a means to influence the spatial ambience: a preliminary study.' *Proceedings of 3rd International Congress on Ambiances. September 2016*. Vol 1,Volos, Greece, 2016

[Chin Kim Lo *et al.* 2015] Chin Kim Lo, Yun Seng Lim & Faidz Abd Rahman, New integrated simulation tool for the optimum design of bifacial solar panel with reflectors on a specific site. *Renewable Energy,2015, 81: 293-307*. DOI: 10.1016/j.renene.2015.03.047

[Cihan Kayaçetin *et al.* 2018] Cihan Kayaçetin N. & Murat Tanyer A., 'Analysis of Embodied Carbon in Buildings Supported by a Data Validation System.' *Embodied Carbon in Buildings. Measurement, Management and Mitigation*. Springer, 2018, 143–64. DOI: 10.1007/978-3-319-72796-7

[Clúa Longás *et al.* 2017] Clúa Longás A., Lufkin S. & Rey E., Concevoir des façades actives bas carbone. *TRACÉS*, 2017, 23–24, dossier

[Commune de Val-d'Illiez 2018] Commune de Val-d'Illiez, *Règlement Des Constructions*., 2018.

[Confédération Suisse 2017] Confédération Suisse, 'Swiss Plateau'. 2017, www.eda.admin.ch

[Confédération Suisse 2018] Confédération Suisse, 'Energy transition', 2018, www.eda.admin.ch

[Construct PV 2018] Construct PV, 'Constructing building with a customizable size PV modules integrated in the opaque part of the building skin'. 2018

[Conseil de Paris 2018] Conseil de Paris, *Plan Local d'Urbanisme de Paris. Reglement (Tome 1).*, 2018.

[Conseil Fédéral Suisse 1988] Conseil Fédéral Suisse, 'Message Concernant Un Arrêté Fédéral Pour l'utilisation Économe et Rationelle de l'énergie', *Arrêté Sur l'énergie, AE,* 1988.

[Conseil Fédéral Suisse 1990] Conseil Fédéral Suisse, Arrêté Fédéral Du 14 Décembre 1990 'Pour Une Utilisation Économe et Rationelle de l'énergie', *Arrêté Sur l'énergie, AE,* 1990.

[Cooke *et al.* 1994] Cooke B. & Walker G., *European Construction. Procedures and Techniques*. London : Palgrave, 1994. ISBN-13: 978-0333594650

[CRB 2012a] CRB, *Handbuch LCC Instandhaltung Und Instandsetzung von Bauwerken*. CRB Schweizerische Zentralstelle für Baurationalisierung, 2012.

[CRB 2012b] CRB, ECCC-Bât: *Code Des Coûts de Consctruction: Bâtiment.*, 2012.

[CRB 2018] CRB, CRB_ Centre suisse d'etudes pour la rationalisation de la construction. 2018. www.crb.ch/crbOnline

[Crassard *et al.* 2007] Crassard F. & Rode, *The Evolution of Building Integrated Photovoltaics (BIPV) in the German and French Technological Innovation Systems for Solar Cells*. Chalmers University of Technology, 2007. ISSN 1404-8167

[Cruz Rios 2015] Cruz Rios F., 'Design for Disassembly and Deconstruction - Challenges and Opportunities.' *Procedia Engineering*, 2015, 118: 1296-1304. DOI: 10.1016/j.proeng.2015.08.485

[CSEM 2016] CSEM, 'Researchers develop novel technology for harvesting solar energy', 2016, [CSEM *et al.* 2015] CSEM, LAST (EPFL) & G2E, PV2050 Project. Photovoltaics into the Built Environment: From Semitransparent PV Glazing to High Efficiency Roof Integrated Solutions, 2015.

[Connaughton *et al.* 2011] Connaughton J., Weight D., Jones C. & Moon D., Cutting emboded carbon in construction projects. 2011. www.wrap.org.uk

[DAEC 2015] DAEC, *Directive Concernant l'intégration Architecturale Des Installations Solaires Thermiques et Photovoltaïques*, 2015.

[Drouilles *et al.* 2018] Drouilles J., Aguacil S., Hoxha E., Jusselme T., Lufkin S. & Rey E., 'Environmental Impact Assessment of Swiss Residential Archetypes: A Comparison of Construction and Mobility Scenarios.', *Energy Efficiency,* 2019, 12(6): 1661-1689. DOI: 10.1007/s12053-019-09811-0

[Dahl Rocha *et al*. 2014] Dahl Rocha I., Leibbrandt C. & Ross K., *Toward an Integral Practice of Architecture*. Basel : Birkhäuser, 2014. ISBN: 978-3-03821-581-3

[Deign 2017] Deign J., Study: flow batteries beat lithium ion. *Energy storage report*, 2017.

[Denzer 2013] Denzer A., *The Solar House, Pioneering sustainable design* : Rizzoli International Publications, Inc., 2013. DOI: 10.3390/arts3030303

[De Wolf *et al*. 2017] De Wolf C., Pomponi F. & Moncaster A., 'Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice.' *Energy and Buildings*, 2017, 140: 68-80. DOI:10.1016/j.enbuild.2017.01.075

[DETAIL 2016] DETAIL, Detail Inspiration. 2016. www.detail-online.com/inspiration

[Delcampe *et al.* 2012] Delcampe D., Transport and Energy Group & European Environmental Agency, GHG emissions of Transport. 2012. www.eutransportghg2050.eu

[DETEC 2017] DETEC, Fiche d'information 'Approvisionnement Énergétique de La Suisse et Évolution Au Niveau International.' Confédération Suisse, 2017.

[DGE 2018] DGE, Programme '100 millions pour les énergies renouvelables et l'efficacité énergetique'. Mise en oeuvre d'un soutien pour les batteries de stockage d'énergie photovoltaïque. 2018. www.vd.ch

[Directive 2010/31/EU 2010] Directive 2010/31/EU, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (Recast), 2010.

[Directive 2012/27/EU 2012] Directive 2012/27/EU, Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on Energy Efficiency, Amending Directives 2009/125/EC and 2010/30/EU and Repealing Directives 2004/8/EC and 2006/32/EC., 2012.

[DOE/EIA 2016] DOE/EIA, *Annual Energy Outlook 2016, with Projections to 2040*. U.S. Energy Information Administration, 2016.

[DOE/EIA 2017] DOE/EIA, *International Energy Outlook 2017 (IEO201)*. U.S. Energy Information Administration, 2017.

[Dong *et al.* 2017] Dong Y. & Hauschild M.Z., 'Indicators for environmental sustainability.' *Procedia CIRP*, 2017, 61: 697-702. DOI: 10.1016/j.procir.2016.11.173

[van Den Berg *et al.* 2009] van Den Berg D.J., de Wijn H., Havik K., Volker L., Zijlstra H., de Jong P., van Dorst M., van Dijk H., Bouman O., Arkesteijn M., den Heijer A. & Vande Putte H., *Building for Bouwkunde - Open to Ideas. Open International Ideas Competition and Think Thank*. TU Delft, Faculty of Architecture, 2009.

[EAAE / AEEA Research centre 2016] EAAE / AEEA Research centre, Framework for architectural research, 2016.

[Ebner *et al.* 2009] Ebner W., Leimeister J.M. & Krcmar H., 'Community engineering for innovations: the ideas competition as a method to nurture a virtual community for innovations.' *R&D Management*, 2009, 39 (4): 342-356. DOI: 10.1111/j.1467-9310.2009.00564.x

[Eckelman *et al.* 2018] Eckelman M.J., Brown C., Troup L.N., Wang L., Webster M.D. & Hajjar J.F., 'Life cycle energy and environmental benefits of novel design-for-deconstruction structural systems in steel buildings.' *Building and Environment*, 2018, 143: 421-430. DOI: 10.1016/j.buildenv.2018.07.017

[Eco-innovation action plan 2011] Eco-innovation action plan, Making building materials greener. 2011. www.ec.europa.eu accessed 15th September 2016.

[Ecoparc 2017] Ecoparc, Association Ecoparc. Concrétiser le développement durable. *Forums Ecoparc*, 2017. www.ecoparc.ch

[EEA 2016] EEA, Carbon Dioxide Emissions from Passenger Transport., 2016.

[Eiffert *et al.* 2002] Eiffert P. & IEA PVPS Task 7, *Building Integrated Photovoltaic Power Systems. Guidelines for Economic Evaluation*. IEA International Energy Agency PVPS, 2002.

[Eiffert *et al.* 2000] Eiffert P. & Kiss G.J., Building-Integrated Photovoltaic Designs for Commercial and Institutional Structures. A Sourcebook for Architects. NREL, 2000.

[El-Haram *et al.* 2002] El-Haram M.A. & Horner M.W., 'Factors affecting housing maintenance cost.' *Journal of Quality in Maintenance Engineering*, 2002, 8 (2): 115-123. DOI: 10.1108/13552510210430008

[El Khouli *et al.* 2015] El Khouli S., John V. & Zeumer M., Sustainable Construction Techniques. From Structural Design to Interior Fit-out: Assessing and Improving the Environmental Impact of Buildings. 1st ed. Kösel GmbH & Co, 2015. ISBN: 978-3-95553-238-3

[El-Baz *et al*. 2018] El-Baz W., Tzscheutschler P. & Wagner U., 'Day-ahead probabilistic PV generation forecast for buildings energy management systems.' *Solar Energy*, 2018, 171: 478-490. DOI: 10.1016/j.solener.2018.06.100

[El-Baz *et al.* 2017] El-Baz W. & Tzscheutschler P., 'Autonomous coordination of smart buildings in microgrids based on a double-sided auction.' *2017 IEEE Power & Energy Society General Meeting*. 2017. DOI: 10.1109/PESGM.2017.8273944

[Eder *et al.* 2017] Eder G., Maul L., Illich P. & Folkerts W., *BIPV Research Teams & BIPV R&D Facilities, an International Mapping*. IEA International Energy Agency PVPS, 2017. ISBN: 978-3-906042-74-9

[EN 2006] EN, *Oriented Strand Boards (OSB) - Definitions, Classifications and Specifications*., 2006.

[EN 50583-1 2016] EN 50583-1, *Photovoltaics in Buildings - Part 1: BIPV Modules*., 2016.

[EnDK 2018] EnDK, *Modèle de Prescriptions Énergétiques Des Cantons (MoPEC).* Edition 2014. Mise à Jour 2018., 2018.

[Espeche *et al.* 2017] Espeche J.M., Noris F., Lennard Z., Challet S. & Machado M., 'PVSITES: Building-Integrated Photovoltaic Technologies and Systems for Large-Scale Market Deployment.' *Proceedings 2017*. Overview of pvsite objectives, 2017. DOI: 10.3390/proceedings1070690

[EOTA 2012] EOTA, *Guideline for European Technical Approval for Structural Sealant Glazing Kits (SSGK)*., 2012.

[Edenhofer *et al.* 2014] Edenhofer O., Pich-Madruga R., Sokona Y., Farahani E., Kadner S., Seyboth K., Adler A., Baum I., Brunner S., Eickemeier B., Kriemann B., Savolainen J., Schlömer S., von Stechow C., Zwickel T. & Minx J.C., IPCC 2014: Climate Change 2014. Mitigation of Climate Change. Working group III contribution to the fifth assessment report of the intergovernmental panel on climate change. 2014.

[Ettlin 2013] Ettlin A., The long road to the 2000-watt society. *Phys.org*, 2013, www.phys.org

[2010/31/EU 2010] 2010/31/EU, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings., 2010.

[EU 305/2011 2011] EU 305/2011, Regulation (EU) No 305/2011 of the European Parliament and of the council of 9 March 2011. Laying down harmonised conditions for the marketing of construction products and repealing council directive 89/106/EEC., 2011.

[EU 2012] EU, DIRECTIVE 2012/19/EU of the European Parliament and of the council of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE)., 2012.

[EU 2014] EU, *Low Voltage Directive (LVD*) / Directive 2014/35/EU., 2014.

[Euroelectric 2011] Euroelectric, Power Statistics & Trends. 2011 Edition. *Euroelectric Electricity for Europe*, 2011.

[European Commission 2012] European Commission, *Energy Roadmap 2050*. 2012. www.ec.europa.eu

[Eurostat 2017] Eurostat, *Generation of waste by waste category, hazardousness and NACE* Rev. 2 Activity. European Comission, 2017.

[European Commission 2019] European Commission, Comission welcomes agreement on energy performance of buildings. *Energy*, 2019. www.ec.europa.eu

[Eurothane 2019] Eurothane, Eurothane *Autopro SI, le panneau haut performance d'isolation thermique support d'étanchéité pour les toitures terrasses*. 2019, www.recticelinsulation.com

[European Parliament 1988] European Parliament, *The Construction Products Directive* (Council Directive 89/106/EEC). 1988. www.eurocodes.jrc.ec.europa.eu

[Farkas *et al.* 2009] Farkas K., Andresen I. & Hestnes A.G., 'Architectural integration of photovoltaic cells - Overview of materials and products from an architectural point of view.' *Proceedings of the 3rd CIB International Conference on Smart and Sustainable Built Environments (SASBE)*. Delft, 2009

[Farkas *et al.* 2012] Farkas K. & Horvat M., *Building Integration of Solar Thermal and Photovoltaics - Barriers, Needs and Strategies*. IEA SHC, 2012.

[Farkas *et al.* 2013] Farkas K., IEA - SHC, Maturi L., Scognamiglio A., Frontini F., Munari Probst M.C. & Roecker C., *Designing Photovoltaic Systems for Architectural Integration. Criteria and Guidelines for Product and System Developers.*, 2013.

[Fermacell 2014] Fermacell, Fermacell Powerpanel H2O. 2014. www.fermacell.ch

[Finnegan *et al.* 2018] Finnegan S., Jones C. & Sharples S., 'The embodied CO2e of sustainable energy technologies used in buildings: A review article.' *Energy and Buildings*, 2018, 181: 50-61. DOI: 10.1016/j.enbuild.2018.09.037

[Finke 1990] Finke R., *Creative Imaginery: Discoveries and Invention in Visualization*. Lawrence Erlbaum Associates, Inc., 1990.

[Finnegan 2018] Finnegan S., 'Embodied Carbon of Sustainable Technologies.' *Embodied Carbon in Buildings. Measurement, Management and Mitigation*. Springer, 2018, 287–300. DOI:10.1007/978-3-319-72796-7

[Finkbeiner *et al*. 2006] Finkbeiner M., Inaba A., Tan R.B.H., Christiansen K. & Klüppel H.-J., 'The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044.' *The International Journal of Life Cycle Assessment*, 2006, 11 (2): 80-85. DOI: 10.1065/lca2006.02.002

[Floyd *et al*. 2009] Floyd J. & Fowler Jr., *Survey Research Methods*. 4th ed. Thousand Oaks, California : SAGE, 2009. ISBN: 0-7619-2190-7

[Florio *et al.* 2018] Florio P., Munari Probst M.C., Schüler A., Roecker C. 'Assessing visibility in multi-scale urban planning: A contribution to a method enhancing social acceptability of solar energy in cities'. *Solar Energy.* 2018, 173: 97-109 . DOI: 10.1016/j.solener.2018.07.059

[FOEN 2015] FOEN, Forest and Wood in Switzerland. 2015. www.bafu.admin.ch

[FOSTEr inMED 2015] FOSTEr inMED, Guidelines on building integration of photovoltaic in the Mediterranean area. 2015

[Fraunhofer ISE 2019] Fraunhofer ISE, *Photovoltaics Report*. Freiburg: Fraunhofer Institute for Solar Energy Systems, ISE, 2019.

[Frontini *et al.* 2012] Frontini F., Manfren M. & Tagliabue L.C., 'A case study of solar technologies adoption: criteria for BIPV integration in sensitive built environment.' *Energy Procedia*, 2012, 30: 1006-1015. DOI: 10.1016/j.egypro.2012.11.113

[Futura Sciences *et al.* 2017] Futura Sciences & Perrin M., *Le Recyclage Des Panneaux Solaires Est-Il Possible?*, 2017.

[Gantner *et al*. 2018] Gantner J., Fawcett W. & Ellingham I., 'Probabilistic Approaches to the Measurement of Embodied Carbon in Buildings.' *Embodied Carbon in Buildings. Measurement, Management Adn Mitigation*. Springer, 2018, 23–50. DOI: 10.1007/978-3-319-72796-7

[Gan 2009] Gan G., 'Effect of air gap on the performance of builing-integrated photovoltaics.' *Energy*, 2009, 34 (7): 913-921. DOI: 10.1016/j.energy.2009.04.003

[Gellings *et al*. 2016] Gellings C.W. & Parmenter K.E., 'Demand-Side Management.' in Goswami D.Y. & Kreith F., *Energy Efficiency and Renewable Energy Handbook*. 2nd ed.Boca Raton : CRC Press, 2016, 289–310. ISBN 9781138749115

[Green *et al*. 2018] Green M.A., Hishikawa Y., Dunlop E.D., Levi D.H., Hohl-Ebinger J. & Ho-Baillie A.W.Y., 'Solar Cell Efficiency Tables (version 52).' *Wiley Progress in Photovoltaics*, 2018, 26 (7): 427-436. DOI: 10.1002/pip.3040

[Gläser *et al*. 2004] Gläser J. & Laudel G., *Experteninterviews Und Qualitative Inhaltsanalyse*. Springer, 2004. ISBN 978-3-531-17238-5

[Gaillard *et al*. 2014] Gaillard L., Ménézo C., Giroux S., Pabiou H. & Le-Berre R., 'Experimental Study of Thermal Response of PV Modules Integrated into Naturally-ventilated Double Skin Facades.' *Energy Procedia*, 2014, 48: 1254-1261. DOI: 10.1016/j.egypro.2014.02.142

[Glaumann *et al*. 2010] Glaumann M., Malmqvist T., Peuportier B., Wetzel C., Scarpellini S., Zabalza I., Diaz de Garayo S., Staller H., Krigsvoll G., Stoykova E., Horvath S., Szalay Z. & Degiovanni V., *Energy Saving through Promotion of Life Cycle Assessment in Buildings. Guidelines for LCA Calculations in Early Design Phases*. ENSLIC BUILDING, 2010.

[Gutschner *et al.* 2002] Gutschner M., Nowak S., Toggweiler P. & Schoen T., Potential for Building Integrated Photovoltaics. Achievable Levels of Electricity from Photovoltaic Roofs and Façades: Methodology, Case Studies, Rules of Thumb and Determination of the Potential of Building Integrated Photovoltaics for Selected Countries. PVPS Photovoltaic Power Systems Programme, 2002.

[Goe *et al.* 2014] Goe M. & Gaustad G., 'Strengthening the case for recycling photovoltaics: An energy payback analysis.' *Applied Energy*, 2014, 120: 41-48. DOI: j.apenergy.2014.01.036

[Goswami *et al.* 2016] Goswami D.Y. & Kreith F., *Energy Efficiency and Renewable Energy Handbook*. Boca Raton : CRC Press, 2016. ISBN 9781138749115

[Goldschmidt 1998] Goldschmidt G., 'Creative architectural design: reference versus precedence.' *Journal of Architectural and Planning Research*, 1998, 15 (3): 258-270

[Grand Conseil GE 1988] Grand Conseil GE, *Loi Sur Les Constructions et Les Installations Diverses (LCI)*., 1988.

[Gray 2016] Gray J., Insulation Materials. *Sustainable Build*, 2016.

[Gray 2019] Gray J., Insulation Materials. *Sustainable Build*, 2019.

[Godina *et al.* 2018] Godina R., Rodrigues E.M.G., Pouresmaeil E. & Catalão J.P.S., 'Optimal residential model predictive control energy management performance with PV microgeneration.' *Computers and Operations Research*, 2018, 96: 143-156. DOI: 10.1016/j.cor.2017.12.003

[Galvez-Martos *et al.* 2018] Galvez-Martos J.-L., Styles D., Schoenberger H. & Zeschmar-Lahl B., 'Construction and demolition waste best management practice in Europe.' *Resources, Conservation and Recycling*, 2018, 136. DOI: 10.1016/j.resconrec.2018.04.016

[Guichi *et al.* 2018] Guichi A., Talha A., Berkouk E.M. & Mekhilef S., 'Energy management and performance evaluation of grid connected PV-battery hybrid system with inherent control scheme.' *Sustainable Cities and Society*, 2018, 41: 490-504. DOI: 10.1016/j.scs.2018.05.026

[Gutschner *et al*. 2001] Gutschner M., Nowak S. & IEA PVPS Task 7, *Potential for Building Integrated Photovoltaics*., 2001.

[Guiavarch *et al.* 2006] Guiavarch A. & Peuportier B., 'Photovoltaic collectors efficiency according to their integration in buildings.' *Solar Energy*, 2006, 80: 65-77. DOI: 10.1016/j.solener.2005.07.004

[Guerrero-Lemus *et al.* 2016] Guerrero-Lemus R., Vega R., Kim T., Kimm A. & Shephard L.E., Bifacial solar photovoltaics - A technology review. *Renewable and Sustainable Energy Reviews, 2016, 60 :1533-1549*. DOI: 10.1016/j.rser.2016.03.041

[H.Glass 2019] H.Glass, H.Glass. 2019. www.h.glass.ch

[Haas *et al.* 2002] Haas R. & IEA PVPS Task 7, Market Deployment Strategies for PV Systems in the Built Environment. An Evaluation of Incentives, Support Programmes and Marketing Activities. IEA International Energy Agency PVPS, 2002.

[Hagen *et al.* 2012] Hagen R. & Bruun Jorgensen O., *The Communication Process. Subtask C: Communication Guideline*. IEA International Energy Agency, 2012.

[Hachem-Vermette 2018] Hachem-Vermette C., 'Multistory building envelope: Creative design and enhanced performance.' *Solar Energy*, 2018, 159: 710-721. DOI: 10.1016/j.solener.2017.11.012

[Häkkinen *et al.* 2015] Häkkinen T., Kuittien M., Ruuska A. & Jung N., 'Reducing embodied carbon during the design process of buildings.' *Journal of Building Engineering*, 2015, 4: 1-13. DOI: 10.1016/j.jobe.2015.06.005

[Hall *et al.* 2017] Hall M. & Geissler A., 'Different balancing methods for Net Zero Energy Buildings -Impact of time steps, grid interaction and weighting factors.' *Energy Procedia*, 2017, 122: 379-384. DOI: 10.1016/j.egypro.2017.07.422

[Hansen *et al.* 2017] Hansen C.W., Riley D., Deline C., Toor F. & Stein J., A detailed performance model for bifacial PV modules. *IEEE 44th Photovoltaic Specialist Conference (PVSC)*, 2017. DOI:10.1109/pvsc.2017.8366045

[Harrison 2009] Harrison C.H., How to frame and explain the survey data in your honors thesis. Harvard Conference 2009.

[Hauberg 2011] Hauberg J., 'Research by design - a research strategy.' *AE.Revista Lusófona de Arquitectura e Educaçao*, 2011, 5

[Hauke *et al.* 2016] Hauke B., Kuhnhenne M., Lawson M. & Veljkovic M., *Sustainable Steel Buildings: A Practical Guide for Structures and Enevelopes*. Wiley-Blackwell, 2016. ISBN 9781118740798

[Hegger *et al.* 2006] Hegger M., Auch-Schwelk V., Fuch M. & Rosenkranz T., *Construction Materials Manual*. Birkhäuser, 2006. ISBN-13: 978-3764375706

[Hegger *et al.* 2008] Hegger M., Fuch M., Stark T. & Zeumer M., *Energy Manual. Sustainable Architecture*. Edition Detail. Birkhäuser, 2008. ISBN: 978-3-7643-8764-8

[Heinstein *et al.* 2013] Heinstein P., Ballif C. & Perret-Aebi L.-E., 'Building Integrated Photovoltaic (BIPV): Review, Potentials, Barriers and Myths.' *Green*, 2013. DOI: 10.1515/green-2013-0020

[Herzog *et al.* 2004] Herzog T., Krippner R. & Lang W., *Facade Construction Manual*. DETAIL. Germany : Birkhäuser, 2004. ISBN: 978-3-0346-1456-6

[Hestnes 1999] Hestnes A.G., 'Building Integration Of Solar Energy Systems.' *Solar Energy*, 1999, 67 (4–6): 181-187. DOI: 10.1016/S0038-092X(00)00065-7

[Hindrichs *et al.* 2006] Hindrichs D.U. & Heusler W., *Façades- Building Envelopes for the 21st Century*. Birkhäuser, 2006. ISBN: 9783764399597

[Horvat *et al.* 2012a] Horvat M. & Dubois M.-C., *Tools and methods for solar design. An overview of IEA SHC Task 41*, Subtask B.2012.

[Horvat *et al.* 2012b] Horvat M. & Wall M., *Solar Design of Buildings for Architects: Review of Solar Design Tools*. IEA International Energy Agency, 2012.

[Husain *et al.* 2018] Husain A.A.F., Hasan W.Z.W., Shafie S., Hamidon M.N. & Pandey S.S., 'A review of transparent solar photovoltaic technologies.' *Renewable and Sustainable Energy Reviews*, 2018, 94: 779-791. DOI: 10.1016/j.rser.2018.06.031

[Hüsser and Nova Energia 2015] Hüsser P. & Nova Energia GmbH, *National Survey Report of PV Power Applications in Switzerland.* IEA International Energy Agency, 2015.

[IEA 2011] IEA, *World Energy Outlook 2011*. International Energy Agency, 2011.

[IEA 2013] IEA, *Energy Efficiency 2013: Market Report, Market Trends and Medium-Term Prospects*. International Energy Agency, 2013.

[IEA 2019] IEA, The International Energy Agency. 2019. www.iea.org, accessed 22nd April 2019.

[IEA PVPS 2016] IEA PVPS, *PVPS Annual Report 2016*. IEA International Energy Agency PVPS, 2016.

[IEA PVPS 2019] IEA PVPS, PV database. Urban scale photovoltaic systems. 2019. www.pvdatabase.org

[Ibn-Mohammed *et al.* 2013] Ibn-Mohammed T., Greenough R., Taylor S., Ozawa-Meida L. & Acquaye A., 'Operational vs. embodied emissions in buildings: A review of current trends.' *Energy and Buildings*, 2013, 66: 232-245. DOI: 10.1016/j.enbuild.2013.07.026

[Ihara *et al.* 2015] Ihara T., Gustavsen A. & Jelle B.P., 'Effect of façade components on energy efficiency in office buildings.' *Applied Energy*, 2015, 158: 422-432. DOI: 10.1016/j.apenergy.2015.08.074

[IPCC 2001] IPCC, *Climate Change 2001: Impacts, Adaptation and Vulnerability*. Intergovernmental Panel on Climate Change, 2001.

[IPCC 2018] IPCC, *Global Warming of 1.5°C*. Summary for Policymakers., 2018.

[IPCC 2019] IPCC, *The Intergovernmental Panel on Climate Change (IPCC)*. 2019. www.ipcc.ch

[*IPCC* 2014] Geneva, Switzerland: Intergovernmental Panel on Climate Change, 2014.

[IRENA 2017] IRENA, *Renewable Power Generation Costs in 2017*. International Renewable Energy Agency, 2017.

[IRENA 2019] IRENA, *Data, research and resources on renewable energy cost*. 2019. www.irena.org

[ISO 2010] ISO, ISO 14025: *Environmental Labels and Declarations.*, 2010.

[ISO 2016] ISO, *Environmental Management, Life Cycle Assessment, Requirements and Guidelines*. International Organization for Standardization, 2016.

[Jackodur 2018] Jackodur. Caractéristiques techniques. 2018. www.jackon-insulation.fr

[Jelle *et al.* 2012] Jelle B.P., Breivik C. & Røkenes H.D., 'Building integrated photovoltaic products: A state-of-the-art review and future research opportunities.' *Solar Energy Materials and Solar Cells*, 2012, 100: 69-96. DOI: 10.1016/j.solmat.2011.12.016

[Jelle 2016] Jelle B.P., 'Building Integrated Photovoltaics: A Concise Description of the Current State of the Art and Possible Research Pathways.' *Energies*, 2016, 9 (1):21. DOI: 10.3390/en9010021

[Jiang *et al.* 2107] Jiang B., Muzhikyan A., Farid A.M. & Youcef-Toumi K., 'Demand side management in power grid enterprise control: A comparison of industrial & social welfare approaches.' *Applied Energy*, 2107, 187: 833-846. DOI: 10.1016/j.apenergy.2016.10.096

[Jolissaint *et al.* 2017] Jolissaint N., Hanbali R., Hadorn J.-C. & Schüler A., 'Colored solar façades for buildings.' Energy Procedia, 2017, 122: 175-180. DOI: 10.1016/j.egypro.2017.07.340

[Jones *et al.* 2015] Jones P., Hou S.S. & Li X., 'Towards zero carbon design in offices: Integrating smart façades, ventilation, and surface heating and cooling.' *Renewable Energy*, 2015, 73: 69-76. DOI: 10.1016/j.renene.2014.06.027

[John 2012] John V., Derivation of Reliable Simplification Strategies for the Comparative LCA of Individual and 'Typical' Newly Built Swiss Apartment Buildings. ETH Zurich, Zurich, 2012. DOI: 10.3929/ethz-a-007607252

[de Jonge *et al.* 2002] de Jonge T.M. & van der Voordt D.J.M., *WAYS to Study and Research Urban, Architectural and Technical Design*. DUP Science, 2002. ISBN: 90-407-2332-X

[Kang *et al.* 2015] Kang J.-E., Ahn K.-U., Park C.-S. & Schuetze T., 'A Case Study on Passive vs. Active Strategies for an Energy-Efficient School Building Design.' *Proceedings of the 8th Conf. Int. Forum Urbanism (IFoU). True Smart and Green city?*, Incheon, Republic of Korea, 2015.

[Karakaya *et al.* 2015] Karakaya E. & Sriwannawit P., Barriers to the adoption of photovoltaic systems: The state of the art. *Renewable and Sustainable Energy Reviews*. 2015, 49: 60–66. DOI: 10.1016/j.rser.2015.04.058

[Kousksou *et al.* 2014] Kousksou T., Bruel P., Jamil A., El Rhafiki T. & Zeraouli Y., 'Energy storage: Applications and challenges.' 2014, 120: 59-80. DOI: 10.1016/j.solmat.2013.08.015

[Knaack *et al.* 2014] Knaack U., Bilow M., Klein T. & Auer T., *Façades. Principles of Construction*. Birkhäuser, 2014. DOI: 10.1515/9783038211457.

[KBOB 2016] KBOB, *Données écobilans dans la construction* 2009/1:2016.

[Khalilpour *et al.* 2015] Khalilpour R. & Vassallo A., 'Leaving the grid: an ambition or a real choice?' *Energy Policy*, 2015, 82: 207-221. DOI: 10.1016/j.enpol.2015.03.005

[Kreinin *et al.* 2016] Kreinin L., Karsenty A., Grobgeld D. & Eisenberg N., 'PV systems based on bifacial modules: Performance simulation vs. design factors.' *IEEE 43rd Photovoltaic Specialists Conference (PVSC)*, Portland, 2016.

[Kuittinen *et al.* 2013] Kuittinen M., Ludvig A., Weiss G., Arfvidsson J., De Angelis E., Dodoo A., Dolezal F., Gustavsson L., Hafner A., Häkkinen T., Linkosalmi L., Mair am Tinkhof O., Mötzl H., Mundt-Petersen S.O., Ott S., Peñaloza D., Pittau F., Sathre R., Spitzbart C., Takano A., Toratti T., Valtonen T., Vares S., Winter S. & Zanata G., *Wood in Carbon Efficient Construction. Tools, Methods and Applications*. Finland : Hämeen Kirjapaino Oy, 2013. ISBN 978-9-0820-9080-2

[Kleinert *et al.* 2016] Kleinert E., McMahon J.E., Rosenquist G., Lutz J., Lekov A., Biermayer P. & Meyers S., 'Energy-Efficient Technologies: Major Appliances and Space Conditioning Equipment.' *Energy Efficiency and Renewable Energy Handbook*. 2nd ed.Boca Raton : CRC Press, 2016, 659–78. DOI: 10.1201/b18947

[Knepell *et al.* 1993] Knepell P. & Arangno D.C., *Simulation Validation. A Confidence Assessment Methodology*. Los Alamitos, California : IEEE Computer Society Press, 1993. ISBN: 0818635118

[Knauf 2018] Knauf, Knauf Silent Board 12.5. 2018.

[Knaack *et al.* 2014a] Knaack U., Bilow M., Klein T. & Auer T., Façades. Principles of Construction. Birkhäuser, 2014. ISBN: 978-30-3821-044-3

[Knaack *et al.* 2014b] Knaack U., Klein T. & Bilow M., *Imagine 03_Performance Driven Envelopes*. Rotterdam : 010 Publishers, 2011. ISBN 978-90-6450-675-8

[Kohli 2008] Kohli R., *Scénarios Des Ménages. Evolution Des Ménages Privés Entre 2005 et 2030*. OFS (Office fédérale de la statistique), 2008.

[Kohli 2017] Kohli R., *Scénarios Des Ménages. Evolution Des Ménages Privés Entre 2017 et 2045*. OFS (Office fédérale de la statistique), 2017.

[Konis *et al.* 2017] Konis K. & Selkowitz S., *Effective Daylighting with High-Performance Façades. Emerging Design Practices*. Springer, 2017. ISBN 978-3-319-39463-3

[Korjenic *et al.* 2011] Korjenic A., Petranek V., Zach J. & Hroudova J., 'Development and performance evaluation of natural thermal-insulation materials composed of renewable resources.' *Energy and Buildings*, 2011, 43 (9): 2518-2523. DOI: 10.1016/j.enbuild.2011.06.012

[Khan *et al.* 2015] Khan A.A., Razzaq S., Khan A. & Khursheed F., 'HEMSs and enabled demand response in electricity market: An overview.' *Renewable and Sustainable Energy Reviews*, 2015, 42: 773-785. DOI: 10.1016/j.rser.2014.10.045

[KRONO 2018] KRONO, KRONOPLY OSB/3- Charakteristische Werte nach DIN EN 13986. 2018.

[Koezjakov *et al.* 2018] Koezjakov A., Ürge-Vorsatz D., Crijns-Graus W. & van den Broek M., 'The relationship between operational energy demand and embodied energy in Dutch residential buildings.' *Energy and Buildings*, 2018, 165: 233-245. DOI: 10.1016/j.enbuild.2018.01.036

[Kuhn *et al.* 2014] Kuhn T.E., Herkel S. & Henning H.-M., *Active solar façades (PV and solar thermal)*. 2014. ISBN: 978-960-6746-08-6

[Kylili *et al.* 2014] Kylili A. & Fokaides P.A., Investigation of building integrated photovoltaics potential in achieving the zero energy building target. *Indoor and Built Environment*, 2014, 23(1): 92-106. DOI: 10.1177/1420326X13509392

[Lazos *et al.* 2012] Lazos D. & Bruce A., 'The value of commercial BIPV systems in the urban environment.' 50th Annual Conference, Australian Solar Energy Society (Australian Solar Council), Melbourne, 2012.

[Lassandro *et al.* 2017] Lassandro P. & Di Turi S., 'Façade retrofitting: from energy efficiency to climate change mitigation.' Vol 140AiCARR 50th International Congress; Beyond NZEB Buildings, 10-11 May, Matera, Italy, 2017.

[Laukamp *et al.* 2002] Laukamp H., Fraunhofer Institut für Solare Energiesysteme & IEA PVPS Task 7, *Reliability Study of Grid Connected PV Systems. Field Experience and Recommended Design Practice*. IEA International Energy Agency PVPS, 2002.

[Lane 2010] Lane T., Embodied energy: the next big carbon challenge. 2010, www.building.co.uk .article, accessed 16th September 2016.

[Lang 2004] Lang A., Charakterisierung des Altholzaufkommens in Deutschland. Rechtliche Rahmenbedingungen - Mengenpotenzial - Materialkennwerte.2004. ISSN 0368-8798

[Lapierre 2005] Lapierre E., Inquiétant ready-made. *Matières*, 2005, 7. ISBN-13: 9782880746216

[LAST 2019] LAST, *Concours Pour Étudiants ACTIVE HOUSING. Rapport Du Jury*. Lausanne (Suisse): Laboratory of Architecture and Sustainable Technologies of the Swiss Federal Institute of Technology Lausanne, 2019.

[Le *et al.* 2018] Le A.T.H., Domingo N., Rasheed E. & Park K.S., 'Building maintenance cost planning and estimating: a literature review.' 34th Annual ARCOM Conference, Belfast, UK, 2018

[Lee 2011] Lee S., *Aesthetics of sustainable architecture.* 010 Publishers, Rotterdam 2011. ISBN: 978-90-6450-752-6

[Lewis *et al.* 1991] Lewis J.O. & De Oliveira Fernandes E., 'European Architectural ideas competition: working in the city.' *Proceedings and Comment on the 8th International 1990 Passive and Low Energy Architecture Conference*. PLEA, 1991

[Lützkendorf *et al.* 2015] Lützkendorf T., Foliente G., Balouktsi M. & Wiberg A.H., 'Net-zero buildings: incorporating embodied impacts.' *Building Research & Information*, 2015, 43:1. DOI: 10.1080/09613218.2014.935575

[Loonen *et al.* 2015] Loonen R.C.G.M., Rico-Martinez J.M., Favoino F., Brzezicki M., Menezo C., La Ferla G. & Aelenei L., 'Design for façade adaptability - Towards a unified and systematic characterization.' *10th Energy Forum - Advanced Building Skins*, Bern, Switzerland, 2015.

[Lobsiger-Kägi *et al.* 2018a] Lobsiger-Kägi E., Tomic U., Spiess H., Kuehn T. & Carabias-Hütter V., 'Acceptance of BIPV Application in Switzerland. A Study on Socio-Political Acceptance among the Broad Public and Local Administration'. ZHAW Institut für Nachhaltige Entwicklung, 2018.

[Lobsiger-Kägi *et al.* 2018b] Lobsiger-Kägi E., Tomic U., Spiess H., Kuehn T. & Carabias-Hütter V., 'Community and socio-political acceptance of building-integrated photovoltaics', 2018.

[Lobsiger-Kägi *et al.* 2018c] Lobsiger-Kägi E., Tomic U., Spiess H., Kuehn T. & Carabias-Hütter V., 'Exploring the Social Acceptance of Building Integrated Photovoltaics in Switzerland.' *5th European Conference on Behaviour and Energy Efficiency*. BEHAVE 2018, Zurich, 2018.

[Lupíšek *et al.* 2015] Lupíšek A., Vaculíková M., Mancík Š., Hodková J. & Ružicka J., Design strategies for low embodied carbon and low embodied energy buildings: principles and examples. *Energy Procedia, 2015, 83: 147-156*. DOI: 10.1016/j.egypro.2015.12.205

[Luthander *et al*. 2015] Luthander R., Widén J., Nilsson D. & Palm J., 'Photovoltaic self-consumption in buildings: A review.' *Applied Energy*, 2015, 142: 80-94. DOI: 10.1016/j.apenergy.2014.12.028

[Lynch 2015] Lynch G., Brickwork: History, Technology and Practice: Volume 2. New York : Routledge, 2015. ISBN-13: 978-18-7339-406-9

[Moussavi Nadoushani *et al.* 2017] Moussavi Nadoushani Z.S., Akbarnezhad A., Ferre Jornet J. & Xiao J., 'Multi-criteria selection of façade systems based on sustainability criteria.' *Building and Environment*, 2017, 121: 67-78. DOI: 10.1016/j.buildenv.2017.05.016

[Mohajeri *et al.* 2016] Mohajeri N., Assouline D., Guiboud B. & Scartezzini J.L., 'Does roof shape matter? Solar PV integration on Roofs.' *Expanding Boundaries: Systems Thinking for the Built Environment*. Sustainable Built Environment (SBE) Regional Conference, Zurich, 2016.

[Marchand 2016a] Marchand B., A l'echelle de la vitesse et du mouvement. Symboliques et plasticités. *Matières*, 2016, 13. ISBN-13: 978-28-8915-171-4

[Marchand 2016b] Marchand B., Editorial. *Matières*, 2016, 13. ISBN-13: 978-28-8915-171-4

[Marsault 2018] Marsault X., Eco-Generative Design for Early Stages of Architecture. Wiley-ISTE, 2018. ISBN: 978-1-786-30180-2

[Maturi 2013] Maturi L., 'Building Skin as Energy Supply: Prototype Development of a Wooden Prefabricated BIPV Wall.' PhD Thesis,Università degli Studi di Trento, 2013.

[Moncaster *et al.* 2018] Moncaster A.M., Birgisdottir H., Malmqvist T., Nygaard Rasmussen F., Houlihan Wiberg A. & Soulti E., 'Embodied Carbon Measurement, Mitigation and Management Within Europe, Drawing on a Cross-Case Analysis of 60 Building Case Studies.' *Embodied Carbon in Buildings. Measurement, Management and Mitigation*. Springer, 2018, 443–462. ISBN: 978-3-319-72795-0

[Messenger *et al.* 2016] Messenger R. & Goswami D.Y., 'Photovoltaics.' *Energy Efficiency and Renewable Energy Handbook*. 2nd ed.Boca Raton : CRC Press, 2016, 1393–1474. ISBN 9781138749115

[Melius *et al.* 2013] Melius J., Margolis R. & Ong S., *Estimating Rooftop Suitability for PV: A Review of Methods, Patents, and Validation Techniques*. National Renewable Energy Laboratory (NREL), 2013.

[Meuser *et al.* 2009] Meuser M. & Nagel U., 'The expert interview and changes in knowledge production.' *Interviewing Experts*. Palgrave Macmillan, 2009, 17–42. DOI: 10.1057/9780230244276_2

[Miao 2016] Miao Z., 'Smart Grid Technology.' *Energy Efficiency and Renewable Energy Handbook*. 2nd ed.Boca Raton : CRC Press, 2016, 983–1090. ISBN 9781138749115

[Minergie 2018] Minergie, Aide à l'utilisation des labels MINERGIE / MINERGIE-P / MINERGIE-A. 2018. www.minergie.ch

[Minergie 2019] Minergie, Minergie - Home. 2019. www.minergie.ch

[Moura *et al.* 2013] Moura P.S., Lopez G.L., Moreno J.I. & de Almeida A.T., 'The role of Smart Grids to foster energy efficiency.' *Energy Efficiency*, 2013, 6 (4): 621-639. DOI: 10.1007/s12053-013-9205-y

[Maturi *et al.* 2015] Maturi L., Lollini R., Moser D. & Sparber W., Experimental investigation of a low cost passive strategy to improve the performance of Building Integrated Photovoltaic systems. *Solar Energy 2015,* 111: 288-296. DOI: 10.1016/j.solener.2014.11.001

[Morvaj *et al*. 2010] Morvaj Z. & Bukarica V., 'Energy efficiency policy.' in Palm J., *Energy Efficiency*. InTech, 2010. ISBN: 978-953-307-137-4

[Mourant 2014] Mourant A., 'BIPV: Better form, improved function.' *Renewable Energy Focus*, 2014, 15 (5): 20-23. DOI: 10.1016/S1755-0084(14)70115-2

[Montoro *et al.* 2011] Montoro D.F., Vanbuggenhout P. & Ciesielska J., Building Integrated Photovoltaics. An Overview of the Existing Products and Their Fields of Application. Report Prepared in the Framework of the European Funded Project SUNRISe. EPIA (European Photovoltaic Industry Association), 2011.

[Munari Probst 2008] Munari Probst M.C 'Architectural Integration and Design of Solar Thermal Systems.' PhD Thesis, EPFL (Ecole Polytechnique Fédérale de Lausanne), Lausanne, 2008. DOI: 10.5075/epfl-thesis-4258

[Munari Probst *et al.* 2007] Munari Probst M.C. & Roecker C., 'Towards an improved architectural quality of building integrated solar thermal systems (BIST).' *Solar Energy*, 2007, 81 (9): 1104-1116. DOI: 10.1016/j.solener.2007.02.009

[Munari Probst *et al.* 2011] Munari Probst M.C. & Roecker C., Architectural Integration and Design of Solar Thermal Systems. Lausanne : EPFL Press, 2011. ISBN: 978-0-415-66791-3

[Munari Probst *et al.* 2012a] Munari Probst M.C., Roecker C., Frontini F., Scognamiglio A., Farkas K., Maturi L. & Zanetti I., *Solar Energy Systems in Architecture, Integration Criteria and Guidelines*. SHC, Solar heating and cooling programme, 2012.

[Munari Probst *et al.* 2012b] Munari Probst M.C. & Roecker C., 'Criteria for Architectural Integration of Active Solar Systems IEA Task 41, Subtask A.' *Energy Procedia*, 2012, 30: 1195-1204. DOI: 10.1016/j.egypro.2012.11.132

[Munari Probst *et al.* 2014] Munari Probst M.C., Deschamps L. & Roecker C., 'Innovative solar products for architectural integration: A joint IEA tasks 41 and 51 website.' EuroSun 2014, Aix-les-Bains, France, 2014. DOI: 10.18086/eurosun.2014.18.05

[Munari Probst *et al.* 2019] Munari Probst M.C. & Roecker C., ' Criteria and policies to master the visual impact of solar systems in urban environments: The LESO-QSV method' *Solar Energy*, 2019, 184: 672-687. DOI: 10.1016/j.solener.2019.03.031

[Mundy 2015] Mundy J., The Green Guide Explained. 2015. www.bre.co.uk

[Nault 2016] Nault E., Solar Potential in Early Neighborhood Design a Decision-Support Workflow Based on Predictive Models. PhD Thesis, EPFL (Ecole Polytechnique Fédérale de Lausanne), Lausanne, 2016. DOI:10.5075/epfl-thesis-7058

[Nyholm *et al.* 2016] Nyholm E., Goop J., Odenberger M. & Johnson F., 'Solar photovoltaic-battery systems in Swedish households - Self-consumption and self-sufficiency.' *Applied Energy*, 2016, 183: 148-159. DOI: 10.1016/j.apenergy.2016.08.172

[Niederle 2016] Niederle W., 'Strategies and Instruments for Renewable Energy and Energy Efficiency: Internationally, in Europe, and in Germany.' in Goswami D.Y. & Kreith F., *Energy Efficiency and Renewable Energy Handbook*. 2nd ed.Boca Raton : CRC press, 2016, 55–70. ISBN: 978-11-3874-911-5

[Novikov *et al.* 2013] Novikov A.M. & Novikov D.A., *Research Methodology. From Philosophy of Science to Research Design*. Boca Raton : CRC Press, 2013. ISBN: 978-03-6738-012-0

[Nehasilova *et al.* 2016] Nehasilova M., Potting J., Soulti E., Birgisdottir H., Houlihan-Wiberg A., Malmqvist T., Moncaster A. & Rasmussen F.N., *IEA EBC Annex 57- Subtask 4: Case Studies and Recommendations for the Reduction of Embodied Energy and Embodied Greenhouse Gas Emissions from Buildings*. Japan: Institute for Building Environment and Energy Conservation, 2016. DOI: 10.1016/j.enbuild.2017.08.030

[NREL 2019] NREL, Best Research-Cell efficiency chart. Photovoltaic research. 2019. www.nrel.gov

[Odersun 2011] Odersun, Manual for BIPV projects. 2011.

[OECD 2011] OECD, Green Growth Studies: Energy., 2011.

[OFEN 2002] OFEN, *Catalogue Construction Neuve*. 2002. www.catalogueconstruction.ch

[OFEN 2012] OFEN, *Statistique Suisse de l'électricité 2012*. Office fédéral de l'energie, 2012.

[OFEN 2013] OFEN, *Statistique Suisse de l'électricité 2013*. Office fédéral de l'energie, 2013.

[OFEN 2014] OFEN, *Statistique Suisse de l'électricité 2014*. Office fédéral de l'energie, 2014.

[OFEN 2015] OFEN, *Statistique Suisse de l'électricité 2015*. Office fédéral de l'energie, 2015.

[OFEN 2016a] OFEN, *Statistique Suisse de l'électricité 2016*. Office fédéral de l'energie, 2016.

[OFEN 2016b] OFEN, *Photovoltaïque: Observations Du Marché* 2016., 2016.

[OFEN 2017a] OFEN, *Energie, faits et chiffres*. 2017. www.eda.admin.ch

[OFEN 2017b] OFEN, *Principales Nouveautés Du Droit de l'energie à Partir de 2018*., 2017.

[OFEN 2017c] OFEN, *Statistique Suisse de l'électricité 2017*. Office fédéral de l'energie, 2017.

[OFEN 2018] OFEN, *La Stratégie Énergétique 2050 Après l'entrée En Vigueur de La Nouvelle Loi Sur l'énergie*, 2018.

[OFS 2011] OFS, *ValueS. Living, Building: Switzerland's Built Environment*. OFS (Office fédérale de la statistique), 2011.

[OFS 2015a] OFS, *Evolution future de la population- Données, Indicateurs - Scénarios suisses. Statistique suisse - L'essentiel en bref*, 2015, www.bfs.admin.ch, accessed 2nd March 2016.

[OFS 2015b] OFS, *Les Scénarios de l'évolution de La Population de La Suisse 2015-2045*. OFS (Office fédérale de la statistique), 2015.

[OFS 2018a] OFS, *Statistical Data on Switzerland 2018*. Neuchâtel: OFS (Office fédérale de la statistique), 2018.

[OFS 2018b] OFS, *Construction et Logement 2016*. Office fédérale de la statistique, 2018.

[Osseweijer *et al.* 2018] Osseweijer F.J.W., van den Hurk L.B.P., Teunissen E.J.H.M. & van Sark W.G.J.H.M., 'A comparative review of building integrated photovoltaics ecosystems in selected European countries.' *Renewable and Sustainable Energy Reviews*, 2018, 90: 1027-1040. DOI: 10.1016/j.rser.2018.03.001

[de Oliveira e Silva *et al.* 2016] de Oliveira e Silva G. & Hendrik P., 'Lead-acid batteries coupled with photovoltaics for increased electricity self-sufficiency in households.' *Applied Energy 178*, 2016. DOI: 10.1016/j.apenergy.2016.06.003

[Onyx Solar 2019] Onyx Solar, Technical Specifications. *Onyx Solar*, 2019. www.onyxsolar.com

[Ortelli 2016] Ortelli L., Considérations sur la notion d'échelle en architecture. *Matières*, 2016, 13. ISBN-13: 978-28-8915-171-4

[Pant 2019] Pant P., How much you should budget for home maintenance. *the balance*, 2019, www.thebalance.com

[Perlin 2013] Perlin J., *Let It Shine. The 6,000-Year Story of Solar Energy*. New World Library, 2013. ISBN: 978-1-60868-132-7

[Perret-Aebi *et al.* 2013] Perret-Aebi L.-E., Heinstein P., Chapuis V., Schlumpf C., Li H.-Y., Roecker C., Schueler A., Le Caër V., Joly M., Tween R., Leterrier Y., Månson J.-A., Scartezzini J.-L. & Ballif C., 'Innovative solution for building integrated photovoltaics.' Proc. CISBAT1. 2013

[Perret-Aebi 2019a] Perret-Aebi L.-E., Vers des façades actives?. Presentation at the *Vernissage du Cahier spécial Solaris #03,* 2019

[Perret-Aebi 2019b] Perret-Aebi L.-E., PV2050: Photovoltaics into the Built Environment: From Semi-Transparent PV Glazing to High Efficiency Roof Integrated Solutions. Swiss National Science Foundation (FNSNF), 2019.

[Pfadenhauer 2009] Pfadenhauer M., 'At eye level: the expert interview-a talk between expert and quasi expert.' *Interviewing Experts*. Palgrave Macmillan, 2009, 81–98. DOI: 10.1057/9780230244276_4

[Prieto *et al.* 2017] Prieto A., Knaack U., Auer T. & Klein T., Solar façades - Main barriers for widespread façade integration of solar technologies. *Journal of Façade Design & Engineering*, 2017, 5 (1): 51-62. DOI: 10.7480/jfde.2017.1.1398

[Polysolar 2015] Polysolar, Guide to BIPV. Building integrated photovoltaics. 2015

[Pomponi *et al.* 2018] Pomponi F. & Medina Campos L., 'Embodied and Life Cycle Carbon Assessment of Buildings in Latin America: State of the Art and Future Directions.' *Embodied Carbon in Buildings: Measurement, Management, and Mitigation*. Springer, 2018, 483–503. DOI: 10.1007/978-3-319-72796-7

[Pomponi *et al.* 2016] Pomponi F. & Moncaster A., 'Embodied carbon mitigation and reduction in the built environment – What does the evidence say?' *Journal of Environmental Management*, 2016, 181: 687-700. DOI:10.1016/j.jenvman.2016.08.036

[Pronovo 2019] Pronovo, Programmes d'encouragement. *pronovo*, 2019, www.pronovo.ch, accessed 7th February 2019.

[Prost 1992] Prost R., Conception Architecturale. Une Investigation Méthodologique. L'Harmattan. Paris, 1992. ISBN: 2-7384-1240-8

[Palm *et al.* 2018] Palm J., Tautenhahn L., Weick J., Kalio R., Kullmann J., Heliand A., Grïnsteid S., Schmidt N., Borowski P. & Karg F., 'BIPV Modules: Critical Requirements and Customization in Manufacturing.' IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC), Waikoloa Village, HI, USA, 2018

[PV cycle 2019] PV cycle, PV cycle. 2019, www.pvcycle.org

[PV Upscale *et al.* 2015] PV Upscale, Intelligent Energy & IEA PVPS Task 10, PV database. 2015. www.pvdatabase.org

[PVPS 2016] PVPS, PVPS Task 7: Photovoltaic power systems in the built environment. 2016. www.iea-pvps.org/?id=53

[PVPS 2019] PVPS, PVPS Task 15: Enabling framework for the acceleration of BIPV. 2019. www.iea-pvps.org/index.php?id=task15

[PVPS 1993] PVPS, International Energy Agency technology collaboration programme: Photovoltaic Power Systems Programme. 1993. www.iea-pvps.org

[PV sites 2018] PV sites, BIPV Demo sites overview. *PV sites*, 2018. www.pvsites.eu

[PwC 2018] PwC, PwC Real Estate Investor Survey. Cap Rates and Letting Assumptions for All Relevant Germand and Swiss Real Estate Submarkets. PricewaterhouseCoopers GmbH Wirtschaftsprüfungsgesellschaft, 2018.

[Rasmussen *et al.* 2016] Rasmussen B.P., Kreider J.F., Claridge D.E. & Culp C.H., 'Heating, Ventilating, and Air Conditioning Control Systems.' in Goswami D.Y. & Kreith F., *Energy Efficiency and Renewable Energy Handbook*. 2nd ed.Boca Raton : CRC Press, 2016, 565–620. ISBN: 978-11-3874-911-5

[Randall 2001] *Photovoltaics and Architecture*, London : Taylor & Francis, 2001. DOI: 10.4324/9780203165829

[Ruggieri *et al*. 2013] Ruggieri G., Dotelli G., Melià P. & Sabbadini S., 'Life cycle assessment of refurbishment strategies for historic buildings.' *Retrofitting the Built Environment*. Wiley, 2013. DOI: 10.1002/9781118273463.ch9

[Redweik *et al.* 2013] Redweik P., Catita C. & Brito M., 'Solar energy potential on roofs and façades in an urban landscape.' *Solar Energy*, 2013, 97: 332-341. DOI: 10.1016/j.solener.2013.08.036

[Reijenga *et al.* 2012] Reijenga T. & Kaan H., 'BIPV in Architecture and Urban Planning.' *Comprehensive Renewable Energy*, 2012, 1: 697-707. DOI: 10.1016/B978-0-08-087872-0.00138-4

[Rekioua 2018] Rekioua D., 'Energy Management for PV installations.' *Advances in Renewable Energies and Power Technologies*. Vol 1,Elsevier Science, 2018, 349–69. ISBN: 978-01-2812-959-3

[reTHINK WOOD 2015] reTHINK WOOD, Evaluating the Carbon Footprint of Wood Buildings. Reducing greenhouse gases with high-performance structures. 2015

[Rey 2011] Rey E., (Re)construire la ville autrement. *TRACÉS*, 2011, 17

[Rey 2018] Rey E., Du territoir au détail. Le projet architectural face aux défis de la transition vers la durabilité. 2018.

[Rey *et al.* 2017] Rey E., Aguacil S., Lufkin S., Perret-Aebi L.-E., Pouchain F., Ménard R., Arni O., Trachsel C., Perraudin R.-L. & Clua Longas A., 9° édition du forum ecoparc. Potentiel solaire des territoires urbains: vers de nouveaux paradigmes? 2017

[Ritzen *et al.* 2014] Ritzen M., van Horrik M., Vroon Z. & IEA PVPS, *Acceleration of BIPV*. IEA International Energy Agency, 2014.

[RIBA 2009] RIBA, Principles of Low Carbon Design and Refurbishment., 2009.

[Riera Perez 2015] Riera Perez M.G., 'Méthodologie multicritères d'aide à la décision pour le renouvellement urbain a l'échelle du quartier.' PhD Thesis EPFL (Ecole Polytechnique Fédérale de Lausanne), Lausanne, 2015. DOI: 10.5075/epfl-thesis-6867

[Richarz *et al.* 2008] Richarz C., Schulz C. & Zeitler F., *Energy-Efficiency Upgrades. Principles, Details, Examples.* DETAIL Practice. Munich : Birkhäuser, 2008. ISBN: 978-3-7643-8121-9

[RLATC, 1987, art. 27] Conseil d'état du canton de Vaud, *Règlement d'application de La Loi Du 4 Décembre 1985 Sur l'aménagement Du Territoire et Les Constructions* (RLATC)., 1987.

[Rodrigez-Ubinas *et al.* 2014] Rodrigez-Ubinas E., Montero C., Porteros M., Vega S., Navarro I., Castillo-Cagigal M., Matallanas E. & Gutiérrez A., 'Passive design strategies and performance of Net Energy Plus Houses.' *Energy and Buildings*, 2014, 83: 10-12. DOI: 10.1016/j.enbuild.2014.03.074

[Roggena 2017] Roggena R., 'Research by design: proposition for a methodological approach.' *Urban Science*, 2017, 1 (1): 2. DOI: 10.3390/urbansci1010002

[Roberts *et al*. 2009] Roberts S. & Guariento, *Building Integrated Photovoltaics / A Handbook*. Birkhäuser, 2009. DOI: 10.1007/978-3-0346-0486-4

[Rütter-Fischbacher *et al.* 2010] Rütter-Fischbacher U., Caspar V. & Leu A., *Gestion Immobilière Durable. Identifier Les Risques Pour Se Donner La Chance de Les Prévenir. Guide Pour La Prise de Décisions*. KBOB _ Conférence de coordination des services de la construction et des immeubles des maîtres d'ouvrage publics, 2010.

[Ruegg *et al.* 1990] Ruegg R. & Marshall H.E., *Building Economics: Theory and Practie*. New York : Van Nostrand Reinhold, 1990. ISBN: 978-1-4757-4688-4

[Sanchez *et al.* 2015] Sanchez E. & Izard J., 'Performance of photovoltaics in non-optimal orientations: An experimental study.' *Energy and Buildings 2015, 87 (1): 211-219*. DOI: 10.1016/j.enbuild.2014.11.035

[Salem *et al.* 2015] Salem T. & Kinab E., 'Analysis of Building-Integrated Photovoltaic Systems: A Case study of Commercial Buildings under Mediterranean Climate.' *Procedia Engineering*, 2015, 118: 538-545. DOI: 10.1016/j.proeng.2015.08.473

[Santos *et al.* 2014] Santos J.M., Moura P.S. & de Almeida A.T., 'Technical and economic impact of residential electricity storage at local and grid level for Portugal.' *Applied Energy*, 2014, 128: 254-264. DOI: 10.1016/j.apenergy.2014.04.054

[Sadineni *et al.* 2011] Sadineni S.B., Madala S. & Boehm R.F., 'Passive building energy savings: A review of building envelope components.' *Renewable and Sustainable Energy Reviews*, 2011, 15 (8): 3617-3631. DOI: 10.1016/j.rser.2011.07.014

[Sanchez-Ostiz Gutiérrez 1996] Sanchez-Ostiz Gutiérrez A., 'Fachadas. Transicion e innovacion tecnologica.' *Revista de edificacion RE*, 1996, 22

[Sanchez-Ostiz Gutiérrez 2003] Sanchez-Ostiz Gutiérrez A., 'Fachadas. Camaras ventiladas Pieles transpirables.' *DETAIL spain*, 2003, 4. ISBN: 1578-5769

[Satterthwaite 2014] Satterthwaite D., 'Getting local governments, residents and enterprises to respond to the new IPCC assessment.' *Environment and Urbanization*, 2014, 26 (1): 3-10. DOI: 10.1177/0956247814522386

[Sauter *et al.* 2013] Sauter R. & Volkery A., *Review of Costs and Benefits of Energy Savings.* Brussels: Institute for European Environmental Policy (IEEP) for the Coalition of Energy Savings, 2013.

[Scognamiglio *et al.* 2014] Scognamiglio A. & Garde F., 'Photovoltaics'architectural and landscape designoptions for Net Zero Energy Buildings, towards Net ZeroEnergy Communities: spatial features and outdoorthermal comfort related considerations.' Vol 2429th EU PVSEC, Amsterdam, The Netherlands, 2014. DOI: 10.1002/pip.2563

[Schittich 2006] Schittich C., *Building Skins*. Detail. Birkhäuser, 2006. ISBN 978-3-0346-1508-2

[Scognamiglio 2017] Scognamiglio A., Cost-Effective Energy Efficient Building Retrofitting. Chapter 6 - BIPV for Cost-Effective Energy-Efficient Retrofitting. Woodhead Publishing, 2017. ISBN: 978-00-8101-128-7

[SFOE 2014] SFOE, *Energy Strategy 2050*. 2014. www.bfe.admin.ch

[SFOE 2016] SFOE, Smart Grids. *Swiss Federal Office of Energy*, 2016, www.bfe.admin.ch

[SHC 1977] SHC, IEA Solar Heating & Cooling Technology Collaboration Programme. 1977, www.iea-shc.org, accessed 22nd April 2019.

[SHC 1995] SHC, SHC Task 16: Photovoltaics in buildings. 1995. www.task16.iea-shc.org [SHC 2013] SHC, SHC EBC Task 40. Net Zero Energy Solar Buildings. 2013, www.task40.iea-shc.org

[SHC 2014] SHC, IEA SHC Task 41. Solar energy and archiecture. 2014, www.task41.iea-shc.org

[Shin *et al.* 2017] Shin J., Park J. & Park N., 'A method to recycle silicon wafer from end-of-life photovoltaic module and solar panels by using recycled silicon wafers.' *Solar Energy Materials and Solar Cells*, 2017, 162: 1-6. DOI: 10.1016/j.solmat.2016.12.038

[Short *et al.* 2016] Short W. & Ruegg R., 'Economics Methods.' *Energy Efficiency and Renewable Energy Handbook*. 2nd ed.Boca Raton : CRC Press, 2016, 187–213. ISBN: 978-11-3874-911-5

[Shukla *et al.* 2016] Shukla A.K., Sudhakar K. & Baredar P., 'A comprehensive review on design of building integrated photovoltaic system.' *Energy and Buildings*, 2016, 128. DOI: 10.1016/j.enbuild.2016.06.077

[SIA 112/1 2004] SIA 112/1, *Construction Durable- Bâtiment. Complements Au Modèle de Prestations SIA 112.*, 2004.

[SIA 112 2017] SIA 112, *Construction Durable*., 2017.

[SIA 2017] SIA, *Construction Durable - Bâtiment. Norme de Compréhension à La Norme SIA 112.*, 2017.

[SIA 180 2014] SIA 180, *Protection Thermique, Protection Contre l'humidité et Climat Intérieur Dans Les Bâtiments*., 2014.

[SIA 181 2006] SIA 181, *Protection Contre Le Bruit Dans Le Bâtiment.*, 2006.

[SIA 260 2013] SIA 260, *Bases Pour l'élaboration Des Projets de Structures Porteusses.*, 2013.

[SIA 265 2012] SIA 265, *Construction En Bois*., 2012.

[SIA 358 2010] SIA 358, *Garde-Corps*., 2010.

[SIA 380/1 2009] SIA 380/1, *L'énergie Thermique Dans Le Bâtiment*., 2009.

[SIA 380 2015] SIA 380, *Bases Pour Les Calculs Énergétiques Des Bâtiments.*, 2015.

[SIA 480 2016] SIA 480, *Calcul de Rentabilité Pour Les Investissements Dans Le Bâtiment.*, 2016.

[SIA 2031 2009] SIA 2031, *Certificat Énergetique Des Bâtiments.*, 2009.

[SIA 2032 2010] SIA 2032, *L'energie Grise Des Bâtiments*., 2010.

[SIA 2010] SIA, *Cahier Technique 2032: L'energie Grise Des Bâtiments.*, 2010.

[SIA 2039 2016] SIA 2039, *Mobilité - Consommation Énérgetique Des Bâtiments En Fonction de Leur Localisation.*, 2016.

[SIA 2040 2017] SIA 2040, *La Voie SIA Vers l'efficacité Énergétique.*, 2017.

[Sica *et al.* 2018] Sica D., Malandrino O., Supino S., Testa M. & Lucchetti M.C., 'Management of end-of-life photovoltaic panels as a step towards a circular economy.' *Renewable and Sustainable Energy Reviews*, 2018, 82 (3): 2934-2945. DOI: 10.1016/j.rser.2017.10.039

[Sick *et al.* 1996] Photovoltaics in Buildings: A Design Handbook for Architects and Engineers, London : James&James Ltd, 1996.

[SIL 2019a] SIL, Tarifs 2019 de l'électricité pour les cantons de Vaud et du Valais. *Ville de lausanne Services Industriels*, 2019. www.lausanne.ch

[SIL 2019b] SIL, Tarifs de l'électricité. Reprise de l'énergie. 2019,

[Skandalos *et al.* 2015] Skandalos N. & Karamanis D., 'PV glazing technologies.' *Renewable and Sustainable Energy Reviews*, 2015, 49: 306-322. DOI: 10.1016/j.rser.2015.04.145

[Song *et al*. 2016] Song A., Lu L., Liu Z. & Wong M.S., 'A Study of Incentive Policies for Building-Integrated Photovoltaic Technology in Hong Kong.' *Sustainability*, 2016, 8(8): 769. DOI: 10.3390/su8080769

[Smith 2019] Smith C., Debate: Not in My Backyard. *Our World Brought to you by United Nations University*, 2019. www.ourworld.unu.edu

[SNBS 2013] SNBS, *Fiches-critères. Mode d'utilisation Habitation*. 2013

[Söderström 2018] Söderström K., CSEM Technical Report: Mesh for Coloring PV Module. CSEM, 2018.

[Sozer *et al.* 2007] Sozer H. & Elnimeiri M., 'Critical Factors in Reducing the Cost of Building Integrated Photovoltaic (BIPV) Systems.' *Architectural Science Review*, 2007, 50 (2): 115-121. DOI: 10.3763/asre.2007.5017

[SolarPower Europe 2017] SolarPower Europe, Global Market Outlook for Solar Power 2017-2021. 2017. www.solarpowereurope.org

[Solar Decathlon 2018] Solar Decathlon, Solar decathon. *Solar decathlon*, 2018. www.solardecathlon.gov

[Solar Agentur 2019] Solar Agentur, Prix Solaire Suisse. 2019. www.solaragentur.ch

[de Sousa Camposinhos 2014] de Sousa Camposinhos R., *Stone Cladding Engineering*. Dordrecht : Springer, 2014. ISBN: 978-94-007-6848-2

[Schoen *et al.* 2000] Schoen T., Prasad D., Ruoss D., Eiffert P. & Sørensen H., *Status Report of Task 7 of the IEA Power Systems Program*. IEA International Energy Agency PVPS, 2000.

[Schoen *et al.* 2001] Schoen T., Prasad D., Ruoss D., Eiffert P. & Sørensen H., *Task 7 of the IEA PV Power Systems Program - Achievements and Outlook*. IEA International Energy Agency PVPS, 2001.

[Souto-Martinez *et al.* 2018] Souto-Martinez A., Sutley E.J., Liel A.B. & Srubar III W.V., 'Embodied Carbon of Wood and Reinforced Concrete Structures Under Chronic and Acute Hazards.' *Embodied Carbon in Buildings. Measurement, Management and Mitigation*. Springer, 2018, 77–103. DOI: 10.1007/978-3-319-72796-7

[Stadt Zürich 2008] Stadt Zürich, 2000-Watt Society. 2008. www.stadt-zuerich.ch/2000-watt-society

[Stevanović 2013] Stevanović S., 'Optimization of passive solar design strategies: A review.' *Renewable and Sustainable Energy Reviews*, 2013, 25: 177-196. DOI: 10.1016/j.rser.2013.04.028

[Strand 1997] Strand D., *Research in the Creative Arts*. Canberra, Australia: Canberra School of Arts for the Department of Employment, Education, Training and Youth Affairs (DEETYA), 1997.

[Suisse Energie 2015] Suisse Energie, Société à 2000 watts. *Société à 2000 watts*, 2015. www.2000watt.ch/fr/societe-a-2000-watts/, accessed 3rd September 2015.

[Suisse Energie 2017] Suisse Energie, Programme bâtiments. 2017. www.suisseenergie.ch

[Suisse Energie 2018] Suisse Energie, *Facts & Figures 2018*., 2018.

[Suisse Energie 2019] Suisse Energie, Calculateur solaire. *Suisse énergie Notre engagement: notre futur*, 2019. www.suisseenergie.ch/page/fr-ch/calculateur-solaire

[SUPSI 2019a] SUPSI, Centre Suisse de compétence BIPV. 2019. www.bipv.ch

[SUPSI 2019b] SUPSI, The University of Applied Sciences and Arts of Southern Switzerland. 2019. www.supsi.ch, accessed 22nd April 2019.

[SUPSI and SEAC 2015] SUPSI & SEAC, *Building Integrated Photovoltaics: Report 2015*. University of

Applied Sciences and Arts of Southern Switzerland and Solar Energy Application Centre The Netherlands, 2015.

[SUPSI and SEAC 2017] SUPSI & SEAC, *Building Integrated Photovoltaics: Product Overview for Solar Building Skins. Status Report 2017*. University of Applied Sciences and Arts of Southern Switzerland and Solar Energy Application Centre The Netherlands, 2017.

[Svetozarevic *et al.* 2019] Svetozarevic B., Begle M., Jayathissa P., Caranovic S., Shepherd R.F., Nagy Z., Hischier I., Hofer J. & Schlueter A., 'Dynamic photovoltaic building envelopes for adaptive energy and comfort management.' Nature Energy, 2019, 4: 671-682. DOI: 10.1038/s41560-019-0424-0

[Swiss architects 2016] *Swiss architects*, 2016. www.swiss-architects.ch

[Sykorova *et al.* 2019] Sykorova B., Lascar A. & Vekony A.T., The opportunities of Solar Panel Recycling. What happens to PV panels when their Life Cycle ends. 2019. www.greenmatch.co

[Taylor 1988] Taylor C., 'Various approaches to and definitions of creativity.' *The nature of creativity: Contemporary psychological perspectves*, 1988, New York, Cambridge University Press.

[Tétreault 2015] Tétreault S., 'Poser sa question de recherche: par où commencer?' Revue Francophone de Recherche en Ergothérapie, 2015, 1 (2). DOI: 10.13096/rfre.v1n2.41

[Tiwari *et al.* 2016] Tiwari G.N., Tiwari A. & Shyam, *Handbook of Solar Energy. Theory, Analysis and Applications*. Singapore : Springer, 2016. ISBN: 978-981-10-0807-8

[UN 2016] U.N., Nouveau Programme Pour Les Villes. Déclaration de Quito Sur Les Villes et Les Établissements Humains Viables Pour Tous. Quito, 2016.

[UNEP 2015] UNEP, Climate Commitments of Subnational Actors and Business: A Quantitative Assessment of Their Emission Reduction Impact. Nairobi: United Nations Environment Programme (UNEP), 2015.

[UNFCCC 2015] UNFCCC, Paris agreement. 2015. www.unfccc.int

[UNFCCC 1997] UNFCCC, Kyoto protocol to the United Nations Framework Convention on Climate Change. 1997. www.unfccc.int

[United Nations 1974] United Nations, Dimensional Co-Ordination in Building. Current Trends and Policies in ECE Countries. New York, 1974.

[US E I A 2016] US Energy Information Administration, *International Energy Outlook*., 2016.

[Vadillo 2016] Vadillo E., KUBIK: Intelligent Energy Building. 2016. www.tecnalia.com

[Van Fan *et al.* 2018] Van Fan Y., Perry S., Klemes J.J. & Lee C.T., 'A review on air emissions assessment: Transportation.' *Journal of Cleaner Production*, 2018, 194: 673-684. DOI: 10.1016/j.jclepro.2018.05.151

[Van Mierlo *et al.* 1999] Van Mierlo B. & Oudshoff B., Literature Survey and Analysis of Non-Technical Problems for the Introduction of Building Integrated Photovoltaic Systems. IEA International Energy Agency, 1999.

[Vardakas *et al.* 2015] Vardakas J.S., Zorba N. & Verikoukis C.V., 'Performance evaluation of power demand scheduling scenarios in a smart grid environment.' *Applied Energy*, 2015, 142: 164-178. DOI: 10.1016/j.apenergy.2014.12.060

[Verberne *et al.* 2014] Verberne G., Bonomo P., Frontini F., van den Donker M., Chatzipanagi A., Sinapis K. & Folkerts W., 'BIPV products for façades and roofs: a market analysis.' *EU PVSEC Proceedings*. EU-PVSEC, Amsterdam, 2014

[Ville de Zurich 2018] Ville de Zurich, Indice Zurichois Des Prix de La Construction de Logements et de Prix Du M3 Du Bâtiment de Référence, Depuis 1986. OCSTAT (Office cantonal de la statistique, Geneve), 2018.

[Ville de Lausanne 2019] Ville de Lausanne, Coût de la vie. 2019. www.lausanne.ch

[Vieira *et al.* 2016] Vieira F.M., Moura P.S. & de Almeida A.T., 'Energy storage system for self-consumption of photovoltaic energy in residential zero energy buildings.' *Renewable Energy 2016, 103: 308-320*. DOI: 10.1016/j.renene.2016.11.048

[Victoria *et al.* 2018] Victoria M. & Perera S., 'Carbon and Cost Hotspots: An embodied carbon management approach during early stages of design.' *Embodied Carbon in Buildings. Measurement, Management and Mitigation*. Springer, 2018, 247–62. ISBN 978-3-319-72796-7

[Volland *et al.* 2011] Volland B., Hänggi M. & UGZ O. for E. and H.P.Z., *On the Way to the 2000-Watt Society. Zurich's Path to Sustainable Energy Use*. Zurich: City of Zurich, 2011.

[Wagner System AG 2019] Wagner System AG, Sekundäre fassaden UK systeme - vertikal. *Wagener System*, 2019. www.wagnersystem.ch

[Wall *et al.* 2012] Wall M., Munari Probst M.C., Roecker C., Dubois M.C., Horvat M., Bruun Jorgensen O., Kappel K., ' Achieving Solar Energy in Architecture - IEA SHC Task 41'. *Energy Procedia, 2012,* 30: 1250-1260. DOI: 10.1016/j.egypro.2012.11.138

[Weibel 2011] Weibel D., The Swiss Feed-in Tariff System. 2011. www.files.ethz.ch

[de Wild-Scholten 2009] de Wild-Scholten M., Energy payback times of PV modules and systems. 2009. www.solaik.ch

[Welsch *et al.* 2017] Welsch M., Pye S., Keles D., Faure A., Dobbins A., Shivakumar A., Deane P. & Howells M., *Europe's Energy Tansition - Insights for Policy Making. Findings Informing the European Commission*. London, UK : Elsevier Academic Press, 2017. ISBN: 978-01-2809-806-6

[WRAP 2014] WRAP, Cutting embodied carbon in construction projects. 2014. www.wrap.org.uk

[Wüest & Partner 2015] Wüest & Partner, *Immo-Monitoring 2015 I 2 Edition de Printemps*. Druckerei Neidhart + Schön SA, Zurich, 2015.

[Wüest & Partner 2018] Wüest & Partner, *Immo-Monitoring 2019 / 1*. Geneve : Wüest&Partmer, 2018.

[Wüest & Partner 2019] Wüest & Partner, Marché immobilier suisse 2019 / 1. 2019.

[Wu, Tazvinga *et al.* 2015] Wu Z., Tazvinga H. & Xia X., 'Demand side management of photovoltaic-battery hybrid system.' *Applied Energy*, 2015, 148: 294-304. DOI: 10.1016/j.apenergy.2015.03.109

[Wüstenhagen *et al.* 2007] Wüstenhagen R., Wolsink M. & Bürer M.J., 'Social acceptance of renewable energy innovation: An introduction to the concept.' *Energy Policy*, 2007, 35 (5): 2683-2691. DOI: 10.1016/j.enpol.2006.12.001

[Yang *et al.* 2017] Yang R.J. & Carre A., 'Design, Simulation, and Assessment of BIPV: A Student Accommodation Building in Australia.' International Conference on Sustainable Infrastructure, 2017

[Yang 2015] Yang R.J., 'Overcoming technical barriers and risks in the application of building integrated photovoltaics (BIPV): hardware and software strategies.' *Automation in Construction*, 2015, 51: 92-102. DOI: 10.1016/j.autcon.2014.12.005

[Yang *et al.* 2015a] Yang M. & Yu X., *Energy Efficiency. Benefits for Environment and Society*. London : Springer, 2015. DOI: 10.1007/978-1-4471-6666-5

[Yang *et al.* 2015b] Yang R.J. & Zou P.X.W., 'Building integrated photovoltaics (BIPV): costs, benefits, risks, barriers and improvement strategy.' *International Journal of Construction Management*, 2015, 16 (1): 39-53. DOI: 10.1080/15623599.2015.1117709

[Yoo *et al.* 1998] Yoo S.-H., Lee E.-T. & Lee J.-K., 'Building Integrated Photovoltaics: a korean case study.' *Solar Energy*, 1998, 64 (4): 151-161. DOI: 10.1016/S0038-092X(98)00115-7

[Young *et al.* 2018] Young J.C., Rose D.C., Mumby H.S., Benitez-Capistros F., Derrick C.J., Finch T., Garcia C., Home C., Marwaha E. & Morgans C., 'A methodological guide to using and reporting on interviews in conservation science research.' *Methods in Ecology and Evolution*, 2018, 9 (1): 10-19. DOI: 10.1111/2041-210X.12828

[Zammit *et al.* 2017] Zammit Y. & Borg S.P., 'Assessing Façade-Integrated Photovoltaics: A methodology for their preliminary assessment.' EU PVSEC 2017, Amsterdam, 2017. DOI: 10.4229/EUPVSEC20172017-6BV.3.45

[Zanetti *et al.* 2010] Zanetti I., Nagel K. & Chianese D., 'Concepts for solar integration development of technical and architectural guidelines for solar system integration in historical buildings.' 25th European Photovoltaic Solar Energy Conference and Exhibition, Valencia - Spain, 2010. DOI: 10.4229/25thEUPVSEC2010-5BV.5

[Zaera-Polo *et al.* 2014] Zaera-Polo A. & Trüby S., 'Façade.' in Koolhaas R., *Elements of Architecture*. Taschen, 2014. ISBN 13: 978-38-3655-614-9

[Zabalza Bribian *et al.* 2011] Zabalza Bribian I., Valero Capilla A. & Aranda Uson A., 'Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential.' *Building and Environment*, 2011, 43 (5): 1133-114. DOI: 10.1016/j.buildenv.2010.12.002

[Zeng *et al.* 2017] Zeng R. & Chini A., 'A review of research on embodied energy of buildings using bibliometric analysis.' *Energy and Buildings*, 2017, 155: 172-184. DOI: 10.1016/j.enbuild.2017.09.025

[Zemella *et al.* 2014] Zemella G. & Faraguna A., Evolutionary Optimisation of Façade Design. A New Approach for the Design of Building Envelopes. London : Springer, 2014. ISBN: 978-1-4471-5652-9

[Zhang *et al.* 2015] Zhang X., Shen J., Lu Y., He W., Xu P., Zhao Xudong, Qiu Z., Zhu Z. & Dong X., 'Active Solar Thermal Façades (ASTFs): From concept, application to research questions.' *Renewable and Sustainable Energy Reviews*, 2015 [Zhang *et al.* 2016a] Zhang Y., Lundblad A., Campana P.E. & Yan J., 'Employing Battery Storage to Increase Photovoltaic Self-sufficiency in a Residential Building of Sweden.' *Energy Procedia*, 2016, 88: 455-461. DOI: 10.1016/j.egypro.2016.06.025

[Zhang *et al.* 2016b] Zhang Y., Lundblad A., Campana P.E. & Yan J., 'Comparative study of Battery Storage and Hydrogen Storage to Increase Photovoltaic Self-sufficiency in a Residential Building of Sweden.' *Energy Procedia*, 2016, 103: 268-273. DOI: 10.1016/j.egypro.2016.11.284

[Zomer *et al.* 2013] Zomer C., Nobre A., Cassatella P., Reindl T. & Rüther R., 'The balance between aesthetics and performance in building-integrated photovoltaics in the tropics.' 28th EU PVSEC, Paris, 2013. DOI: 10.1002/pip.2430

9. Appendix

A.1 List of abbreviations

a-Si: amorphous silicon

A_{th}: Thermal envelope surface

AAF: Advanced Active Façade

AC: Alternating current

ACL: Angela Clua Longas

AEIAI: Association des établissements cantonaux d'assurance incendie

ARE: Federal office for Spatial Development (CH)

ARY: All-risk yield

BAPV: Building attached photovoltaics

BIPV: Building integrated photovoltaics

BOS: Balance of system

BP: Best practice

BRE: Building research establishment

CdTe: Cadmium Telluride

CDW: Construction and demolition waste

CHF: Swiss francs

CIGS: Copper Indium Gallium Selenide

CO_2: Carbon dioxide

CP: Common practice

CPR: Construction product regulation

CRB: Centre Suisse d'études pour la rationalisation de la construction

CSEM: Swiss center for electronics and microtechnology

DB: Design Builder

DC: Direct current

DHW: Domestic hot water

DPB: Discounted payback

DSSC: Dye sensitized solar cell

DSEMS: Demand side energy management strategies

EDAR: Doctoral program architecture and sciences of the city

EIA: Energy information administration

EMS: Energy management strategies

ENAC: School of architecture, civil and environmental engineering

EPFL: Swiss Federal Institute of Technology Lausanne

EPS: expanded polystyrene

ERA: Energy reference area

ES 2050: Energy Strategy 2050

EU: European Union

ETH: Swiss Federal Insitute of Technology Zurich

FIT: Feed-in tarif

GGBS: Ground granulated blast-furnace slag

GHG: Greenhouse Gas

GL: Guideline

GWP: Global warming potential

HIT: Heterojunction with intrinsic thin layer

HP: High-performance

IEA: International Energy Agency

INES: French national institute for solar energy

IPCC: Intergovernmental Panel on Climate Change

IRR: Internal rate of return

ISAAC: Institute for applied sustainability to the built environment

ISO: International Standard Organisation

JB: Junction box

KBOB: Co-ordination Conference for Construction Services and Buildings of Public Owners

LAST: Laboratory of Architecture and Sustainable Technologies of the EPFL

LCA: Life cycle assessment

LCC: Life cycle cost

LCCO2A: Life cycle carbon emissions assessment

LCEA: Life cycle energy assessment

LEn: Swiss energy law

MR: Market-ready

NIMBY: Not in my backyard

NPV: Net present value

NREL: National renewable energy laboratory of the U.S.

NRP: National research programme

NRPE: Non-renewable primary energy

NZEB: Net Zero Energy Building

OFS: Swiss federal office of statistics

OSB: Oriented strand board

PBT: Payback time

PE: Primary energy

PFA: Pulverised fuel ash

PPA: Partial zoning plan

PV: Photovoltaics

PV2050: Joint research project: PV into the built environment

PVPS: Photovoltaic power systems programme

PwC: Price Waterhouse Cooper

RIBA: Royal institute of British architects

RLATC: Règlement d'application de la loi sur l'aménagement du territoire et les constructions

RPE: Renewable primary energy

SFOE: Swiss federal office of energy

SHC: Solar heating and cooling programme

SIA: Swiss society of engineer and architects

SIL: Lausanne industrial services

SNBS: Swiss standard of sustainable construction

SNSF: Swiss national science foundation

SUPSI: University of applied sciences and arts of southern Switzerland

SSG: Structural sealant glazing

SSR: Self-sufficiency ratio

U: Thermal transmittance value

UNFCCC: The United Nations framework convention on climate change

US: United States

USA: United States of America

WEEE: Waste electrical and electronic equipment

WRAP: Waste & Resources Action Programme

XPS: Extruded polystyrene

ZHAW: Zurich University of Applied Sciences

A.2 List of interviews and collaborations

C: collaboration

I: interview

C.1: **CSEM: Laure-Emanuelle Perret, Gianluca Cattaneo, Patrick Heinstein, Karin Söderström**

Neuchâtel

Integration of BIPV into façades

05.2015-02.2019

C.2: **Evelyn Lobsiger-Kägi**. Senior research associate, ZHAW

Neuchâtel

AAF social acceptance assessment

11.2016 - 11.07.2017

C.3: **Dan Bolomey**. Lecturer: sustainable construction, EPFL

Lausanne

AAF Construction System development

04.2017-09.2017

C.4: **Renée Itten**. Research associate, ZHAW

Neuchâtel

AAF environmental impact assessment

12.2017-02.2019

I.1: **Pierre Olivier Cuche**, Director Solarwall

Bussigny

BIPV technology and panels

19.02.2016/9.08.2016

I.2 : **Andrea Stitic.** Doctoral assistant, iBOIS – EPFL

Lausanne

AAF's timber substructure design

21.06.2017

I.3: **Ivano Pola.** Test Manager H.glass

Villaz-Saint-Pierre

BIPV panels composition technical properties and performance

26.06.2017

I.4: **Sylvain Mercier**. Façade specialist, directeur PREFACE

Lausanne

AAF Construction System design_advisor

29.06.2017

I.5: **Bertrand Leuenberger**. Technical consultant SIKA

Email exchanges

AAF Construction system_fastening system

23.08.2017

I.6: **Ignacio Dahl Rocha.** Architect, founder RDR

Lausanne

AAF expert interview. Transfer potential assessment

17.11.2017

I.7: **Stefan Goeddertz.** Façade specialist and associate at Herzog & de Meuron

Basel

AAF expert interview. Transfer potential assessment

30.11.2017

I.8: **Alexandre Chaffard**. Technical consultant Knauf AG

Lausanne

Study of the integration of wood-cement panels into AAF

22.10.2018

I.9: **Bec Partners SA**. experts économie de la construction

Bussigny

AAF economic assessment

7.05.2018

I.10: **Gino Angelini.** Façade specialist, directeur PREFACE

Lausanne

Façade cost per square meter evaluation

12.06.2018

I.11: **Jean Baptiste Ferrari.** Architect, principal at Ferrari architectes

Lausanne

AAF expert interview. Transfer potential assessment

14.06.2018

I.12: **Hiéronyme Lacroix.** Architect, partner at Lacroix Chessex

Geneva

AAF expert interview. Transfer potential assessment

24.07.2018

I.13: **Philippe Meyer.** Architect, principal Philippe Meyer achitecte

Geneva

AAF expert interview. Transfer potential assessment

27.07.2018

I.14: **Gianluca Cattaneo.** R&D Engineer

Neuchâtel

BIPV panels and systems composition, technical properties and performance

11.09.2018

I.15: **Sebastien Piguet.** Coordiateur romand eco-bau

Prilly

AAF environmental impact evaluation

29.10.2018

I.16: **Jonathan Rojon.** Group development manager SERGE FERRARI

Lausanne

Integration of windproof membranes in timber façades, and their environmental impact

6.11.2018

I.17: **Team 12: Grégory Dos Santos, Sébastien Lorenzini, Nordine Mahmoudi, Tobias Richterich**. Winners of the ACTIVE HOUSING student competition

Lausanne

ACTIVE HOUSING competition feedback: integration of AAF into architectural design processes

02.05.2019

I.18: **Astrid Dettling**. Architect and ACTIVE HOUSING student competition_ Jury member

Lausanne

ACTIVE HOUSING competition feedback: transfer potential of the AAF into architectural professional practices

06.05.2019

A.3 List of architecture experts

Expert A:

Ignacio Dahl Rocha, Partner at Richter Dahl Rocha & Associés architects

The firm is of the largest offices in Lausanne and has won a total of 18 different national and international awards. Their work has been published more than 100 times in different international architectural magazines and 8 books have been published presenting their work. With a total of 48 residential buildings constructed, this office is considered to have a large experience in this field and hence its founder, Ignacio, regarded as a residential architecture expert.

Location: Lausanne

Expert B:

Stefan Goeddertz, Façade specialist and associate at Herzog & de Meuron

Laureated with most prestigious architecture award in 2001: The Pritzker Architecture Prize.

With a large collective residential housing experience the firm has constructed more than 80 residential buildings completed worldwide.

Location: Basel

Expert C:

Jean Baptiste Ferrari, Founder of Ferrari architectes

The firm states to be strongly motivated to develop their architectural practices according to sustainable design principles. With more than 20 residential buildings constructed and 50 publications on their work, they are considered as experts in the field.

Location: Lausanne

Expert D:

Hiéronyme Lacroix, Partner at Lacroix Chessex

Founded in 2005 has already cumulated 3 architecture awards and 18 project competition prizes. Their work has been published in 2 monographs, 9 books and more than 65 paper architectural magazines. Moved by sustainable design, they have built 4 residential buildings and are considered experts in the field.

Location: Geneva

Expert E:

Philippe Meyer, Founder at Meyer architecte

Their work is characterized by a strong intention of minimizing the building energy needs integrating passive design strategies. They have constructed 4 residential buildings and have won 4 architecture prizes.

Location: Geneva

A.4 List of analysed façade projects

A.4.1 Sample of Swiss collective residential buildings

Ref. number	PROJECT NAME	LOCATION	ARCHITECT	YEAR	FAÇADE COMPOSITION	FAÇADE MORPHOLOGY
1	Areal Giessen	Meilen	Max Dudler	2014	SLAB TO SLAB	BALCONY
2	Avenue des Uttins	Rolle	RDR	2007	SLAB TO SLAB	BALCONY
3	Multifamily House Haldenstrasse	Zurich	Leuppi & Schafroth Architekten	2011	SLAB TO SLAB	LOGGIAS
4	Zweigesicht	Meggen	Cometti Truffer Architekten	2012	TOTAL STOREY	LOGGIAS
5	Cooperative Building and Park	Geneva	GM Architectes Associés	2011	TOTAL STOREY	BALCONY
6	Wohnsiedlung Guggach	Zurich	Althammer Hochuli Architekten	2011	TOTAL STOREY	BALCONY
7	Wohnen am alten Rebberg	Liestal	ROSENMUND + RIEDER Architekten BSA	2014	BALUSTRADE	BALCONY
8	Wohnüberbauung Erlenmatt	Basel	Fankhauser, Morger + Dettly	2009	BALUSTRADE	LOGGIAS
9	Überbauung Rotmatt	Meggen	Marques Architekten AG	2015	BALUSTRADE	BALCONY
10	House of the future	Brütten	Renée Schmid	2017	TOTAL VOLUME	LOGGIAS
11	Mehrfamilienhaus in Brugg	Brugg	Walker Architekten	2010	TOTAL VOLUME	BALCONY
12	Swisswoodhouse	Nebikon	Bauart	2014	TOTAL VOLUME	LOGGIAS
13	Marin	Lausanne	TRIBU architecture	2017	TOTAL STOREY	CLEAN VOLUME
14	Logements - Bâtiment Sirocco	Geneva	LIN.ROBBE.SEILER	2013	SLAB TO SLAB	CLEAN VOLUME
15	Überbauung Citybay	Luzern	Lussi+Partner	2011	BALUSTRADE	CLEAN VOLUME
16	Neubau Wohnüberbauung Pro Vivaint	Samedan	UC'NA	2013	SLAB TO SLAB	LOGGIAS
17	Überbauung Wigarten	Büron	BAUREAG Architekten	2017	BALUSTRADE	BALCONY
18	Wohnüberbauung Chriesimatt	Baar	Graber Pulver Architekten	2014	TOTAL VOLUME	LOGGIAS
19	6 Logements de haut standing en PPE	La Tour-de-Peliz	CbMm SA	2010	BALUSTRADE	BALCONY
20	Maestrani areal	Gossau	Fürer+Gastau Architektur	2006	SLAB TO SLAB	BALCONY
21	Ottenbergstrasse	Zurich	EMWE Architektur AG	2018	BALUSTRADE	BALCONY
22	Wohnüberbauung mit 149 Wohnungen	Glattpark	Moser Wegenstein Architekten AG	2014	BALUSTRADE	BALCONY
23	Gesamtsanierung und Aufstockung	Winterthur	Hinder Kalberer Architekten	2015	TOTAL VOLUME	BALCONY
24	Mehr als Wohnen «Haus G»	Zurich	Pool Architekten	2015	TOTAL VOLUME	LOGGIAS
25	Grossmatte West, Luzern-Littau	Luzern- Littau	Juventino Mateo Leon	2018	TOTAL VOLUME	LOGGIAS
26	Apartment building in the contryside	Presinge	meier + associés architectes	2017	BALUSTRADE	BALCONY
27	Freilager Albisrieden	Zurich	Rolf Mühlethaler	2015	BALUSTRADE	BALCONY
28	Mehrfamilienhäuser Fegetz Süd - Solothurn	Solothurn	baderpartner ag planen bauen nutzen	2016	TOTAL VOLUME	BALCONY
29	Wohnen am Ebisquare	Ebikon	TGS Architekten	2017	SLAB TO SLAB	LOGGIAS
30	Wohngenossenschaft Gartenstrasse	Basel	Flubacher_Nyfeler_Partner	2016	BALUSTRADE	BALCONY
31	Sonnenhof	Regensdorf	Fischer Architekten AG	2015	BALUSTRADE	BALCONY
32	Ecoplace	Zurich	Fischer Architekten AG	2012	BALUSTRADE	BALCONY
33	Ensemble Résidentiel Cézille	Bassins	Giovanoli-Mozer architectes	2012	BALUSTRADE	BALCONY
34	Immeuble Alice -Rivaz	Geneva	Giovanoli-Mozer architectes	2011	BALUSTRADE	BALCONY
35	Ensemble Résidentiel Le Corbusier	Geneva	Giovanoli-Mozer architectes	2012	SLAB TO SLAB	BALCONY
36	Quartier Sully 2 112 logements locatifs	La Tour-de-Peilz	Giovanoli-Mozer architectes	2017	SLAB TO SLAB	BALCONY
37	Byfangweg	Basel	HHF architects	2016	TOTAL VOLUME	CLEAN VOLUME
38	Wohnüberbauung Chriesimatt	Baar	Graber Pulver Architekten AG	2014	TOTAL VOLUME	LOGGIAS
39	Wohnüberbauung Drusbergstrasse	Zurich	Felix Partner Architektur AG	2016	BALUSTRADE	BALCONY
40	Wohnüberbauung Edenfünf Zürich	Zurich	Philipp Wieting – Werknetz Architektur	2015	BALUSTRADE	BALCONY
41	6 Logements de haut standing en PPE	La Tour-de-Peilz	cBmM SA	2010	BALUSTRADE	BALCONY
42	Logements Barton	Geneva	LIN.ROBBE.SEILER	2016	TOTAL VOLUME	BALCONY
43	Wohnen und Kindergarten	Dietikon	Eglin Schweizer Architekten	2016	TOTAL VOLUME	LOGGIAS
44	Pflegeheim Arosa	Arosa	Clea Gross Architekten GmbH	2014	TOTAL VOLUME	BALCONY
45	Wohnen und Bibliothek	Regensdorf	Eglin Schweizer Architekten	2017	TOTAL VOLUME	BALCONY
46	Geschäfts- und Wohnhaus	Brig-Glis	Albrecht Architekten	2018	TOTAL STOREY	LOGGIAS
47	Gartenstadt Frohburg	Zurich	Thomas Schregenberger GmbH	2017	SLAB TO SLAB	BALCONY
48	Erlenmatt F	Basel	F.A.B. - Forschungs- und Architekturbüro	2015	SLAB TO SLAB	BALCONY
49	Wohnhochhäuser One One Cham	Cham	CSL Partner Architekten AG	2017	BALUSTRADE	LOGGIAS
50	Wohnsiedlung Hohlstrasse	Zurich	Althammer Hochuli Architekten	2014	BALUSTRADE	BALCONY
51	Wohnüberbauung Suurstoffi Risch-Rotkreuz	Zug	Lussi+Partner	2012	TOTAL VOLUME	LOGGIAS
52	Zentrumsüberbauung Näfels	Näfels	Lussi+Partner	2012	TOTAL VOLUME	LOGGIAS
53	Mehrfamilienhäuser Schupferzälg	Thurgau	Fierz Architekten AG	2017	SLAB TO SLAB	BALCONY

Ref. number	PROJECT NAME	LOCATION	ARCHITECT	YEAR	FAÇADE COMPOSITION	FAÇADE MORPHOLOGY
54	Logements Les Vergers	Delémont	COMAMALA ISMAIL ARCHITECTES	2014	SLAB TO SLAB	BALCONY
55	ALMA | Ringstrasse	Zurich	emwe architekten ag	2017	SLAB TO SLAB	BALCONY
56	La Résidence à Neuchâtel-Serrière	Serrière	cBmM SA	2016	SLAB TO SLAB	CLEAN VOLUME
57	Multigenerational building «Giesserei»	Winterthur	Galli Rudolf	2013	TOTAL STOREY	BALCONY
58	Housing estate Sihlgarten	Leimbach	Galli Rudolf	2007	BALUSTRADE	LOGGIAS
59	House A4 «am Rietpark»	Schlieren	Galli Rudolf	2009	BALUSTRADE	BALCONY
60	Wohnpark Sonnenring	Romanshorn	BISCHOF PARTNER ARCHITEKTUR	2017	BALUSTRADE	BALCONY
61	Housing Raising Sécheron	Geneva	Burrus Nussbaumer	2014	SLAB TO SLAB	CLEAN VOLUME
62	Sony-Areal Schlieren	Zurich	steigerconcept	2014	BALUSTRADE	BALCONY
63	Suhrportal Bahnhofareal Nord, Suhr	Suhr	Metron	2015	SLAB TO SLAB	LOGGIAS
64	Arealüberbauung rudolfstrasse	Winterthur	Dahinden Heim Architekten AG	2011	SLAB TO SLAB	BALCONY
65	Wohnüberbauung Am See	Pfäffikon	Reto Visini Architekten	2016	SLAB TO SLAB	LOGGIAS
66	Kläymatte	Zollikifen	matti ragaz hitz architekten ag	2007	TOTAL STOREY	BALCONY
67	Sanierung Wohnüberbauung Uetlibergstrasse	Zurich	Rothen Architektur GmbH	2014	BALUSTRADE	BALCONY
68	Lukas Hof	Zurich	Rothen Architektur GmbH	2015	TOTAL VOLUME	LOGGIAS
69	MIN MAX Building Glattpark	Opfikon	Edelaar Mosayebi Inderbitzin Architekten	2016	SLAB TO SLAB	CLEAN VOLUME
70	Schönberg Ost Feld F	Bern	matti ragaz hitz architekten ag	2014	TOTAL VOLUME	LOGGIAS
71	Birsmatt Aesch	Aesch	SSA Architekten	2016	SLAB TO SLAB	BALCONY
72	Rosmarinweg / Dörflistrasse	Zurich	emwe architekten ag	2017	TOTAL VOLUME	BALCONY
73	Dürntnerstrasse	Hinwil	emwe architekten ag	2013	TOTAL VOLUME	LOGGIAS
74	Pfannenstielstrasse	Meilen	emwe architekten ag	2015	SLAB TO SLAB	LOGGIAS
75	Pfannenstielstrasse	Meilen	emwe architekten ag	2009	SLAB TO SLAB	BALCONY
76	Bachofnerstrasse	Zurich	emwe architekten ag	2011	TOTAL VOLUME	BALCONY
77	Bruechstrasse	Meilen	emwe architekten ag	2015	SLAB TO SLAB	BALCONY
78	Im Eichacher	Bonstetten	emwe architekten ag	2013	TOTAL VOLUME	BALCONY
79	Wohnüberbauung am Amselweg | 1. Rang	Rupperswill	Husistein & Partner AG	2018	SLAB TO SLAB	BALCONY
80	Alterszentrum und Wohnsiedlung Eichrain	Zurich	Leuppi & Schafroth Architekten	2015	TOTAL STOREY	BALCONY
81	Haus am Kapuzinerweg Luzern	Luzern	Architekturbüro Iwan Bühler GmbH	2013	BALUSTRADE	BALCONY
82	Central Park	Wetzikon	matti ragaz hitz architekten ag	2016	BALUSTRADE	BALCONY
83	SIEB 10	Winterthur	MOKA	2007	SLAB TO SLAB	LOGGIAS
84	Wohn- und Bürohaus, Pfäffikon SZ	Pfäffikon	Fröhlich Architektur	2012	SLAB TO SLAB	CLEAN VOLUME
85	Kuben Bialavesta	Breil	maurusfrei	2013	BALUSTRADE	BALCONY
86	Wohnbauten am Bahnhof	Frauenfeld	Stutz + Bolt + Partner Architekten AG	2011	TOTAL VOLUME	LOGGIAS
87	Wilhelm und Bertha	Küsnacht	maurusfrei	2014	SLAB TO SLAB	BALCONY
88	Alterswohnungen Sagi	Regensdorf	phalt Architekten	2016	TOTAL VOLUME	BALCONY
89	Limmat West	Zurich	ATP architects engineers Zurich AG	2002	BALUSTRADE	BALCONY
90	Bonne-Espérance	Lausanne	TRIBU architecture	2013	SLAB TO SLAB	BALCONY
91	Toblerstrasse Housing Estate	Zurich	Baumberger & Stegmeier AG	2017	SLAB TO SLAB	BALCONY
92	Gesamtsanierung und Aufstockung	Zurich	ERNST & HUMBEL	2012	BALUSTRADE	CLEAN VOLUME
93	Neubau Wohnüberbauung	Zurich	ERNST & HUMBEL	2014	BALUSTRADE	BALCONY
94	Wohnüberbauung Holeegarten	Binningen	Burckhardt+Partner AG, Basel	2016	BALUSTRADE	LOGGIAS
95	Alterswohnungen Emmenfeld	Emmen	MMJS Jauch-Stolz Architekten AG	2015	SLAB TO SLAB	LOGGIAS
96	Wohnbauten Kastanienbaum	Horw	MMJS Jauch-Stolz Architekten AG	2015	BALUSTRADE	BALCONY
97	Wohnbau Schellenmatt Nordost	Kriens	MMJS Jauch-Stolz Architekten AG	2014	SLAB TO SLAB	BALCONY
98	Wohnbauten Schellenmatt	Kriens	MMJS Jauch-Stolz Architekten AG	2008	BALUSTRADE	BALCONY
99	Wohnbauten Eschenweg	Kriens	MMJS Jauch-Stolz Architekten AG	2010	BALUSTRADE	BALCONY
100	Alterswohnungen "Sophie Guyer"	Pfäffikon	MMJS Jauch-Stolz Architekten AG	2010	SLAB TO SLAB	LOGGIAS
101	Residenz Gasthaus Wylen	Wilen bei Wollerau	Fröhlich Architektur	2017	TOTAL VOLUME	BALCONY
102	Wohnen an der Aare	Döttingen	Haefeli Architekten	2015	SLAB TO SLAB	CLEAN VOLUME
103	Alterswohnen Feldstrasse	Zurich	Patrik Linggi Architekten	2012	TOTAL STOREY	BALCONY
104	Krieg - Housing	Geneva	NOMOS - Groupement d'Architectes	2015	TOTAL VOLUME	BALCONY
105	Jolimont - Housing	Geneva	NOMOS - Groupement d'Architectes	2015	SLAB TO SLAB	BALCONY
106	„Tic Tric Trac“	Zurich	Baumschlager Eberle Architekten	2014	BALUSTRADE	CLEAN VOLUME
107	Am Katzenbach III Residential Development	Zurich	Baumberger & Stegmeier AG	2013	BALUSTRADE	BALCONY
108	Am Katzenbach IV Residential Development	Zurich	Baumberger & Stegmeier AG	2015	BALUSTRADE	BALCONY
109	Brüggliäcker Housing Estate	Zurich	Baumberger & Stegmeier AG	2014	SLAB TO SLAB	BALCONY
110	Guggach Residential Development	Zurich	Baumberger & Stegmeier AG	2015	BALUSTRADE	LOGGIAS
111	Wohnüberbauung Labo Golette	Meyrin	Aebi & Vincent	2016	TOTAL VOLUME	BALCONY
112	The Metropolitans	Zurich	Baumschlager Eberle Architekten	2015	SLAB TO SLAB	BALCONY
113	Blumenhaus	Zurich	Wiel Arets Architects	2016	BALUSTRADE	LOGGIAS
114	Weberei-Areal	Walenstadt	atelier-f architekten	2015	BALUSTRADE	BALCONY
115	Sanierung Hochhaus Kasparstrasse 17	Bern	reinhardpartner	2014	BALUSTRADE	BALCONY
116	Neubau Wohnüberbauung Wijermatt	Kerns	Durrer Architekten	2016	BALUSTRADE	BALCONY

Ref. number	PROJECT NAME	LOCATION	ARCHITECT	YEAR	FAÇADE COMPOSITION	FAÇADE MORPHOLOGY
117	Casa Vista Lago di Lugano	Lugano	STUDIOFORMA	2016	SLAB TO SLAB	BALCONY
118	Wydengarten	Breitenbach	Jeker Architekten	2016	BALUSTRADE	BALCONY
119	Westside 9 - Residential building	Lugano	Architetti Tibiletti Associati	2013	SLAB TO SLAB	BALCONY
120	Wohnsiedlung Hohlstrasse	Zurich	Althammer Hochuli Architekten	2014	BALUSTRADE	LOGGIAS
121	Wieshof	Winterthur	A.D.P. Walter Ramseier Partner	2014	BALUSTRADE	BALCONY
122	Neubau Mehrfamilienhaus Bedastrasse	St. Gallen	Markus Alder	2014	BALUSTRADE	BALCONY
123	Baar City	Baar	Theo Hotz Partner Architekten	2007	BALUSTRADE	LOGGIAS
124	Housing Development «Eulachhof»	Winterthur	Dietrich Schwarz Architekten	2007	BALUSTRADE	BALCONY
125	Residenz 2 Eichen	Zollikerberg	m3 Architekten	2014	BALUSTRADE	BALCONY
126	Bauerneuerung MFH	Hinwil	Architekturbüro Hilpertshauser AG	2004	BALUSTRADE	BALCONY
127	Wohnüberbauung Hofstatt	Zuchwil	phalt Architekten	2014	BALUSTRADE	LOGGIAS
128	Housing Development Limmatfeld	Dietikon	Stücheli Architekten	2014	TOTAL VOLUME	LOGGIAS
129	Wohnüberbauung Widmi, Baufeld 1	Lenzburg	am-architektur	2013	SLAB TO SLAB	LOGGIAS
130	Haus Friedau	Sempach	dolmus architekten	2018	BALUSTRADE	LOGGIAS
131	Apartment building Wasserstelzenweg	Riehen	Flubacher_Nyfeler_Partner	2012	SLAB TO SLAB	LOGGIAS
132	Palazzo Nobile	Lugano	atelier AMC SA	2010	SLAB TO SLAB	LOGGIAS
133	6 Familienhaus Staldern	Regensberg	L3P Architekten AG FH SIA	2008	SLAB TO SLAB	LOGGIAS
134	Ersatz-Neubau MFH Glättlistrasse 31+33	Zurich	L3P Architekten AG FH SIA	2011	TOTAL VOLUME	BALCONY
135	Haus am Waldrand	Films Waldhaus	Marcus Gross+Werner Rüegg Architekten	2013	BALUSTRADE	BALCONY
136	Grischuna	Films Waldhaus	Marcus Gross+Werner Rüegg Architekten	2012	TOTAL VOLUME	LOGGIAS
137	Alterssiedlung Tgea Colani	Andeer	Marcus Gross+Werner Rüegg Architekten	2012	TOTAL VOLUME	BALCONY
138	Apartement House Birchsteg	Zurich	spillmann echsle architekten eth sia	2014	TOTAL VOLUME	CLEAN VOLUME
139	EMMI-Areal – neuer Hauptsitz & Wohnen	Luzern	Rüssli Architekten AG	2015	SLAB TO SLAB	LOGGIAS
140	Geschichtete Gärten	Chur	maurusfrei	2007	BALUSTRADE	LOGGIAS
141	Wohn- und Gewerbesiedlung	Zurich	Dr. Lüchinger + Meyer	2014	SLAB TO SLAB	LOGGIAS
142	Areal Suttergut	Burgdorf	Leutwyler Partner Architekten	2013	BALUSTRADE	BALCONY
143	Wohnüberbauung Halten	Oberägeri	Leutwyler Partner Architekten	2018	SLAB TO SLAB	BALCONY
144	Wohnsiedlung Wohnungsgenossenschaft Freidorf	Muttenz	ROSENMUND+RIEDER Architekten BSA	2006	SLAB TO SLAB	LOGGIAS
145	Wohnen im Lutzertgarten	Muttenz	ROSENMUND+RIEDER Architekten BSA	2015	BALUSTRADE	BALCONY
146	Mehrfamilienhaus Wiltisgasse	Küsnacht	mbb architekten	2013	BALUSTRADE	BALCONY
147	Gebreite Park	Visp	SSA Architekten	2014	BALUSTRADE	BALCONY
148	Erlenmatt Baufeld G	Basel	SSA Architekten	2015	SLAB TO SLAB	BALCONY
149	Housing Neufrankengasse	Zurich	EM2N	2013	BALUSTRADE	CLEAN VOLUME
150	Wohnhäuser Central Park Luzern	Luzern	Schärli Architekten AG	2014	BALUSTRADE	LOGGIAS
151	Housing Complex Grange Canal	Geneva	Gigon / Guyer Architects	2012	SLAB TO SLAB	LOGGIAS
152	Résidence "Le Corylus"	Geneva	Gigon / Guyer Architects	2017	SLAB TO SLAB	BALCONY
153	Löwenbräu-Areal	Zurich	Gigon / Guyer Architects	2014	SLAB TO SLAB	CLEAN VOLUME
154	Wohnüberbauung Sonnentalstrasse	Regensdorf	Fischer Architekten AG	2017	BALUSTRADE	BALCONY
155	Wohnüberbauung Pinchat	Geneva	Weber + Brönnimann	2011	SLAB TO SLAB	BALCONY
156	Überbauung Schlossmattstrasse	Thun	Dällenbach/Ewald Architekten AG	2010	SLAB TO SLAB	BALCONY
157	Corner building	Geneva	meier + associés architectes	2006	BALUSTRADE	BALCONY
158	120 affordable apartments	Geneva	meier + associés architectes	2011	BALUSTRADE	BALCONY
159	Wohnbauten Speerstrasse	Wädenswil	Züst Gübeli Gambetti	2012	SLAB TO SLAB	BALCONY
160	Stadtbaustein Schaffhauserstrasse	Zurich	Züst Gübeli Gambetti	2014	BALUSTRADE	BALCONY
161	Wohnüberbauung Erlenmattquartier	Basel	Züst Gübeli Gambetti	2012	SLAB TO SLAB	BALCONY
162	Industrieareal Cham Nord 01	Cham	Züst Gübeli Gambetti	2013	TOTAL STOREY	CLEAN VOLUME
163	Neubau Wohnsiedlung Brunmatt	Sarnen	Beda Dillier	2013	BALUSTRADE	BALCONY
164	Neubau Wohn- und Geschäftshaus Dreispitz	Köniz	Rykart Architekten AG	2015	SLAB TO SLAB	BALCONY
165	Logements à Neuchâtel	Neuchâtel	LOCALARCHITECTURE	2015	SLAB TO SLAB	BALCONY
166	Bommert - Minergie-P Eco Siedlung	Widnau	Bänzigers Architektur AG	2013	BALUSTRADE	BALCONY
167	Neubau Wohnhäuser im Schlosspark	Zentralschweiz	Matei Manaila Architekten	2014	BALUSTRADE	LOGGIAS
168	Casa d'appartamenti Mariöl	Zuoz	Könz architetto	2007	TOTAL VOLUME	BALCONY
169	Neubau Seniorenwohnungen Teufen	Teufen	Hörler Architekten	2011	SLAB TO SLAB	LOGGIAS
170	Wohnüberbauung Schutzengel	Zug	Leutwyler Partner Architekten	2011	SLAB TO SLAB	LOGGIAS
171	Erstatzneubau Wohnsiedlung Holunderhof	Zurich	Schneider Studer Primas	2018	TOTAL VOLUME	BALCONY
172	Siedlung Buchegg	Zurich	DUPLEX architekten AG	2018	SLAB TO SLAB	BALCONY
173	Wohnüberbauung Bifang	Büron	mbb architekten	2007	SLAB TO SLAB	BALCONY
174	Housing Im Forster	Zurich	EM2N	2011	SLAB TO SLAB	LOGGIAS
175	Apartment Block	Kilchberg	Meury Architektur	2006	TOTAL VOLUME	LOGGIAS
176	Wohnüberbauung Werk 3	Winterthur	Rothen Architektur GmbH	2016	TOTAL VOLUME	LOGGIAS
177	Wohnüberbauung Sandfelsen	Erlenbach	phalt Architekten	2014	BALUSTRADE	BALCONY

Ref. number	PROJECT NAME	LOCATION	ARCHITECT	YEAR	FAÇADE COMPOSITION	FAÇADE MORPHOLOGY
178	Autofreie Wohnsiedlung, Oberfeld	Ostermundigen	Halle 58 Architekten	2012	BALUSTRADE	BALCONY
179	Promenada Flem, Segnes Nord	Flims	HP Fontana & Partner AG	2009	TOTAL VOLUME	LOGGIAS
180	Mobimo Tower Zürich	Zurich	Atelier für Architekturfotografie René C. Di	2011	SLAB TO SLAB	CLEAN VOLUME
181	Wohnüberbauung Edendrei Zürich	Zurich	Philipp Wieting – Werknetz Architektur	2010	SLAB TO SLAB	LOGGIAS
182	Sonne im Schatten	Wollishofen	Guagliardi Ruoss Architekten, Zürich	2010	BALUSTRADE	BALCONY
183	Wohnüberbauung Binningen	Binningen	SSA Architekten	2007	SLAB TO SLAB	LOGGIAS
184	Brückenweg	Visp	SSA Architekten	2013	BALUSTRADE	BALCONY
185	Quartier d'habitations Im Vieri Schwerzenbach	Schwerzenbach	Bauart	2012	SLAB TO SLAB	BALCONY
186	Immeuble d'habitation NEOCASA	La Neuveville	Bauart	2018	TOTAL VOLUME	BALCONY
187	Wohnüberbauung Casinostrasse	Dübendorf	Rykart Architekten AG	2018	SLAB TO SLAB	BALCONY
188	Mehrfamilienhaus Bachstrasse	Würenlos	10:8 Architekten GmbH	2016	TOTAL VOLUME	BALCONY
189	Mehrfamilienhaus Heinrütirank	Widen	bark | büro für architektur, raum & konzep	2016	SLAB TO SLAB	BALCONY
190	Hagmannareal	Winterthur	Kuhn Landschaftsarchitekten GmbH	2018	SLAB TO SLAB	BALCONY
191	MALVA | Ringstrasse	Zurich	emwe architekten ag	2015	SLAB TO SLAB	LOGGIAS
192	Hardegg	Bern	matti ragaz hitz architekten ag	2008	BALUSTRADE	BALCONY
193	Gurtenareal, Wabern	Köniz	matti ragaz hitz architekten ag	2014	BALUSTRADE	BALCONY
194	Wright-Place	Opfikon	matti ragaz hitz architekten ag	2014	SLAB TO SLAB	BALCONY
195	Tscharnergut, Waldmannstrasse 25	Bern	matti ragaz hitz architekten ag	2015	BALUSTRADE	LOGGIAS
196	Mehr als Wohnen	Zurich	Müller Sigrist Architekten AG	2015	TOTAL VOLUME	LOGGIAS
197	Umbau MFH	Rüschlikon	Architektur - Nil - Hürzeler	2016	SLAB TO SLAB	LOGGIAS
198	Wohnhäuser Oberdorf	Zurich	SLIK Architekten	2015	BALUSTRADE	BALCONY
199	Kläymatte	Zollikofen	matti ragaz hitz architekten ag	2007	TOTAL STOREY	BALCONY
200	Dreifamilienhaus	Oberrieden	pool Architekten	2014	TOTAL VOLUME	BALCONY
201	Neubau Wohn-/Geschäftshaus	Wetzikon	GKS Architekten Generalplaner AG	2009	TOTAL VOLUME	CLEAN VOLUME
202	Neubau Aletsch Campus Naters	Naters	RLC Architektur, Projektentwicklung	2015	TOTAL STOREY	BALCONY
203	Neubau 36.5 Grad Heerbrugg	Heerbrugg	RLC Architektur, Projektentwicklung	2016	SLAB TO SLAB	BALCONY
204	Dorfzentrum «Baubereich A»	Recherswil	zsb architekten	2016	SLAB TO SLAB	BALCONY
205	Feinspinnerei Kunzareal	Windisch	Liechti Graf Zumsteg Architekten	2017	SLAB TO SLAB	LOGGIAS
206	In Dämmbeton gehüllte Ortsgeschichte	Meilen	atelier-f architekten	2017	TOTAL STOREY	BALCONY
207	Wohnhaus am Oeschbrig	Zurich	Althammer Hochuli Architekten	2016	SLAB TO SLAB	BALCONY
208	MFH Zuchwil	Zuchwil	E+P Architekten	2017	SLAB TO SLAB	BALCONY
209	Mehrfamilienhaus	Rain	dolmus architekten	2016	TOTAL STOREY	BALCONY
210	Hofhaus und Vorderhaus Sempacherstrasse	Basel	August + Margrith Künzel	2015	TOTAL STOREY	LOGGIAS
211	Lindengarten	Dagmersellen	Lussi+Partner	2017	BALUSTRADE	BALCONY
212	Obere Bergstrasse	Luzern	Lussi+Partner	2015	SLAB TO SLAB	BALCONY
213	Arealüberbauung Weiherstrasse	Winterthur	Dahinden Heim Architekten	2016	BALUSTRADE	BALCONY
214	Wohnüberbauung Belétage	Baden	Burkard Meyer Architekten	2015	BALUSTRADE	LOGGIAS
215	Ardislapark	Domat Ems	Giubbini Architekten	2015	TOTAL STOREY	BALCONY
216	Wohnsiedlung Aarenau	Aarau	Metron	2014	SLAB TO SLAB	BALCONY
217	Mehrfamilienhaus Enzenbühlstrasse	Zurich	Burkhard & Lüthi Architektur	2009	TOTAL VOLUME	BALCONY
218	Mehrfamilienhäuser Gjuchstrasse	Dietikon	Burkhard & Lüthi Architektur	2015	SLAB TO SLAB	LOGGIAS
219	Neubau MFH, Müllheimerstrasse	Basel	Lo Verdi Architekten AG ETH/SIA	2015	SLAB TO SLAB	LOGGIAS
220	Polycarbon	Schöftland	Ken Architekten	2011	TOTAL VOLUME	LOGGIAS
221	VIVA	Adliswil	ZINDEL BRÖNNIMANN FERRARIO	2015	BALUSTRADE	BALCONY
222	MFH Schläppliweg	Buchs	Kaundbe Architekten	2015	SLAB TO SLAB	BALCONY
223	Leimgrübelstrasse	Zurich	emwe architekten ag	2008	BALUSTRADE	BALCONY
224	Kalkbreite	Zurich	Müller Sigrist Architekten AG	2014	TOTAL VOLUME	LOGGIAS
225	Avellana Housing Complex	Zurich	Edelaar Mosayebi Inderbitzin Architekten	2012	TOTAL VOLUME	BALCONY
226	Steinwiesstrasse/Irisstrasse Housing	Zurich	Edelaar Mosayebi Inderbitzin Architekten	2015	SLAB TO SLAB	LOGGIAS
227	Glattpark Jardin Dufaux	Zurich	neff neumann	2015	SLAB TO SLAB	LOGGIAS
228	Dollikerstrasse	Meilen	neff neumann	2014	TOTAL VOLUME	LOGGIAS
229	Strickler Areal	Horgen	neff neumann	2017	TOTAL VOLUME	BALCONY
230	Mühledorfstrasse	Bern	W2H Architekten AG	2015	BALUSTRADE	LOGGIAS
231	Wohnüberbauung Bellariarain	Zurich	manoa Landschaftsarchitekten GmbH	2015	SLAB TO SLAB	BALCONY
232	Ersatzneubau MFH Wyler	Bern	reinhardpartner	2014	TOTAL STOREY	BALCONY
233	Neubau Mehrfamilienhaus Ebnat	Schaffhausen	Oechsli + Partner	2015	BALUSTRADE	BALCONY
234	Mehrfamilienhäuser Horn	Horn	plan b architekten gmbh	2015	TOTAL STOREY	BALCONY
235	Neubau Wohnüberbauung	Flims	Giubbini Architekten	2011	TOTAL VOLUME	BALCONY
236	Chilestieg	Rümlang	Baumschlager Eberle Architekten	2014	TOTAL VOLUME	LOGGIAS
237	Wohnüberbauung Schwanengasse, Baufeld A	Biel	Kistler Vogt Architekten	2015	BALUSTRADE	LOGGIAS
238	Meiriacker housing association	Binningen	Flubacher_Nyfeler_Partner	2015	BALUSTRADE	BALCONY
239	Wohnüberbauung Minoletti	Kriens	BlessHess AG	2013	SLAB TO SLAB	LOGGIAS

Ref. number	PROJECT NAME	LOCATION	ARCHITECT	YEAR	FAÇADE COMPOSITION	FAÇADE MORPHOLOGY
240	Wohnhaus WOOON	Zurich	mischa badertscher architekten	2017	BALUSTRADE	BALCONY
241	Résidence Cassarde	Neuenburg	Gebert Architekten	2008	SLAB TO SLAB	BALCONY
242	Wohnhaus Erguelweg	Biel	Gebert Architekten	2007	SLAB TO SLAB	BALCONY
243	Überbauung Lindenhof	Reinach	Weber Architekten	2016	SLAB TO SLAB	BALCONY
244	Housing for the Elderly	Domat Ems	Dietrich Schwarz Architekten	2004	SLAB TO SLAB	LOGGIAS
245	Mehrfamilienhäuser	Uetikon am See	m3 Architekten	2014	SLAB TO SLAB	BALCONY
246	Neubau MFH	Beringen	Architekturbüro Hilpertshauser AG	2015	SLAB TO SLAB	BALCONY
247	Wohnüberbauung Hofstatt	Zuchwil	phalt Architekten	2014	BALUSTRADE	BALCONY
248	MFH Bahnhofstrasse	Lenzburg	am-architektur	2014	BALUSTRADE	BALCONY
249	Wohnüberbauung am Park	Allschwil	PROPLANING AG	2012	TOTAL VOLUME	BALCONY
250	Wohnquartier Rheinfels	Chur	maurusfrei	2013	BALUSTRADE	BALCONY
251	Wohnhaus Aarestrasse	Aarau	Pfiffner.Fischer	2011	BALUSTRADE	BALCONY
252	Wohneigentum Langmattstrasse	Muttenz	ROSENMUND + RIEDER Architekten BSA	2008	BALUSTRADE	BALCONY
253	Bethanie	Lausanne	TRIBU architecture	2013	TOTAL VOLUME	CLEAN VOLUME
254	Chauderon	Lausanne	TRIBU architecture	2005	SLAB TO SLAB	LOGGIAS
255	New build zero-energy apartment house	Zurich	Kämpfen für Architektur	2011	TOTAL STOREY	BALCONY
256	Residential complex Sunny Watt	Zurich	Kämpfen für Architektur	2010	BALUSTRADE	BALCONY
257	Business and Residential Pilatusplatz	Luzern	Theo Hotz Partner Architekten	2006	SLAB TO SLAB	CLEAN VOLUME
258	Überbauung Walke	Reiden	Alberati Architekten	2013	TOTAL VOLUME	BALCONY
259	Wohnüberbauung „im Feld“	Oberrohrdorf	Walker Architekten	2017	BALUSTRADE	LOGGIAS
260	Wohnhäuser Bionstrasse	Zurich	Züst Gübeli Gambetti	2013	TOTAL STOREY	BALCONY
261	Wohnüberbauung Schlierenstrasse	Uitikon	Züst Gübeli Gambetti	2012	SLAB TO SLAB	LOGGIAS
262	Erneuerung Fassade Hochhaus «Shoppi»	Spreitenbach	TK Architekten	2007	TOTAL STOREY	CLEAN VOLUME
263	Neubau Wohnsiedlung	Dietikon	Schneider Studer Primas	2013	SLAB TO SLAB	LOGGIAS
264	Cascada Laret	Pontresina	Greutol AG	2011	TOTAL VOLUME	LOGGIAS
265	Mehrfamiliengebäude Wohnsiedlung Dietlimoos	Adliswil	Greutol AG	2011	TOTAL STOREY	BALCONY
266	Überbauung Margrethenhof	Ballwil	Lengacher Emmenegger Partner	2010	SLAB TO SLAB	LOGGIAS
267	3MFH Oberchärns	Rothenburg	Lengacher Emmenegger Partner	2008	BALUSTRADE	BALCONY
268	Wohnüberbauung Reblage	Zeiningen	Rapp Architekten	2011	SLAB TO SLAB	BALCONY
269	Industriestrasse	Luzern	lilin architekten	2011	TOTAL STOREY	BALCONY
270	Wohnüberbauung Langhagweg - Wohnen	Zurich	Chebbi | Thomet | Bucher Architektinnen	2012	BALUSTRADE	BALCONY
271	Housing Complex Binzallee	Zurich	Leuppi & Schafroth Architekten	2010	TOTAL STOREY	LOGGIAS
272	Wohnquartier Bronschhofen	wil	Ferrier Architekten	2012	SLAB TO SLAB	BALCONY
273	Überbauung Haldengutareal West	Winterthur	Ferrier Architekten	2010	TOTAL STOREY	BALCONY
274	Mehrfamilienhaus Ottenbergstrasse	Zurich	Leutwyler Partner Architekten	2006	SLAB TO SLAB	BALCONY
275	New residential development "Elco Park"	Allschwil	Burckhardt+Partner	2012	TOTAL VOLUME	LOGGIAS
276	Überbauung Seestrasse	Thun	Fahrni Architekten	2012	SLAB TO SLAB	BALCONY
277	Wohnüberbauung Sonnmatt	Willisau	BAUREAG Architekten	2012	SLAB TO SLAB	LOGGIAS
278	Genossenschaftlicher Wohnbau Gütschhöhe	Luzern	MMJS Jauch-Stolz Architekten AG	2012	TOTAL STOREY	LOGGIAS
279	Housing at Herti 6	Zug	ASTOC Architects and Planners	2011	TOTAL STOREY	BALCONY
280	Mehrfamilienhäuser "Alte Riedikerstrasse"	Uster	Dahinden Heim Architekten	2013	SLAB TO SLAB	BALCONY
281	Mehrfamilienhäuser "Am Römerweg"	Winterthur	Dahinden Heim Architekten	2012	BALUSTRADE	LOGGIAS
282	Arealüberbauung "rudolfstrasse.ch"	Winterthur	Dahinden Heim Architekten	2011	SLAB TO SLAB	BALCONY
283	Neubau Wohnhaus Kirchstrasse	Sarnen	Beda Dillier	2010	TOTAL STOREY	BALCONY
284	Wohnüberbauung Rütliweg	Muri	Hegi Koch Kolb + Partner	2010	SLAB TO SLAB	BALCONY
285	Mehrfamilienhaus	Lohn-Ammannsegg	phalt Architekten	2011	TOTAL VOLUME	BALCONY
286	Siedlung Obere Au	Heimberg	Hebeisen+Vatter Architekten AG	2007	SLAB TO SLAB	LOGGIAS
287	1-3 Familienhaus in der Eierbrecht	Zurich	Eidenbenz . Architekt	2006	SLAB TO SLAB	BALCONY
288	Wohnsiedlung Entlisberg	Zurich	Althammer Hochuli Architekten	2009	BALUSTRADE	BALCONY
289	Wohnsiedlung Wasserschöpfi	Zurich	Althammer Hochuli Architekten	2011	TOTAL STOREY	BALCONY
290	Wohnungsbau	Unterägeri	Cometti Truffer Architekten	2005	SLAB TO SLAB	LOGGIAS
291	Umbau und Aufstockung Wohnhaus Bristenstrasse	Zurich	Forster & Uhl Architekten	2011	TOTAL VOLUME	BALCONY
292	Neubau Mehrfamilienhaus Gebhartstrasse	Liebefeld	Halle 58 Architekten	2006	SLAB TO SLAB	BALCONY
293	Wohnüberbauung Wart- / Äckerwiesenstrasse	Winterthur	Zach + Zünd	2016	SLAB TO SLAB	BALCONY
294	Neubau 2 MFH	Volketswil	Heinz Müller + Partner Architekten	2006	SLAB TO SLAB	BALCONY
295	Wohnbauten Chrezgass	Birmenstorf	mischa badertscher architekten	2011	BALUSTRADE	BALCONY
296	Seehäuser	Meilen	E2A	2010	TOTAL STOREY	BALCONY
297	Wohnüberbauung In Wannen	Winterthur	ERP Architekten AG egli rohr partner	2007	SLAB TO SLAB	LOGGIAS
298	Überbauung Wagnerfeld Zwei	Wagen	Halter Hunziker Architekten AG	2014	BALUSTRADE	BALCONY
299	MFH Hädrichpark Uürich	Zurich	Haerter & Partner AG	2006	BALUSTRADE	LOGGIAS
300	Überbauung Ufenau-Park	Pfäffikon	Halter Hunziker Architekten AG	2017	BALUSTRADE	BALCONY
301	Überbauung «Wendelin»	Rickenbach	zsb architekten	2016	SLAB TO SLAB	BALCONY

Ref. number	PROJECT NAME	LOCATION	ARCHITECT	YEAR	FAÇADE COMPOSITION	FAÇADE MORPHOLOGY
302	Ergänzungsbauten zur Arealüberbauung	Zurich	ERP Architekten AG egli rohr partner	2009	BALUSTRADE	LOGGIAS
303	Wohnüberbauung Wolfswinkel	Zurich	ERP Architekten AGegli rohr partner	2007	BALUSTRADE	BALCONY
304	Le foyer	Lausanne	Ferrari Architectes	2018	BALUSTRADE	BALCONY
305	La Vignettaz	Pully	Ferrari Architectes	2019	SLAB TO SLAB	BALCONY
306	Les Balcons du Lavaux	Jongny	Ferrari Architectes	2016	SLAB TO SLAB	BALCONY
307	Les Marinières	Morges	Ferrari Architectes	2015	BALUSTRADE	BALCONY
308	Clos du Merisier	Cossonay	Ferrari Architectes	2018	BALUSTRADE	BALCONY
309	Les Boverattes	Pully	Ferrari Architectes	2018	SLAB TO SLAB	BALCONY
310	Concorde Secteur L	Vernier	Ferrari Architectes	2017	SLAB TO SLAB	LOGGIAS
311	Fiches Nord Lot 11	Lausanne	Ferrari Architectes	2018	SLAB TO SLAB	LOGGIAS
312	Epalinges 501	Epalinges	Ferrari Architectes	2018	TOTAL VOLUME	LOGGIAS
313	Galicien 7	Prilly	Ferrari Architectes	2012	BALUSTRADE	BALCONY
314	Eikenott	Gland	Ferrari Architectes	2014	SLAB TO SLAB	BALCONY
315	Champs-Meunier Sud	Lausanne	RDR	2014	SLAB TO SLAB	BALCONY
316	L'Ilot du Centre	Lausanne	RDR	2011	SLAB TO SLAB	BALCONY
317	La Verrière	Montreux	RDR	2005	SLAB TO SLAB	BALCONY
318	Pic-Pic	Geneva	RDR	2014	SLAB TO SLAB	BALCONY
319	Hotel Bains Saillon	Saillon	RDR	2016	TOTAL STOREY	CLEAN VOLUME
320	Avenue Gilamont	Vevey	RDR	2015	TOTAL STOREY	BALCONY
321	Chemin des Peupliers	Pully	RDR	2013	BALUSTRADE	BALCONY
322	Grand-Pré Sud	Cheseaux-sur-Lsnne	RDR	2015	BALUSTRADE	LOGGIAS
323	Les fiches nord	Lausanne	RDR	2016	TOTAL VOLUME	BALCONY
324	Champs-Meunier Nord	Lausanne	RDR	2013	SLAB TO SLAB	BALCONY
325	Les Triaudes	Ecublens	RDR	2017	TOTAL STOREY	BALCONY
326	Avenue de Tivoli	Lausanne	RDR	2014	BALUSTRADE	BALCONY
327	Maison des étudiants	Geneva	Lacroix Chessex	2012	BALUSTRADE	BALCONY
328	Immeuble de logements	Saint-Sulpice	Lacroix Chessex	2016	BALUSTRADE	BALCONY
329	MERET OPPENHEIM HOCHHAUS	Basel	Herzog & de Meuron	2019	TOTAL STOREY	BALCONY
330	Jakob Tower	Basel	Herzog & de Meuron	2005	TOTAL STOREY	CLEAN VOLUME
331	Südpark	Basel	Herzog & de Meuron	2012	TOTAL VOLUME	CLEAN VOLUME
332	ELLI – Residential Building and Studio	Zurich	Holzer Kobler Architekturen	2016	TOTAL STOREY	CLEAN VOLUME
333	Swiss House XXXIV Galbisio	Bellinzona	Davide Macullo Architects	2017	SLAB TO SLAB	BALCONY
334	Hammam and Apartements in Patumbah-Park	Zurich	Miller & Maranta	2013	TOTAL VOLUME	BALCONY
335	Casa Pico Building	Lugano	SPBR Arq, Baserga Mozzetti Architetti	2013	TOTAL STOREY	BALCONY
336	Escherpark	Zurich	E2A	2015	TOTAL STOREY	BALCONY
337	Zellwegerpark	Uster	Herzog & de Meuron	2015	BALUSTRADE	BALCONY
338	Le Stelle Housing	Solduno	Buzzi Architetti	2015	TOTAL VOLUME	LOGGIAS
339	MFH Glattlistrasse	Bassersdorf	L3P Architekten AG FH SIA	2010	TOTAL VOLUME	BALCONY
340	WohnWerk	Basel	Christ & Gantenbein	2010	TOTAL VOLUME	CLEAN VOLUME
341	VoltaMitte	Basel	Christ & Gantenbein	2010	BALUSTRADE	LOGGIAS
342	Bamboo Residency	Geneva	group8	2011	SLAB TO SLAB	BALCONY
343	Coral House	Geneva	group8	2011	SLAB TO SLAB	CLEAN VOLUME
344	Housing Neufrankengasse	Zurich	EM2N	2008	TOTAL VOLUME	LOGGIAS
345	Housing Im Forster	Zurich	EM2N	2011	TOTAL VOLUME	LOGGIAS
346	Affoltern Housing Development	Zurich	EM2N	2012	BALUSTRADE	BALCONY
347	Residential Building In Cureglia	Cureglia	Stefano Moor+Bonetti e Bonetti Architetti	2009	SLAB TO SLAB	BALCONY
348	Residential Building Zug Schleife	Zug	Valerio Olgiati	2012	SLAB TO SLAB	BALCONY
349	Coupe Gordon-Bennett	Vernier	LRS Architectes, 3BM3, group8	2013	BALUSTRADE	BALCONY
350	Urban Villa Beaumont	Lausanne	2b architectes	2011	TOTAL VOLUME	CLEAN VOLUME
351	Student Apartments in Luzern	Luzern	Durisch + Nolli Architetti	2013	SLAB TO SLAB	CLEAN VOLUME
352	Conversion Hammergut	Cham	EM2N	2013	BALUSTRADE	CLEAN VOLUME
353	St-Sulpice	Saint-Sulpice	FHV Architectes	2014	BALUSTRADE	BALCONY
354	Boissonnet Building	Lausanne	TRIBU architecture	2014	TOTAL VOLUME	BALCONY
355	Stone H	Zurich	Gus Wüstemann Architects	2014	TOTAL VOLUME	LOGGIAS
356	Student housing in Geneva	Geneva	Frei Rezakhanlou Architects	2013	SLAB TO SLAB	LOGGIAS

A.4.2 Sample of BIPV façade projects

Ref. number	PROJECT NAME	LOCATION	ARCHITECT	YEAR	VISUAL FEATU	FUNCTION FEATURE	SIZE (kWp)
1	Monte Rosa Hutte	Zermatt	ETH Studio	2009	OPAQUE	FAÇADE CLADDING	16 kWp
2	E Kita	Marburg	Opus Architekten	2013	OPAQUE	FAÇADE CLADDING	52 kWp
3	Mixed commercial and residential building	Munich	a+p Architekten	2004	OPAQUE	FAÇADE CLADDING	3.9 kWp
4	Hofberg 6/7	Will	Fent Solare Archite	2011	OPAQUE	FAÇADE CLADDING	52 m2
5	AGC Glass Europe Technovation Centre	Gosselies	ASSAR ARCHITECTS	2014	TRANSLUCENT	FAÇADE GLAZING	19.37 kWp
6	Stadtwerke Konstanz, Customer Service Centre	Konstanz	Arnold Wild	2011	TRANSLUCENT	FAÇADE GLAZING	24.5 kWp
7	Fire station	Houten	Samyn and Partners	2000	TRANSLUCENT	FAÇADE GLAZING	23.9 kWp
8	Photovoltaic pavillion	Postdam	Ortner+Ortner Baukunst	2011	TRANSLUCENT	FAÇADE GLAZING	7.8 kWp
9	Cambridge Bidwell House	Cambridge	Consarc Architects	2018	TRANSPARENT	FAÇADE GLAZING	
10	Azurmendi restaurant	Larrabetzu	Naia Eguino	2014	TRANSPARENT	FAÇADE GLAZING	21 kWp
11	ICSE	Las Palmas	ACH Arquitectos	2015	TRANSPARENT	FAÇADE GLAZING	
12	Brunel University	London	Onyx solar	2016	TRANSPARENT	FAÇADE GLAZING	
13	STIMicroelectronics	Grenoble	Tenesol	2001	TRANSLUCENT	FAÇADE SECURITY	35 kWp
14	Solarsiedlung Hintere Laugeten	Einsiedeln	Sanjo Group	2012	OPAQUE	FAÇADE SECURITY	34.4 kWp
15	Paul-Horn Arena	Tübingen	Allmann Sattler Wappn	2004	OPAQUE	FAÇADE CLADDING	43 kWp
16	Academy of Further Education "Mont-Cenis"	Herne	Jourda & Perraudin	1999	TRANSLUCENT	FAÇADE GLAZING	1000 kWp
17	14 Unit Housing Development	Ijsselstein	Kiss + Cathcart	2002	OPAQUE	FAÇADE CLADDING	30 m2
18	Casa Solara	Laax	Giovani Cerfeda	2012	OPAQUE	FAÇADE CLADDING	346 m2
19	GreenPix – Zero Energy Media Wall	Beijing	Simone Giostra	2008	TRANSLUCENT	FAÇADE CLADDING	2200m2
20	Student Housing	Aarhus C	Arkitema Architects	2001	OPAQUE	FAÇADE CLADDING	15.8 kWp
21	Turnhalle Burgweinting	Regensburg	Tobias Ruf	2004	TRANSLUCENT	FAÇADE GLAZING	10 kWp
22	Natura Towers	Lisbon	GJP arquitectos	2009	TRANSLUCENT	FAÇADE GLAZING	24 kWp
23	Q-Cells OF1	Thalheim	bhss Architects	2008	TRANSLUCENT	SOLAR CONTROL	48 kWp
24	Life Science Building	Washington	Perkins + Will	2018	TRANSLUCENT	SOLAR CONTROL	
25	Alan Gilbert Building	Melbourne	Metier3	2001	TRANSLUCENT	FAÇADE GLAZING	46 kWp
26	K2 Apartments	Melbourne	DesignInc	2007	OPAQUE	FAÇADE CLADDING	22 kWp
27	Terfens-Community center	Terfens	Raim-Michl-Architekten	2006	OPAQUE	FAÇADE SECURITY	23.4 kWp
28	Power Tower	Linz	Weber + Hofer	2008	OPAQUE	FAÇADE CLADDING	66 kWp
29	Sport- und Wellnessbad Eggenberg	Graz	Fasch & Fuchs Architekt	2011	OPAQUE	FAÇADE CLADDING	
30	TROP	St Johann in Tirol	Architektengrupe P3	2004	OPAQUE	FAÇADE CLADDING	
31	Dauwalder House	Birmenstorf	Reto Miloni	2009	OPAQUE	SOLAR CONTROL	1.5 kWp
32	Wirtschaftshof Linz	Linz	Schimek Architekten	1999	TRANSLUCENT	SOLAR CONTROL	20 kWp
33	Sonnenpark Dornbirn	Dornbirn	Architekturbüro MHM	1998	TRANSLUCENT	FAÇADE GLAZING	18.1 kWp
34	Haus Frick	Batschuns in Vorarlberg	Architektur Atelier Unte	1995	OPAQUE	FAÇADE CLADDING	0,4 kWp
35	Copenhagen International School	Copenhagen	C.F. Møller	2017	OPAQUE	FAÇADE CLADDING	
36	Dwelling Houses Spinnereistrasse	Hard	HK Architekten	2003	OPAQUE	SOLAR CONTROL	
37	Primary Health Care Centre "Roger de Flor"	Barcelona	Francisco Gallardo	2007	TRANSLUCENT	FAÇADE GLAZING	10 kWp
38	Social Center "El Barranquet"	Alicante	Aljibe, Peral, Garcia	2007	TRANSLUCENT	FAÇADE GLAZING	5.4 kWp
39	Froniuswerk-Sattledt	Sattledt	Belfanti, Füreder, Meidl	2007	TRANSLUCENT	FAÇADE GLAZING	608 kWp
40	"Magic Box" solar house	Madrid	ETS arquitectura	2007	TRANSLUCENT	FAÇADE GLAZING	8.1 kWp
41	Leicester University Library	Leicester	Romag	2007	OPAQUE	SOLAR CONTROL	37 kWp
42	Zero-energy building of Acciona Solar	Sarriguren	Garaikoetxea, Ansa, Itu	2006	TRANSLUCENT	SOLAR CONTROL	48.3 kWp
43	William Rankine Building	Edinburgh	Hurd Rolland	2006	OPAQUE	FAÇADE CLADDING	26.35 kWp
44	Power Plant Dorferbach	Prägraten	Ing. Erwin Mair	2005	OPAQUE	FAÇADE CLADDING	2.83 kWp
45	Kyocera Mita Hirakata factory	Hirakata	Takenaka corporation	2006	OPAQUE	FAÇADE CLADDING	60 kWp
46	Development of a façade	Munkebo	Lind-Alleen	2005	OPAQUE	FAÇADE CLADDING	4 kWp
47	SDED Office building	Valence	Andre Salnais	2005	OPAQUE	SOLAR CONTROL	14.5 kWp
48	Office Building Bauerfeind AG	Zeulenroda-Triebes	Alfred Görstner	2004	TRANSLUCENT	SOLAR CONTROL	34 kWp
49	Solar Info Center	Freiburg	Guido Epp	2004	TRANSLUCENT	FAÇADE GLAZING	6 kWp
50	Plan Nijrees	Almelo	HBG-Vastgoed BV	2001	OPAQUE	SOLAR CONTROL	25.3 kWp
51	Fraunhofer ISE - Magistrale, facade	Freiburg	Dissing + Weitling	2001	TRANSLUCENT	FAÇADE GLAZING	2.4 kWp
52	"Casa Verde" CEMACAM	Torreguil	Vega and Arribas	2001	TRANSLUCENT	FAÇADE GLAZING	11.1 kWp
53	Oversea Building	Chioggia	Simone Micheli	2011	TRANSLUCENT	FAÇADE SECURITY	20 kWp
54	Rembrandt College	Veenendaal	Van den Dikkenberg & B	1998	TRANSLUCENT	SOLAR CONTROL	37 kWp
55	Rathaus	Freiburg	ingenhoven	2018	OPAQUE	SOLAR CONTROL	
56	Active townhouse	Frankfurt	HHS Planer + Architekte	2015	OPAQUE	FAÇADE CLADDING	118 KWP
57	Largo Europa Building	Padova	Gianmaria Scalcon	2010	OPAQUE	FAÇADE CLADDING	10 kWp
58	MFH Raeber	Biel	Avir Architektur	2010	OPAQUE	FAÇADE CLADDING	87 m2
59	A22 Autobrennero	Trento	Studio Asociato Giovana	2009	OPAQUE	FAÇADE CLADDING	7 kWp
60	Bühler Electricité	Monthey	Kurmann & Cretton	2011	OPAQUE	FAÇADE CLADDING	
61	FEAT Headquarters	Lugano	Claudio lo Riso	1997	OPAQUE	SOLAR CONTROL	3.8 kWp
62	Ferdinand Braun Institute	Berlin	MSP Architekten	2006	OPAQUE	FAÇADE CLADDING	39 kWp

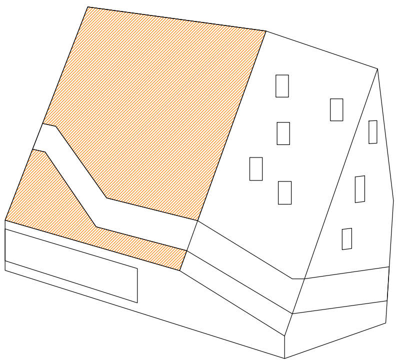
Ref. number	PROJECT NAME	LOCATION	ARCHITECT	YEAR	VISUAL FEATU	FUNCTION FEATURE	SIZE (kWp)
63	GDF Suez	Dijon	Atelier Phileas	2013	TRANSLUCENT	FAÇADE GLAZING	85 kWp
64	Power Grid Control centre	Vienna	Podwin and Marginter	2009	TRANSLUCENT	SOLAR CONTROL	5 kWp
65	SG Ennstal	Liezen	Kreiner architektur	2011	OPAQUE	FAÇADE CLADDING	1.9 kWp
66	UNIFIMM Tower	Bologna	Open Project	2011	OPAQUE	FAÇADE CLADDING	54 kWp
67	World Join Center	Milan	Marco Cerri & Urbam	2010	TRANSLUCENT	FAÇADE GLAZING	80 kWp
68	Elobau Factory 2	Leutkirch	HHS Planer + Architekte	2012	TRANSLUCENT	SOLAR CONTROL	52 kWp
69	Heizplan Solar Park	Gams	atm 3	2010	OPAQUE	FAÇADE CLADDING	28.2 kWp
70	Expo 2010 German Pavillion	Shanghai	Schimidhuber / Milla	2010	TRANSLUCENT	FAÇADE GLAZING	16 kWp
71	Kriengerhornbahn	Lech	Architekturbüro Riemel	2004	TRANSLUCENT	FAÇADE GLAZING	9.5 kWp
72	Meyer Hospital	Florence	CSPE	2007	TRANSLUCENT	FAÇADE GLAZING	33 kWp
73	Staatliche Tealschule	Landshut	A-R.T	2009	OPAQUE	FAÇADE CLADDING	8 kWp
74	Multi-storey parking	Zwolle	Uytenhaak Architekten	2004	OPAQUE	FAÇADE CLADDING	27 kWp
75	B.O.C. Bonneshof Office Center	Düsseldorf	RKW Rhode Kellermann	2014	OPAQUE	FAÇADE CLADDING	63 kWp
76	Fraunhofer ISE	Freiburg	Dissing + Weitling Arkit	2004	OPAQUE	SOLAR CONTROL	4 kWp
77	NCC Holmen and Grynnan	Stockholm	Kjell Torstensson, White	2004	OPAQUE	FAÇADE CLADDING	34,7 kWp
78	MSK Nagano factory	Saku	Ichikawa Sokuryo Sekkei	2004	TRANSPARENT	FAÇADE GLAZING	62 kWp
79	The OpTIC Centre	St Asaph	Capita Percy Thomas	2004	OPAQUE	FAÇADE CLADDING	85 kWP
80	Technological Center "Eduard Soler"	Ripoll	Jerónimo Vega García	2004	TRANSLUCENT	FAÇADE GLAZING	15 kWp
81	Böwe Cardtec	Paderborn	Völse & Rath - Architekt	2003	TRANSLUCENT	FAÇADE GLAZING	9 kWp
82	ZICER Building, University of East Anglia	Norwich	RMJM	2003	TRANSLUCENT	FAÇADE GLAZING	33,88 kWp
83	Casa da Enerxía - As Pontes	A Coruña	Carlos Fernández Garcí	2003	TRANSLUCENT	FAÇADE GLAZING	5 kWp
84	Itoman city government building	Itoman, Okinawa	Nihon Sekkei	2002	OPAQUE	SOLAR CONTROL	195,6 kWp
85	Solar façade "Schott Iberica"	Barcelona	Torsten Masseck	2006	TRANSLUCENT	FAÇADE GLAZING	1,35 kWp
86	EFH	Lech am Arlberg	Pichelr Bau + Plan	2013	TRANSLUCENT	FAÇADE SECURITY	7.6 kWp
87	La CUB	Bordeaux	BDM Architectes	2011	OPAQUE	FAÇADE CLADDING	40 kWp
88	Ales Tourist Office	Ales	Jean-François Rougé	2001	TRANSLUCENT	FAÇADE GLAZING	9.1 kWp
89	Apartments « Gele Lis » Nieuwland	Amersfoort	Atelier Z	2000	TRANSLUCENT	SOLAR CONTROL	32 kWp
90	« Noise Wall Houses » in the Nieuwland district	Amersfoort	Atelier BAK	1998	TRANSLUCENT	FAÇADE GLAZING	9 kWp
91	Siloturm Schapfenmühle Ulm	Ulm	Seidel:Architekten	2004	TRANSLUCENT	SOLAR CONTROL	97 kWp
92	Tourist Information Centre	Hameln	rolf + hotz	2000	TRANSLUCENT	SOLAR CONTROL	9 kWp
93	Wasserwerk Mühlenscharrn	Schwerin	Roland Schulz	1999	TRANSLUCENT	SOLAR CONTROL	7 kWp
94	Tobias Grau Production Building	Rellingen	BRT Architects	2001	TRANSLUENT	FAÇADE GLAZING	10 kWp
95	Solar Power Die Delfgaauwse Weye	Delft	Archictectenbureau Van	2002	OPAQUE	FAÇADE CLADDING	33 kWp
96	Wereldnatuurfondswoningen in Galecop	Nieuwegein	JHK Architecten	1998	TRANSLUCENT	SOLAR CONTROL	31.8 kWp
97	PV sunshading in Monte Malaga Hotel	Malaga	JM Rojas, JR Montoya	2005	OPAQUE	SOLAR CONTRON	54 kWp
98	Isofoton Headquarters	Malaga	Vega, Arribas, Eyras	2005	OPAQUE	FAÇADE CLADDING	84.1 kWp
99	Pompeu Fabra Library	Mataro	Miquel Brullet i Tenas,	1996	TRANSLUCENT	FAÇADE GLAZING	20 kWp
100	Swiss Tech convention Center	Lausanne	RDR	2014	TRANSLUCENT	SOLAR CONTROL	2 kWp
101	Matterhorn Glacier Paradise	Zermatt	Peak Architekten	2009	OPAQUE	FAÇADE CLADDING	
102	New Tracuit Mountain hut	Zinal	Savioz Fabrizzi	2013	OPAQUE	FAÇADE CLADDING	11 kWp
103	ZICER Building, University of East Anglia	Norwich	RMJM	2003	TRANSLUCENT	FAÇADE GLAZING	6.7 kWp
104	Neuer Firmensitz	Sursee	Berger&Frank Architekt	2012	OPAQUE	FAÇADE CLADDING	18 kWp
105	Swiss House of Beauty	Suhr	MGT	2012	OPAQUE	FAÇADE CLADDING	16,8 kWp
106	Werkhof Mels	Mels	Brunhart Brunner Kranz	2011	TRANSLUCENT	SOLAR CONTROL	13.5 kWp
107	Verona Forum	Verona	Mario Bellini Associati S	2010	TRANSLUCENT	FAÇADE GLAZING	20 kWp
108	CSEM Façade	Neuchâtel	René Schmid Architekte	2015	TRANSLUCENT	FAÇADE CLADDING	70 kWp
109	Logistic Center V-Zug	Zug	Betrix & Consolascio Ar	2009	TRANSLUCENT	FAÇADE GLAZING	19.25 kWp
110	New Hall 3 RP Technik	Bönen	Planungsteam Krynowje	2008	TRANSLUCENT	FAÇADE GLAZING	8,4 kWp
111	Wohnhaus Solaris	Zurich	Huggenbergerfries Arch	2017	OPAQUE	FAÇADE CLADDING	74 kWp
112	Schmölzer House	Pratteln	Reto Miloni	2003	TRANSLUCENT	SOLAR CONTROL	3,12 kWp
113	Solares Hochhaus Grosspeter Tower	Basel	Burckhardt+Partner AG	2016	OPAQUE	FAÇADE CLADDING	540 kWp
114	Solar Silo	Basel	Baubüro in situ AG	2015	OPAQUE	FAÇADE CLADDING	24 kWp
115	Sanitary complex of the Alzheimer Project" - Reina So	Madrid	Estudio de Arquitectura	2007	OPAQUE	SOLAR CONTROL	19,92 kWp
116	EWE Arena	Oldenburg	'asp' Architekten	2006	OPAQUE	SOLAR CONTROL	14 kWp
117	CTS Strasbourg	Strasbourg	Apex Bp Solar	2005	OPAQUE	SOLAR CONTROL	60 kWp
118	SOL4-Eichkogel	Mödling	Ruth König	2004	OPAQUE	FAÇADE CLADDING	28 kWp
119	True North/ Lux Nova	Vancouver	Sarah Hall Studio	2007	TRANSLUCENT	FAÇADE GLAZING	
120	Cathedral of the Holy Family	Saskatoon	Sarah Hall Studio	2005	TRANSLUCENT	FAÇADE GLAZING	
121	Pearl River Tower	Guangzhou	SOM	2008	OPAQUE	SOLAR CONTROL	
122	Institute premises	Beijing	Mario Cucinella	2006	TRANSLUCENT	SOLAR CONTROL	
123	Energimidt	Silkeborg	Årstiderne Arkitekter A/	2010	TRANSLUCENT	SOLAR CONTROL	
124	House of Musich	Aalborg	Coop Himmelb(l)au	2014	TRANSLUCENT	SOLAR CONTROL	
125	[Pod # 001]	Copenhagen	Collective N55	2007	TRANSLUCENT	SOLAR CONTROL	0,26
126	Copenhagen towers hotel	Copenhagen	Norman Foster	2009	OPAQUE	FAÇADE CLADDING	

Ref. number	PROJECT NAME	LOCATION	ARCHITECT	YEAR	VISUAL FEATU	FUNCTION FEATURE	SIZE (kWp)
127	Aarhus Municipality Low-Energy Offices C.F.	Aarhus	Møller Architects, Aarhu	2010	OPAQUE	SOLAR CONTROL	170 m2
128	SDED Office building	Valence	Andre Salnais	2005	OPAQUE	SOLAR CONTROL	14,5 kWp
129	Cité du Design	Saint-Etienne	LIN Architects	2009	TRANSLUCENT	FAÇADE GLAZING	
130	MIBI – Montpellier International Business Incubator	Montpelier	Emmanuel Nebout	2011	TRANSLUCENT	SOLAR CONTROL	
131	Juwi Verwaltungsgebäude	Bolanden	Oehler & Faigle Archcor	2004	OPAQUE	FAÇADE CLADDING	10 kWp
132	Zara, Hohe Strasse 128-132	Cologne	Angela und Georg Feinl	2003	OPAQUE	FAÇADE CLADDING	12 kWp
133	Solar Tower	Hauptbahnhof Freiburg	Harter + Kanzler, Waldk	1999	OPAQUE	FAÇADE CLADDING	34 kWp
134	Energiepark West	Satteins	Heim + Müller	1996	OPAQUE	FAÇADE CLADDING	150 m2
135	Hauptbahnhof	Berlin	Meinhard von Gerkan	2003	OPAQUE	FAÇADE CLADDING	180 kWp
136	Haus der zukunft	Regensburg	fabi arrchitekten	2009	OPAQUE	FAÇADE CLADDING	55 m2
137	Swimmingpool	Nivelles	Arcadus	2016	TRANSLUCENT	FAÇADE GLAZING	
138	PEB Renovation	Zurich	Viridén + Partner AG	2013	OPAQUE	FAÇADE CLADDING	170 kWp
139	PEB Fitness/Wellness NEST	Dübendorf	dransfeldarchitekten ag	2017	TRANSLUCENT	SOLAR CONTROL	24,2 Kwp
140	PEB-MFH SonnenparkPLUS	Wetzikon	arento ag - nachhaltige	2017	TRANSLUCENT	FAÇADE SECURITY	80,7
141	PEB-Clevergie AG	Wyssachen	Zürcher & Partner	2017	OPAQUE	FAÇADE CLADDING	90 kWp
142	Talstation Klein Matterhorn Bahn	Zermatt	Solarbau Lowel GmbH	2017	TRANSLUCENT	FAÇADE GLAZING	136 kWp
143	Solares Mehrfamilienhaus	Reichenburg	Sanjo Management	2017	OPAQUE	FAÇADE SECURITY	59 kWp
144	PEB-MFH Immobilien	Bätterkinden	AVI Immobilien Treuhar	2017	OPAQUE	FAÇADE SECURITY	31 kWp
145	PEB-EFH und Büro Güller	Würenlos	Oldani Architektur & Ba	2016	OPAQUE	FAÇADE CLADDING	24,1 kWp
146	PEB-MFH Ebneter	Appenzell	MFW Architekten AG	2016	OPAQUE	FAÇADE CLADDING	40,7 kWp
147	Collège solaire «Le Suchet»	Leysin	ATLANTE SA	2016	OPAQUE	FAÇADE CLADDING	231 kWp
148	Solares Parkhaus	Kaiseraugst	Wobatech AG	2016	OPAQUE	FAÇADE SECURITY	634 kWp
149	Solarer Anbau	Muttenz	Allsoll GmbH	2017	TRANSLUCENT	FAÇADE GLAZING	76 kWp
150	Energieautarkes MFH Unterdorfstr	Brütten	René Schmid Architekte	2015	OPAQUE	FAÇADE CLADDING	206 kWp
151	Soleol SA	Estavayer-le-lac	Collbert Engineering SA	2015	OPAQUE	FAÇADE CLADDING	231 kWp
152	PEB-Doppelfamilienhaus Fent	Will	Fent solare Architektur	2015	OPAQUE	FAÇADE SECURITY	21,7
153	Jugendstil-PEB-MFH Culmannstr.	Zurich	Fent Solar Architektur	2015	OPAQUE	FAÇADE CLADDING	27,9 kWp
154	Mehrfamilienhaus Chrüzmatte	Aesch	Mark Röösli	2015	OPAQUE	FAÇADE CLADDING	229,9 kWp
155	NTNU - Norwegian University of Science and Technolo	Trondheim	NTNU - Norwegian Univ	2000	TRANSLUCENT	SOLAR CONTROL	16 kWp
156	Primary Health Care Centre "Roger de Flor"	Barcelona	Francisco Gallardo	2007	TRANSLUCENT	FAÇADE GLAZING	10 kWP
157	Social Center "El Barranquet"	El Campello	Dolores Aljibe Varea, Ar	2007	TRANSLUCENT	FAÇADE GLAZING	5,4 kWp
158	PV-Ceramic ventilated façade	Castellon de la Plana	Atersa	2007	OPAQUE	FAÇADE CLADDING	6 kWp
159	Froniuswerk	Sattledt	Belfanti | Füreder | Me	2007	TRANSLUCENT	FAÇADE GLAZING	608 kWp
160	William Rankine Building, the University of Edinburgh	Edinburgh	Hurd Rolland	2006	OPAQUE	FAÇADE CLADDING	26,35 kWp
161	Kyocera Mita Hirakata factory	Hirakata	Takenaka corporation	2006	TRANSLUCENT	FAÇADE GLAZING	60 kWp
162	BANDAI Hobby Center	Aoi	Tomii-Kenchiku corporat	2006	OPAQUE	FAÇADE CLADDING	70 kWp
163	CIS Solar Tower Manchester	Manchester	Sharp	2006	OPAQUE	FAÇADE CLADDING	391 kWp
164	Development of a façade covering element for flexible	Munkebo	Lind-alleen	2006	OPAQUE	FAÇADE CLADDING	4 kWp
165	Torregarena	lAlcalá de Henares	BP Solar España	2005	OPAQUE	SOLAR CONTROL	80 kWp
166	PV sunshading in Monte Malaga Hotel	Malaga	Juan Manuel Rojas Fern	2005	OPAQUE	SOLAR CONTROL	54 kWp
167	Gresivaudan High School	Meylan	Apex Bp Solar	2004	TRANSLUCENT	FAÇADE GLAZING	45 kWp
168	Christian Kindergarten Ulmenstrasse	Dresden	Reiter architekten	2003	TRANSLUCENT	FAÇADE GLAZING	
169	UBA building extension	Dessau	Anderhalten Architekter	2017	OPAQUE	FAÇADE CLADDING	
170	Social Housing residential building	Best	NBArchitecten	2018	OPAQUE	FAÇADE CLADDING	
171	The Treurenberg building	Brussels	ASSAR ARCHITECTS	2015	OPAQUE	FAÇADE CLADDING	122 kWp
172	Haus F87	Berlin	Werner Sobek	2011	OPAQUE	FAÇADE CLADDING	
173	Leitec Firmengebäude	Heilbad Heiligenstadt	Stadermann, Hausen	2011	OPAQUE	FAÇADE CLADDING	
174	Hochregallager Ernsting's family	Coesfeld	Wortmann	2014	TRANSLUCENT	SOLAR CONTROL	
175	SIMS-Samundra Institute for Marine Studies	Mumbai	CCBA	2007	TRANSLUCENT	FAÇADE GLAZING	
176	Hybrid Solar Façade of Fiat Research Centre	Orbassano	Aste and Finzi	2003	OPAQUE	FAÇADE CLADDING	19.5 Wp
177	Xeliox Energy Lab	Medolago	Marco Acerbis	2011	OPAQUE	FAÇADE CLADDING	
178	Galleria Naviglio	Faenza	Studio Technico	2003	OPAQUE	SOLAR CONTROL	23 kWp
179	Energy box	L'Aquila	Pier-Luigi Bonomo, L'Aq	2013	OPAQUE	FAÇADE CLADDING	
180	Porta Susa Railway station	Turin	Silvio d'Ascia	2013	TRANSLUCENT	FAÇADE GLAZING	
181	MSK Nagano factory	Saku, Nagano	Ichikawa Sokuryo Sekkei	2004	TRANSLUCENT	FAÇADE GLAZING	
182	Daito Bunka University, Itabashi Campus, building 3	Tokyo	YAMAMOTO HORI	2003	TRANSLUCENT	FAÇADE GLAZING	
183	PV façade Mathildelaan	Eindhoven	3.11 Design Essentials	2000	TRANSLUCENT	FAÇADE CLADDING	25.4 kWp
184	Bursagaz	Bursa	Tago Architects	2016	TRANSLUCENT	SOLAR CONTROL	4.1 kWp
185	Union National Bank	Giza	APG	2017	TRANSPARENT	FAÇADE GLAZING	20.6 kWp
186	Valladoid University	Valladolid	Francisco Valbuena	2015	TRANSLUCENT	FAÇADE GLAZING	6 kWp
187	Genyo Building	Granada	Planho	2008	TRANSLUCENT	FAÇADE CLADDING	19.3 kWp
188	Oslo Opera	Oslo	Snoeta	2007	TRANSLUCENT	FAÇADE GLAZING	38 kWp
189	Municipal Kinder Garden "El Blauet"	Sant Celoni	CISOL + Petrixol 6	2008	TRANSLUCENT	SOLAR CONTROL	
190	Universidad La Salle	Barcelona	Roberto & Esteve Terrac	2002	TRANSLUCENT	SOLAR CONTROL	18 kWp

Ref. number	PROJECT NAME	LOCATION	ARCHITECT	YEAR	VISUAL FEATU	FUNCTION FEATURE	SIZE (kWp)
191	Flotane Rest Stop	Aurland	L J B	2011	OPAQUE	FAÇADE CLADDING	
192	Oseana	Os Norge	Grieg Architects	2012	OPAQUE	FAÇADE CLADDING	463 m2
193	Bungalow	Karlsruhe-Durlach	Hinrich Reyelts	2003	OPAQUE	FAÇADE CLADDING	
194	CeRN building	Bursins	Atelier Niv-o	2005	OPAQUE	FAÇADE CLADDING	
195	Church Hall	Wels	Luger & Maul	2001	OPAQUE	FAÇADE CLADDING	22.6 kWp
196	Exposing lifestiles	Toronto	Michael Clesle	2006	OPAQUE	FAÇADE CLADDING	
197	Haus fur Europa	Wuppertal	BUW	2009	OPAQUE	FAÇADE CLADDING	6.4 kWp
198	KTH Auditorium	Stockholm	Stadion Arkitekter	2006	TRANSLUCENT	SOLAR CONTROL	
199	Home +	Stuttgart	HFT	2009	OPAQUE	FAÇADE CLADDING	
200	North house	Ontario	RVTR	2009	OPAQUE	FAÇADE CLADDING	13.6 kWp
201	One tonne Life	Stockholm	Wingårdh Arkitektkonto	2008	OPAQUE	FAÇADE CLADDING	6 kWP
202	Solar XXI Building	Lisbon	Cabrito and Diniz	2007	OPAQUE	FAÇADE CLADDING	12 kWp
203	National Test Centre	St. Gallen	Theo Hotz AG	1996	OPAQUE	SOLAR CONTROL	45.5 kW
204	Caltrans District 7 Headquarters	Los Angeles	Morphosis	2007	TRANSLUCENT	SOLAR CONTROL	
205	Sun Microsystems Clock Tower	Burlington, MA	HOK Architects	1998	TRANSLUCENT	FAÇADE GLAZING	2,5
206	Green Dot Animo Lennox High School	Inglewood	Brooks + Scarpa	2013	OPAQUE	FAÇADE CLADDING	
207	Dubai Frame	Dubai	Fernando Donis	2015	TRANSLUCENT	FAÇADE GLAZING	28kWp
208	Valdecilla Hospital	Santander	Herraez Arquitectura	2016	TRANSLUCENT	FAÇADE GLAZING	26.5 kWp

A.4.3 Best-practice BIPV façades analysed

NEW MONTE ROSA HUT



MAIN AKNOWLEDGMENTS

2010 Swiss Solar Prize

2008 Holcim Award Bronze Europe

In close collaboration between the ETH Zurich and the Swiss Alpine Club (SAC), the New Monte Rosa Hut SAC was developed as a sustainable building in the high Alps (2883 m above sea level) in the hillside of the Monte Rosa peak. The ETH intends the building to serve as a model for the successful linkage of architecture with sustainability and modern technology. The first wooden hut in this spot was built in 1895 and has been replaced, reconstructed and enlarged several times during the 20th century. The project was developed with students at the ETH Monte Rosa Studio and participating interdisciplinary specialists. A new integrated solution was found to replace the existing hut, incorporating architectural expression, material implementation, energy supply, water storage, and sewage disposal.

As another rock on the mountains, the New Monte Rosa Hut stands among Gorner, Grenz and Monte Rosa Glaciers. This faceted metal volume looks like a glittering crystal shape where the South facet is regularised to accommodate the integration of a Photovoltaic system. The defining feature of the architectural concept is its splendid isolation within the Alpine landscape, in an extreme climatic location far from supply networks. Therefore, the new hut had to be as autonomous as possible. The photovoltaic panels are integrated into the facade of the building, adding a dual function to the building's envelope and introducing a dialogue with the shimmering aluminium claddings. It is the south façade which integrates a photovoltaic façade cladding that produces electricity. The building will be able to supply at least 90 per cent of its energy demand.

The concept of the highly insulated façade is the result of a mixture of energy saving and energy production. A spiral-shaped glass band follows the sun and conducts passive energy into the dining room and the peripherally ascending staircase around the whole building. The building looks like a glazed crystal on the glacier, and it is almost entirely self-sufficient.

Architect:	ETHZ + Bearth & Deplazes
Year:	2009
Location:	Zermatt, Switzerland
Typology:	Mountain Hut
Client:	SAC Sektion Monte Rosa-
Urban Morphology:	Class C
PV Technology:	Monocrystalline
Orientation:	South
Inclination:	62.2 °
PV Area:	110.4 m^2
Installed Nominal Power:	16 kWp
Yield:	210000 kW/h year-
Efficiency:	14%
Energy consultant:	3S Swiss Solar Systems
Module Size:	Customized
Colour:	Dark Blue
Transparency:	Opaque
Fixing System:	Framed with sealing-
Dummy Panels:	No

GENERAL ANALYSIS

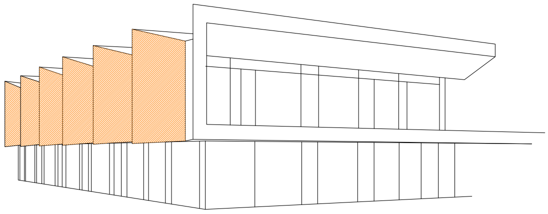
The PV system is integrated into the building's morphology, and it is considered an adequate installation given the building typology we are analysing: a remote mountain hut with no access to the electric network.

The PV installation has been taken into consideration from the very first design phases, it is materials combination, and the volumetric definition is enriched with the integration of the photovoltaic system.

The contrast between materials is directly related to the orientation and the interior distribution of the building. The south façade meets the two functions that are required to classify a PV system as a BiPV: on the one hand it produces electricity, and on the other hand, it protects and isolates against the weather.

In this case, the PV material replaces the aluminium coverage that might have been chosen to protect the south façade.

E-KITA



Architect:	Opus Architekten
Year:	2014
Location:	Marburg, Germany
Typology:	Education
Client:	City of Marburg-
Urban Morphology:	Class B
PV Technology:	Monocrystalline
Orientation:	South
Inclination:	90º
PV Area:	365 m^2
Installed Nominal Power:	52.2 kWp
Yield:	40690 kW/h year-
Efficiency:	--
Energy consultant:	360 Ertex Solar
Module Size:	Standard: 1507 x 637 mm
Colour:	Black
Transparency:	Opaque
Fixing System:	Rear ventilated-
Dummy Panels:	No

MAIN AKNOWLEDGMENTS

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The site is located south of Marburg's city centre on the northern edge of the so-called Vitosareal that was created in the 19th century as a park-like area for a psychiatric hospital.

The location reference, the use as a kindergarten and the Plus Energy standard are the three essential design parameters. The design refers primarily to the landscape and does not compete with the historic building stock: a nearby chapel. The architects have taken advantage of the site slope to place the building in the way that it there is only one storey seen from the chapel but enables the children in both floors direct and continuous access to the space.

In order to achieve the Plus Energy standard, the roof surfaces and the southwestern facade (upper floor) incorporate a BIPV system, generating two distinctive volumes composing the building. Its pitched roof has a visual relation with the existing buildings, and the glazed plinth defines a continuous space with the garden.

In order to reduce energy demand, a compact structure and an optimised orientation of the transparent surfaces is designed. For the quality of the building envelope, high thermal insulation is chosen. This envelope incorporates BIPV panes as an integral part of the façade design and construction. Ultimately, the building elements are 100% recycled material.

The building has a final energy demand of more than 25,000 kWh of electricity per year. To cover this power requirement, the ventilated BIPV system of Ertex Solar coupled to 3 inverters has a total module output of 52.22 kWp. The yield of the BIPV installation is calculated on average 40 690 kWh / yr; which corresponds to almost the electricity needs of 13 statistical sample households in Germany.

GENERAL ANALYSIS

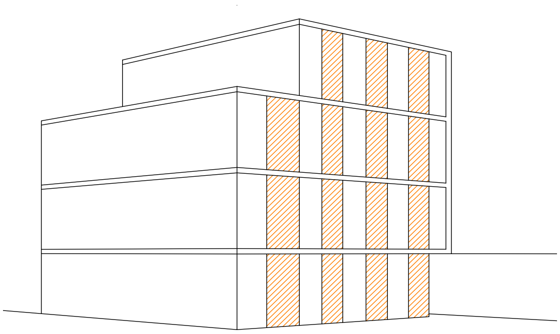
This building is located in a forest clearing where the ground floor disappears while reflecting the trees and vegetation around it and the main floor is perceived as a floating dark dynamic element.

The whole surface of this “floating element” consists of a dark façade cladding that has been replaced by PV material in the south orientation. The colour combination of all the materials creates a unitary perception of the volume with well-defined morphology and precise modulation.

The south façade's surface is modified in order to generate openings for lighting and ventilation and to reach the ideal orientation for the BIPV installation. As the façade orientation is not optimal for efficient use of PV technology, the mentioned façade modification orients the opaque surfaces to profit from of the south orientation and the glazed openings to profit from indirect lighting in the classrooms towards a northwest orientation.

This project is an example of how the designer has in mind from the very beginning and as an essential requirement, the integration of the BIPV system and its efficient installation.

MIXED COMMERCIAL AND RESIDENTIAL BUILDING



MAIN AKNOWLEDGMENTS

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This four storey building is located in an inner court in Munich surrounded by firewalls with garages. The ground and first floor contain offices, the two floors above form a maisonette, and on the roof, there is a terrace that can be used by the office staff. The building steps back on the North and East sides to maintain the required clearances to the neighbouring buildings and also to improve the quality of the living conditions in the maisonette.

The north façade is a plain firewall without openings, merely narrow window slits on the upper floors to illuminate the ancillary rooms on this side of the building. The strictly segmented west façade of the building, facing the inner court, consists of storey-high elements. Full-height openings alternate with panels of the same height, each consisting of four thin-film photovoltaic modules.

The frame-less laminates, separated only by thin black silicon joints, appear to be single units; metal strips delineate the vertical edges. These photovoltaic panels form the cladding between the windows and feed the electricity they produce into the building's electrical installation. As the glazing constitutes more than 50% of the façade area, shading to prevent over-heating of the rooms on hot, sunny days is necessary. This is provided in the form of sliding aluminium louvre shutters that are neatly parked behind the stationary photovoltaic panels when not in use and therefore protected against the weather.

Architect:	a+p Architekten
Year:	2004
Location:	Munich, Germany
Typology:	Residential
Client:	-
Urban Morphology:	Class A
PV Technology:	Thin- film
Orientation:	South-West
Inclination:	90º
PV Area:	41 m^2
Installed Nominal Power:	3.9 kWp
Yield:	2000 kW/h year-
Efficiency:	--
Energy consultant:	Würth Solar, Schwäbish Hallr
Module Size:	Standard: 1200x600 mm
Colour:	Blue
Transparency:	Opaque
Fixing System:	-
Dummy Panels:	No

GENERAL ANALYSIS

With white mat coverage, the architects are trying to foreground the slab band; hence, for space in between, dark and bright materials have been chosen in order to maximise the contrast.

These materials are a PV cold façade and aluminium solar shading modules that will hide behind the PV substructure. The PV modules chosen are a standard small size, so they have been installed in groups of four completing all the height in between floor and ceiling.

The combination of all these elements results in an elegant composition that respects a clear pattern where the variation and dynamism are given by the solar shading elements. These elements are part of a different plan that we can identify while reading the façade: the first plan establishes the general composition and order with the PV panels and the with slab bands while the second plan is composed by the windows and solar shading elements that contribute to the movement and dynamism of this facade of the building.

HOFBERG 6/7

MAIN AKNOWLEDGMENTS

Norman Foster Solar Award_Plus Energy Building 2012

Architect:	Fent Solare Architektur
Year:	2011
Location:	Wil, Switzerland
Typology:	Residential
Client:	Giuseppe Fent
Urban Morphology:	Class B
PV Technology:	Monocrystalline
Orientation:	South
Inclination:	0° / 90°
PV Area:	294 + 51 m^2
Installed Nominal Power:	142.84 + 8 kWp
Yield:	49 650 + 5 650 kW/h year-
Efficiency:	--
Energy consultant:	Sunpowerr
Module Size:	Standard: SunPower
Colour:	Black
Transparency:	Opaque
Fixing System:	-
Dummy Panels:	Yes

The 7-storey building (4 of which aboveground) is located near the historic centre of Will, in Canton St. Gallen, on a steep plot. It is a collective residential building built according to Minergie-P standard, and that received the Norman Foster Award in 2012 for Plus Energy Building. Thanks to high-efficiency monocrystalline modules installed both on the roof and the south façade, in correspondence of the floor bands, the building produces 186% of its energy demand, generating a surplus that enables charging 16 electric cars. The solar architecture of the façade considers the seasonal position of the sun and adapts its geometry to avoid overheating in summer and maximise the solar energy intake in winter without additional energy use or mechanical control.

The building aims to emphasise the horizontality by changing the material on the horizontal slab band. The chosen materials are wood as façade cladding and a dark coating as slab coating.

The heat needs are provided with a heat pump system with two geothermal probes at 211 m depth that, at 14.5°C of temperature, produces enough heat for heating and hot water.

GENERAL ANALYSIS

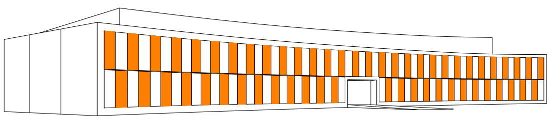
The building presents a coherent PV integration in a building element that has similar orientation requirements. This is to say, both balconies and BIPV panels are usually South-oriented due to the façade's solar control, exterior spaces use and energy performance reasons.

On the south façade, the dark slab coating consists of photovoltaic panels of the same size and colour so that the perception of the building is unitary independently of the orientation. The PV modules also match the glass balustrade size, so that the result has a unitary image.

The PV material reinforces the general concept of the building, and it does not intend to hide. It is the coating of the slab band on the other facades, which have been chosen regarding the pre-existing characteristics of the photovoltaic panel. As the PV panel is dark and has a particular module size, the other material has been selected with a similar colour and a similar size to match the PV installation and to permit the horizontality to be expressed all around the building.

It could have also been integrated substituting the glass balcony, but it would have impeded the views over the valley.

AGC GLASS EUROPE TECHNOVATION CENTRE



Architect:	Assar architectes
Year:	2013
Location:	Gosselies, Belgium
Typology:	Office Building
Client:	AGO
Urban Morphology:	Class C
PV Technology:	Monocrystalline
Orientation:	South
Inclination:	90º
PV Area:	192.28 m^2
Installed Nominal Power:	19.37 kWp
Yield:	--
Efficiency:	--
Energy consultant:	AGCr
Module Size:	Customized: 3308 x 1138
Colour:	Black
Transparency:	Translucent 50.3 %
Fixing System:	Horizontal guides in substructure
Dummy Panels:	No

MAIN AKNOWLEDGMENTS

2015 Finalist MIPIM Award

The AGC technovation centre is a fully dedicated facility to research, development and analysis of AGC glass products. It contains within a single and unique building laboratory, research equipment's, halls, industrial areas, offices, and meeting-room dedicated to the different AGC services and research team.

As the North part of the project is dedicated to halls, laboratories, research and volume consuming pilot activities, the curved zone in the South part includes the main entrance, the public areas and part of the management and administrative activities.

The curved facade is the main visible and emblematic part of the building. Facing South, the cladding of this façade is made of white lacquered glass defining a large horizontal frame. Within the white frame, a double-layered open skin façade is developed. Sun-shaded and protected by alternated photovoltaics glass panels, a thermal high performance glazed façade is developed in retreat. A gallery is created between those two layers adding sun shading benefits and easy walkable maintenance access.

This industrial research building is designed with the optimal horizontal flow for people, equipment's, material, or research samples, with a pertinent use of the natural topographic constraints of the site. Its footprint on site also takes into account all the potential future AGC extensions for the next decades or research and development.

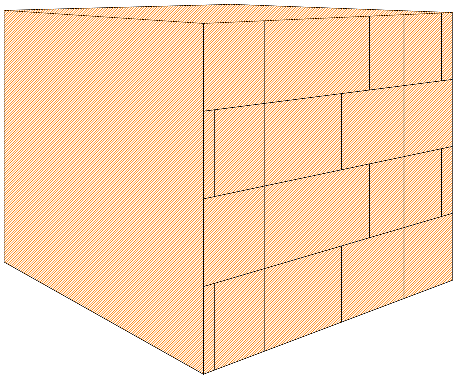
GENERAL ANALYSIS

As a derivate of a double skin facade (with no special thermal performance) the south orientation of this building presents a translucent BIPV installation that acts as solar shading, and, somewhat, as privacy filter between the people outside the building and those working inside.

The elongated proportion of the facade is animated by the rhythm of the photovoltaic panels, which create a subtle succession of shadows and a variety of reflections.

The fact that the panels are around one meter away from the windows provides filtered lighting of the interior spaces. Similarly, this distance seems to provide more pleasing sights than if the translucent panels were directly incorporated into the façade glazing mainly because the latter generates neat grid shadows that can perturb interior visual comfort.

CUSTOMER SERVICE CENTRE KONSTANZ



MAIN AKNOWLEDGMENTS

Plus Energy Building

Architect:	Arnold Wild
Year:	2011
Location:	Konstanz, Germany
Typology:	Administration
Client:	Stadtwerke Konstanz
Urban Morphology:	Class B
PV Technology:	Monocrystalline
Orientation:	South/ Roof
Inclination:	90°/ 0°
PV Area:	230 m^2
Installed Nominal Power:	23.20 kWp
Yield:	-
Efficiency:	-
Energy consultant:	Ertex Solar
Module Size:	Customized: 3000 x4000 mm-
Colour:	Black
Transparency:	Translucent 22%
Fixing System:	Glass Fixing
Dummy Panels:	No

This building, known as the "energy cube" is the Stadtwerke Konstanz Customer Center in Constance. It is a plus-energy house, which means that it generates more energy than it consumes over its useful life.

The cube shape with an edge length of 15 m is chosen as the most energetically optimal geometric shape for a building, and it draws its energy from geothermal and PV mounted on the south side of the facade as well as on the roof.

In cooperation with the Fachhochschule Rosenheim, the Lindner Group developed a custom function glazing. The inner shell of the installed double facade was carried out highly insulated. The outer shell is transparent and serves as a chamber window.

The 20 glass modules integrated on the south facade are custom-made measuring 3 x 4 meters with solar control function. The space between the glass panels is mechanically ventilated.

The energy cube currently offers 20 workplaces and is the focal point for all products and services around the topics of energy, mobility and leisure. Apart from consultations with individuals and corporate clients also exhibitions, seminars and the sale of tickets will be held there in the future.

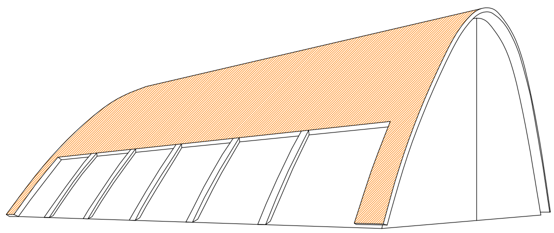
GENERAL ANALYSIS

The Customer Service Centre in Konstanz presents a quasi-total integration of PV technology. The PV installation is adapted depending on the use of the interior spaces: some areas have a light transmissive panel, and others have opaque panels for privacy. This results in a variation of densities and a dynamic façade at night.

The chosen panels are large format panels so that the façade has fewer accidents enhancing the purity of the volume. In addition, the pattern has similar proportions as the façade's general contour; hence, the "cube" global perception is maximised.

Opaque panels and semitransparent panels are intercalated except on the staircase space, where a semitransparent panel is installed in a vertical zigzag directly related to the dynamic character of this communication space.

FIRE DEPARTMENT



MAIN AKNOWLEDGMENTS

First Prize_Nationale Staalprijs 2002

The building design represents the idea of the shelter, the independence of the shell from the building itself. The choice of a parabolic form for the roof is the result of the search for the elegance of form and optimisation of the structure. The fast method of construction was a further significant factor favouring this choice at the design stage.

There is a two-way split of the interior. The south side has been conceived as a completely transparent space in which just glass has been used. Here, the firefighting equipment is kept in what resembles a large shop window.

This barely heated hall is intended to serve as a climatic buffer zone, both in winter and in summer. All the other functions have been gathered together in the northern half of the building, a construction built of load-bearing brickwork which houses office spaces, a conference room, a cafeteria, changing rooms and storage rooms for mechanical equipment.

The glazed façade incorporates large overhead gates designed to allow the firefighting force to make a quick operational exit. The building's length runs in an east-west direction, which allows the southern façade to incorporate photovoltaic cells. The fire station's overall form appears as a modern variant on the traditional theme of the shed.

Architect:	Samyn and Partnerst
Year:	2002
Location:	City of Houten
Typology:	Fire Department
Client:	Municipality of Houten
Urban Morphology:	Class C
PV Technology:	Monocrystalline
Orientation:	South
Inclination:	Variable
PV Area:	400 m^2
Installed Nominal Power:	23.90 kWp
Yield:	30000 kW/h yrr
Efficiency:	-
Energy consultant:	Stroomwerk
Module Size:	Standard-
Colour:	Crystal Blue
Transparency:	Translucent
Fixing System:	Glass Fixing
Dummy Panels:	No

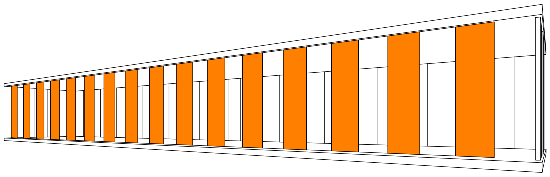
GENERAL ANALYSIS

The project presents a continuous curved surface, which can be considered as a hybrid roof-facade. The architect has taken advantage of this fact to incorporate a translucent BIPV system which enables the natural lighting of the interior spaces. The whole surface has been treated homogeneously with the semitransparent BIPV panels; this fact reinforces the volume identity.

This volume requires a south orientation so that the BIPV system has an optimal efficiency.

The building design required the interior of the building to be seen from the outside, but at the same time, the south façade had to be protected from the sun. The PV system gives solution to these constraints without adding external elements that would spoil the purity of the volume.

PHOTOVOLTAIC PAVILION



Architect:	Ortner + ortner Baukunst
Year:	2011
Location:	Postdam, Germany
Typology:	Publico
Client:	Fachhochschule Postdam
Urban Morphology:	Class C
PV Technology:	Thin-film
Orientation:	N/S/E/W
Inclination:	90°
PV Area:	163.80 m^2
Installed Nominal Power:	7.8 kWp
Yield:	-r
Efficiency:	-
Energy consultant:	Odersun
Module Size:	Customized:3900 x 1050 mm-
Colour:	Black
Transparency:	Translucent
Fixing System:	Metal frame
Dummy Panels:	No

MAIN AKNOWLEDGMENTS

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Ortner + Ortner Baukunst's 35-meter-long x 7.5 meter-wide photovoltaic pavilion adds the finishing touch to the university campus of Potsdam and is to be used as a space for social events, brainstorming ideas and presentations.

The four sides of the building incorporate 4-meters tall and 1 meter wide photovoltaic modules spaced by 1-meter intervals generating a permeable enclosure. Specially manufactured for this application, the solar absorbing units are composed of 25 mm thick security glass. The outward-facing side of the panels is a black reflective finish while the inward-facing side shows a copper-coloured surface.

Defining the external appearance, the shell also contributes to the electrical concept and sustainability goals.

The idea of integrating the green building concept into the redesign of the campus site was part of the project from the outset. Architects Ortner + Ortner Berlin developed this idea further in conjunction with students from the University of Applied Sciences and module manufacturer Odersun which specialises in solar architecture. The result is a symbiosis of sustainable architecture, functionality and efficiency – in short, a solar façade that not only generates power but is also aesthetically attractive.

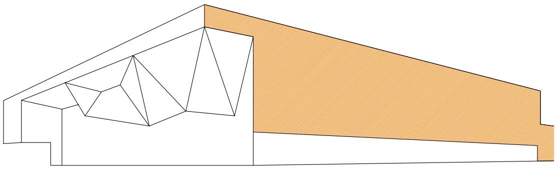
GENERAL ANALYSIS

This building is a conceptual pavilion which houses a polyvalent space without strict requirements regarding space distribution or facade constraints.

All facade orientations have a similar treatment, that is why the thin-film technology is the most appropriate one as it produces electricity also with non-direct sunlight exposure.

The panels are dimensioned according to the full height of the pavilion so that they reinforce the unitary character of the pavilion space.

PAUL HORN ARENA



MAIN AKNOWLEDGMENTS

Hugo-Häring-Prize 2009
Design Award of the Wüstenrot Foundation for "energy-efficient architecture in Germany " 2008
IOC/IAKS Award 2007
German Steel Construction Award 2006

This multi-function facility is located near the sports grounds of Tubingen and the spacious leisure area along the banks of the River Neckar. It is designed to be a representative project for the city as a monolithic block that denotes the end of the sports grounds.

Through the realisation of the sports hall's concept, the requirements of professional sports, sports clubs and school sports are all combined and met within one building. Depending on the type of sport, up to 3.000 seats have been constructed for the lower level sports area.

The multi-functional sports hall is characterised by four different facades that are an integral part of the building's concept. All four facades have additional functions to the weather protection function. For example, a climbing wall is designed as the north-western façade and facilities for streetball skating, and skateboarding is placed along the southeastern exterior wall. The southwest facade is covered with a rear ventilated green PV system. This PV wall is composed of green coloured polycrystalline BIPV panels fixed by a point fixing system. The green facade is meant to optically sustain the green environment and sports areas enlarging the colour spectrum.

Architect:	Allmann, Sattler, Wappner
Year:	2004
Location:	Tübingen, Germany
Typology:	Sports Hall
Client:	Universtiätsstadt Tübingen
Urban Morphology:	Class C
PV Technology:	Polycrystalline
Orientation:	South-West
Inclination:	90°
PV Area:	318 m^2
Installed Nominal Power:	40 kWp
Yield:	30000 kW/h yr
Efficiency:	13.90 %
Energy consultant:	Trans Solar Energietechnikr
Module Size:	Customized
Colour:	Green
Transparency:	Opaque
Fixing System:	Spot fixing, rear ventilated
Dummy Panels:	No

GENERAL ANALYSIS

The PV installation shapes an elegant background for the local sporting events. The southwest façade has no windows, which avoids glare inside the sports hall and suits the choice of a homogeneous opaque material for the entire surface.

The polycrystalline technology has vibrant light reflections which provide an aesthetically attractive texture to the large homogeneous façade. The panel format includes a visible white background behind de cells that creates a delicate pattern giving rhythm to the surface. Ultimately, the no-joint system enhances the elegance and the "background character" of the façade.

STUDENT HOUSING IN AARHUS

MAIN AKNOWLEDGMENTS

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In addition to creating housing for students, the aim was to demonstrate the use of solar cells as an architectural instrument in the design. The facade is dominated by horizontal bands of windows broken by the zigzag of vertically-oriented solar panels, where staggered rows create a consistent pattern across the facade.

The facade contains polycrystalline BIPV modules, which are part of the composition of the horizontal window sections. The facade consists of a tight, three-light module: two bays of windows and a solar panel.

The solar panels act as both a cladding system and an energy producer. They are also a part of the facade's sound reduction system. At the rear of the panel, there is an air intake into the apartment, which is preheated as the sun shines on the solar panel. The facade elements include frosted glass, in combination with solar elements and translucent glass windows.

Architect:	Arkitema Architects
Year:	2001
Location:	Aarhus C, Denmark
Typology:	Residentiall
Client:	Boligkontoret Aarhus
Urban Morphology:	Class B
PV Technology:	Polycrystalline
Orientation:	South
Inclination:	90°
PV Area:	134 m^2
Installed Nominal Power:	15.8 kWp
Yield:	8200 kW/h yr
Efficiency:	
Energy consultant:	Oi-electrio
Module Size:	Customized: 600 x 2700 mm
Colour:	Bright Blue
Transparency:	Opaque
Fixing System:	Aluminium frame
Dummy Panels:	No

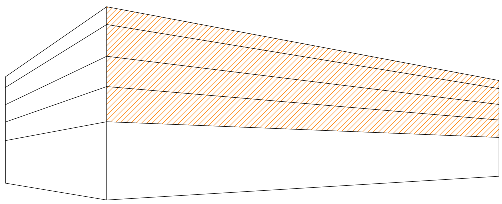
GENERAL ANALYSIS

The project has a cold façade where the PV module size and proportions determine the geometry of the windows and the general rhythm of the whole façade. The panel dimension is the one setting the façade pattern of the whole façade. Therefore the BIPV seems well integrated into the façade composition.

The PV installation adds complexity and richness to this residence's façade. The south façade incorporates the BIPV elements as another construction material and an integral part of the façade composition. This is an example of how building integrated photovoltaics can improve not only the performance but also the aesthetics of a building.

The panels are installed with a regular zigzag rhythm and customised to fit in one storey height. They substitute de plain light aluminium panels seen on the east face changing completely the perception of the façade: while on the east side we can see an aluminium surface with windows in it, on the south façade we have a complex combination where windows, PV panels and aluminium elements create a regular and vibrant tempo.

TURMHALLE BURGWEINTING



Architect:	Tobias Ruf
Year:	2004
Location:	Burgweinting, Germany
Typology:	Sports Hall
Client:	City of Regensburg
Urban Morphology:	Class B
PV Technology:	Polycrystalline
Orientation:	South
Inclination:	90°
PV Area:	117 m^2
Installed Nominal Power:	10 kWp
Yield:	6666 kW/h yr
Efficiency:	
Energy consultant:	Scheuten Solar
Module Size:	Customized:-
Colour:	Bright Blue
Transparency:	Translucent
Fixing System:	White frVame(horiz.) & Black(vert.)
Dummy Panels:	No

MAIN AKNOWLEDGMENTS

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The goal was to realise a gymnasium where high daylight autonomy is achieved while assuring visual and thermal comfort. The south orientation of the main façade was convenient for an active solar system which also satisfies shading needs. So PV cells were integrated into the South facing windows. The east and west facades are built with light-dispersing glass. The PV modules were specially developed and adjusted for this project. The following three materials dominate the facades of the gymnasium: Dark PV cells, which are integrated into the glazing, permitting the transmission of diffuse daylight; larch wood boarding and sand-blasted glazing on the east and west façades, which

only transmits diffuse radiation.

In order to optimise the spaces between the single PV cells, thermal and daylight simulations were done. The 20 mm spaces between the cells are the result of these simulations, maximising daylight utilisation while avoiding overheating on warm days is achieved.

Following the design phase, a nationwide open competition for the technical and economic feasibility was published with a subsequent restricted invitation for facade construction companies and manufacturers of specialised components.

GENERAL ANALYSIS

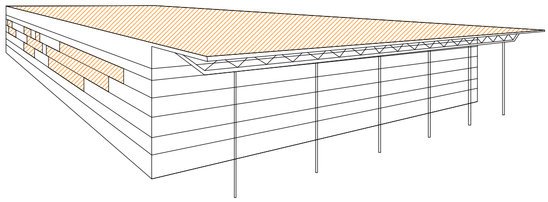
The project presents a clean parallelepiped glass volume with a wooden skirting board.

As a sports hall requires, there is a low solid surface that will receive all the ball knocking and an upper surface that allows the space lighting.

On its south façade, the glass panels have been substituted by a PV integrated installation whose homogeneity respects the buildings' general concept and perception. The PV cells provide the building of solar shading, which is complemented by a translucent back layer of glass to avoid glare in the interior.

The slightly darker tone of the PV material reinforces the contrast with the horizontal white joints, while it minimises the perception of the vertical black ones. In addition, the smaller cells composing the panel creates a texture in the entire surface. This effect does not occur on the other facades where the joints are pretty visible because of the uniformity of the material.

ACADEMY OF FURTHER EDUCATION "MONT-CENIS"



Architect:	Jourda. Architectes
Year:	1999
Location:	Herne-Sodingen,Germany
Typology:	Public
Client:	Entwicklungsgesellschaft
Urban Morphology:	Class C
PV Technology:	Polycrystalline/ Monocrystalline
Orientation:	Roof / West
Inclination:	5° / 90°
PV Area:	10533.52 m^2
Installed Nominal Power:	1000 kWp
Yield:	650000 kW/h yr
Efficiency:	
Energy consultant:	ASE / Solarex
Module Size:	Standard:110/120x280 mm
Colour:	Blue
Transparency:	Translucent
Fixing System:	
Dummy Panels:	No

MAIN AKNOWLEDGMENTS

Architectural Review 10 / 1999

Hagemann, Ingo: Gebäudeintegrierte

Photovoltaik. Cologne 2002

Situated on a deserted industrial site in the Ruhr area, this education centre represents an architectural milestone in terms of low energy consumption. The construction of a greenhouse over thirteen thousand square metres generates a natural microclimate where the different programmatic elements are situated. The scheme engages in various environmental protection and enhancement systems: soil de-contamination, exploitation of released mine gases, rainwater collection, natural drainage of the site, passive use of solar energy, active exploitation of solar energy, and use of natural and recyclable building materials.

Photovoltaic glass modules cover about half of the roof and facade surfaces and are integral components in the design concept; apart from generating electricity, they also provide sun shading and control the amount of incoming daylight. In order to realise a "clouds effect", the modules were installed in different densities. The protection from the weather and the solar energy gains result in a mild climate, which makes the glass enclosure usable as an external space and reduces the energy requirements of the buildings within it. The building envelopes of the structures within the glass enclosure need to be neither airtight nor rainproof, and simple forms of construction are therefore possible.

There is a battery with an energy content of 1.2 MWh that reduces peak demands loads, compensates system fluctuations and supply emergency power. This battery was not necessary, but it was installed as a demonstration project for the export of such technology.

GENERAL ANALYSIS

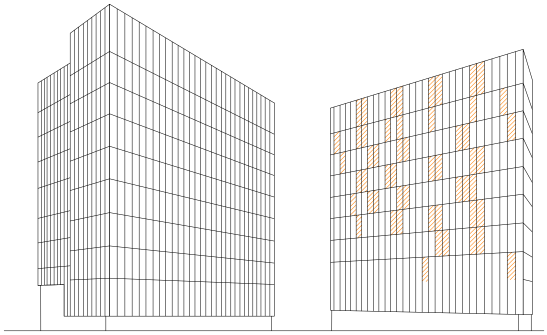
As a vast greenhouse, the Mont-Cenis Academy consists of a glass building that contains other buildings, creating a comfortable atmosphere that protects the interior from the weather adversities.

The glass panels and substructure have been adapted to the standard module of the PV system chosen so that the uniform aspect and partitions are maintained.

On the roof, solar protection is needed, so the glass panels have been substituted by the PV panels in almost all the surface.

The interior lighting conditions are controlled and through the PV installation, which does not cover all the glass surface, giving rise to a vibration in the interior light intensity.

NATURA TOWERS



Architect:	GJP arquitectos
Year:	2009
Location:	Lisboa, Portugal
Typology:	Offices
Client:	MSF
Urban Morphology:	Class A
PV Technology:	Polycrystalline
Orientation:	South
Inclination:	90°
PV Area:	217.40 m^2
Installed Nominal Power:	24 kWp
Yield:	21925 kW/h yr
Efficiency:	
Energy consultant:	EPPE
Module Size:	Customized: 943 x 3976 / 4976 mm
Colour:	Blue
Transparency:	Translucent
Fixing System:	Glass fixing
Dummy Panels:	No

MAIN AKNOWLEDGMENTS

"Best new European building of the year" Green Building Awards 2011_ European Commission in Brussels.

The MSF Group has built its new offices in Lisbon, the Natura Towers, reflecting the company's outspoken commitment to sustainability. As a showcase to encourage active and innovative construction, the building is characterised by vegetal surfaces as well as a BIPV translucent vertical array. The 56 bespoke modules, some of which have a length of nearly 5 meters, provide a total power of 24 kWp.

The project consists of two double-parallelepiped volumes of 8 floors each, joined at the bottom by a plinth that solves the terrain height difference and the entrance to the complex.

The use of saving techniques to control ventilation, heat retention, electricity production and water saving, make this building highly sustainable. These functional aspects are combined with the introduction of prominent vegetated elements, which are also contributing to the urban experience of building a city sustainable and responsible city.

GENERAL ANALYSIS

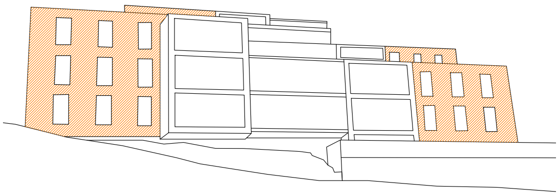
This project presents two identical towers with different orientations. A PV system has been integrated into the tower whose larger façade faces South.

The panels are disposed according to the sun radiation: more at the top of the façade and less at the bottom. They are fitted into the façade's substructure substituting glass panels and adding visual movement and vibration to the surface. The dark panels play with the depth effect that they produce there where there are placed as it is identified with the colour of the glass where there is nothing behind.

The panels have one-storey height size, or multiple so that they suit not only the vertical glass frames but also the horizontal cutting of the storeys.

On the contrary, it does not suit the interior distribution; we can identify regular openings where additional interior solar shading has been installed. For the lack of rational relation between the PV panels placing and the interior spaces, it follows that the PV pattern is guided only by aesthetical values.

CASA SOLARA



MAIN AKNOWLEDGMENTS

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Architect:	Giovanni Cerfeda
Year:	2012
Location:	Laax, Switzerland
Typology:	Residential
Client:	Ecobauhaus AG
Urban Morphology:	Class C
PV Technology:	Monocrystalline
Orientation:	South
Inclination:	90°
PV Area:	346 m^2
Installed Nominal Power:	34.4 kWp
Yield:	25000 kW/h yr
Efficiency:	--
Energy consultant:	MGT-esys GmbH
Module Size:	Customized:
Colour:	Black
Transparency:	Opaque
Fixing System:	Invisible mechanical anchoring
Dummy Panels:	No

The residential building, built with Minergie standard, is located at an altitude of 1050 m above sea level in the ski centre of Laax (Graubunden Canton in Switzerland).

The south facade is composed of customised PV modules with high-efficiency monocrystalline cells. The cold facade system, installed onto a wooden substructure, allows appropriate ventilation of the panels and is equipped with a mechanical anchoring system that is invisible from the outside.

The architectural language is characterised by the dark appearance of the solar cladding obtained by the all-black modules. The PV panel texture creates a uniform striped effect similar to the wooden cladding of the other facades. The PV plant, grid-connected, produces enough energy to supply the apartments.

GENERAL ANALYSIS

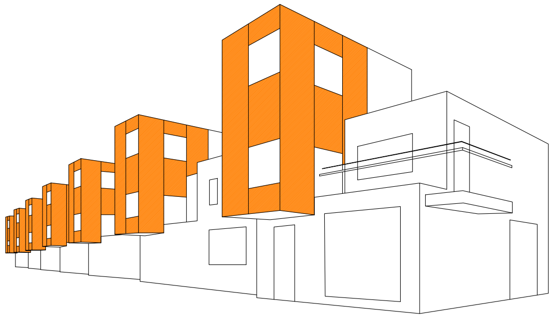
With a successful composition, it treats the photovoltaic panels as a thin skin that covers the whole south façade of the two volumes that compose the project.

The casa Solara is a case where the PV panels have been treated as a construction material, substituting an alternative façade cladding material and profiting from the optimal orientation of the South façade.

A wooden element perforates the PV skin where the interior distribution requires the opening of large windows. A wooden box shapes these openings so that the PV skin is only interrupted in the central part of the building. The small openings required by the rest of the housing distribution are all the same size and respect a regular composition, enhancing the uniformity of the volume.

The project has no particular design to adapt the project to the PV integration; it is a straightforward installation where the dark PV sets a contrast between materials and establishes a façade that shows the interior distribution of the building.

IJSSELSTEIN HOUSING PROJECT



MAIN AKNOWLEDGMENTS

Sustainable energy NOVEM

Architect:	Kiss + Cathcart Architects
Year:	2002
Location:	Ijsselstein
Typology:	Residental
Client:	Thomasson Dura
Urban Morphology:	Class B
PV Technology:	Thin-Flim
Orientation:	South / West/ East
Inclination:	90°
PV Area:	30 x 14 m^2
Installed Nominal Power:	1.6 x 14 kWp
Yield:	-r
Efficiency:	--
Energy consultant:	Terrasolar
Module Size:	Standard: EPV
Colour:	Black
Transparency:	Opaque and Translucent
Fixing System:	--
Dummy Panels:	No

These rowhouse units were built in a « new town » development in the Netherlands following space and budget guidelines.

The PV panels are integrated into raised two-level sunrooms and take advantage of the fact that, at high latitudes, vertically-oriented PV panels have good efficiency. The panels are interspersed with glass, wood, and translucent materials in a wood frame. Solar thermal panels for hot water are also integrated into the wall.

The building is brick-clad with the two-story « solariums » clad in an innovative wooden curtain wall which incorporates a photovoltaic rain screen. The façade also integrates translucent PV glazing into the South, East and West façades and solar thermal panels. This was the first time amorphous silicon BIPV panels were used in a building project in Holland.

The wooden curtain wall also integrates vertically-mounted solar thermal panels to produce domestic hot water.

The result for the IJsselstein project is an attractive multilevel solarium on each unit that's completely encased in photovoltaic panels—except for a few windows that open to the outside—and provides over 30% of the total energy needs of each house.

All in all, the project reflects the Dutch emphasis on conservation of space and resources—as well as innovative architecture.

GENERAL ANALYSIS

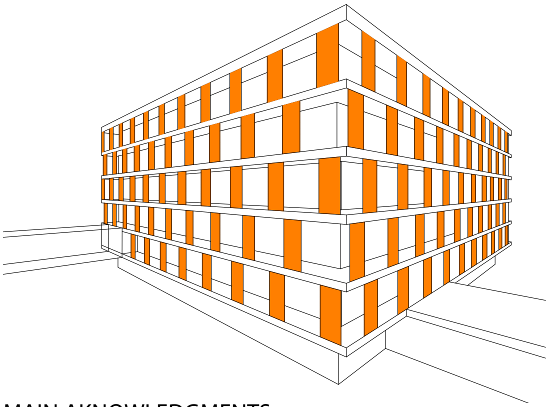
The project consists of a series of juxtaposed volumes where the superior ones are finished with different material: PV panels. This dark finish reflects light and its environment; therefore, it has a lighter aspect than the bricks that compose the lower volumes.

The material variation helps to identify the different volumes of the general composition. It is suitable that the PV material has been integrated into the upper level, as there are minimum casted shadows, and it has better sun exposure than the lower level.

This project is a low budget one, so standard panels have been chosen to reduce costs. Due to this fact, the windows have been adapted to match the panel's joints pattern and substructure.

As a critic, the lecture of the superior volumes is linked to a technological language that is hardly in good relation with the brick volumes in the lower plinth. It matches nor in its colour, neither in the size and proportions of its windows and other openings. We could think that the upper PV covered volumes are construction for enlarging an existing building.

NEW Q CELLS S.E HEADQUARTERS



MAIN AKNOWLEDGMENTS

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Architect:	bhss architecten gmbh
Year:	2010
Location:	Thalheim, Germany
Typology:	Offices
Client:	Q-Cells SE
Urban Morphology:	Class C
PV Technology:	Monocrystalline
Orientation:	south-east and west facades
Inclination:	90°
PV Area:	--
Installed Nominal Power:	--
Yield:	-r
Efficiency:	-
Energy consultant:	-
Module Size:	14000 x 35000 mm
Colour:	Blue
Transparency:	Translucent
Fixing System:	Linearly supported
Dummy Panels:	No

A new office building has been constructed in the "Solar Valley" in Thalheim for the company Q-Cells SE. The interior distribution is defined by the concept of interconnecting professionals, fostering interaction among workers in a flexible office plan.

There is a central courtyard around which the communicative areas are grouped. The project-oriented workspaces are located in the outer ring form. One of the main requirements of the floor plan is the adaptability during different uses of the building.

The chimney effect of the naturally ventilated courtyard permits a natural cooling in the summer, reducing the building's energy demand.

The building concept is based on the principles of sustainability: it is a compact building that benefits of an efficient ratio of usable space and a high degree of flexible use.

The use of renewable energies is incorporated into the façade design as an essential technical and architectural element. An active sun and glare protection system incorporates PV elements with a daylight-optimised exposure.

GENERAL ANALYSIS

PV panels in this building help to structure the facade: they give rhythm and movement. At the same time, they provide solar shading to the windows behind and, as fixed elements, they house the rest of the non-active mobile solar-control elements.

The panel's glass surface reflects light and the surroundings creating an effect of detachment between the horizontal white slabs and the body of the storeys, giving the building a lighter aspect.

A.5 Detailed data of the quantitative assessment

A.5.1 Environmental data

This section presents the environmental impact values used in the LCA calculations integrated into the quantitative assessment presented in Chapter 5. These values are taken from the KBOB database [KBOB 2016], for a building lifespan of 60 years. In case of missing data, the collaboratin team from ZHAW has provided the environmental impact data.

Regarding the environmental impact of BIPV panels, the presented values have been assumed based on the 2018's draft of the Product Environmental Footprint Category Rules (PEFCR) of BIPV panels. The provided data considers BIPV panel replacement after 30 years.

NRPE: Non renewable primary energy

GWP: Global warming potential

KBOB ref. number	MATERIAL	ref. unit	DENSITY (kg/m³)	NRPE (kWh)	GWP (kg CO_2-eq)
02.001	Ceramic bricks	kg	900	0,791	0,258
03.002	Fibrocement board	kg	1800	2,450	0,727
03.008	Plasterboard	kg	850	1,350	0,293
04.001	Lime plaster	kg	1100	0,692	0,147
04.008	Mortar	kg	1400	1,600	0,406
04.009	Cement coating	kg	1550	0,728	0,269
04.014	Roughcast exterior coating	kg	1550	1,000	0,328
06.002.01	Aluminium substructure	kg	2690	13,600	2,940
06.012	Steel substructure	kg	7850	3,460	0,734
07.009	Solid wood (pine)	kg	485	0,504	0,101
07.009.01	Solid wood (pine, Swiss production)	kg	485	0,459	0,087
07.012	Medium Density Fibreboard	kg	685	4,880	1,040
07.013	OSB 3	kg	605	2,760	0,614
09.002	Vapour barrier	kg	920	24,800	5,330
10.004	Polystyrene insulation (EPS)	kg	30	29,800	7,640
10.008	Rockwool insulation	kg	60	4,330	1,130
10.009.01	Wood fibre insulation	kg	140	3,140	0,440
10.010	Cellulose insulation	kg	50	1,030	0,257
14.001	Paint (2 layers)	m^2	0,3	4,210	1,360
14.002	Exterior finish: paint	m^2	0,3	6,510	1,600
* ZHAW	Autoclave treatment	m^2		1,580	0,500
(assumption)	Opaque monocrystalline BIPV panel	m^2		26,190	6,870
(assumption)	Opaque polycrystalline BIPV panel	m^2		23,580	6,180
(assumption)	Opaque Thin-Film BIPV panel	m^2		12,050	3,160
* ZHAW	Opaque Tandem-Perovskite BIPV panel	m^2		19,810	6,160
(assumption)	Translucent Monocrystalline BIPV panel	m^2		17,020	4,020
(assumption)	Translucent Polycrystalline BIPV panel	m^2		15,330	4,020
(assumption)	Translucent Thin-Film BIPV panel	m^2		7,830	2,050
(assumption)	Translucent Tandem Perovskite BIPV panel	m^2		12,880	4,000
(assumption)	Translucent DSSC	m^2		6,550	1,720
34.026	Opaque Monocrystalline BAPV Roof panels	m^2		26,600	7,100

A.5.2 Energy model and simulation assumptions

This section provides information related to the building design that affects the energy simulation model presented in Chapter 5.

concept	notes	value	units
AAF building scenarios			
ACTIVITY			
Occupation rate		0,02	people / m^2
Schedule	Dwellling template		
Metabolic rate	(Factor (men=1, women= 0.85, children = 0.75)	0,9	
Activity template	Resting		
Metabollic rate per person		70	W/person
Domestic hot water	consumption	0,801	litres / m2 day
Environmental control			
Heating set point temperatures	Set point	20	°C
	Set back	17	°C
Equipments	Home equipments template		
Gain		6,2	W/m2
Radiant fraction		1,368	
CONSTRUCTION			
External walls	as described in Chapter 4		
Roof	Flat roof		
Thermal transmittance		0,148	W/m2K
Interior partitions	Double gypsum + airgap		
Ground floor	Cast concrete + mineral fibre wool (35 cm) + timber flooring		
Thermal transmittance		0,1	W/m2K
Interior floors	flooring bricks+ MW glass wool (15cm)		
Thermal transmittance		0,177	W/m2K
Airtightness	constant rate	0,3	ac/h
Lightning			
Target illuminance		150	lux
HVAC			
Heating	Heat pump		
Humedity control	No humedity control		
Ventilation	mechanical ventilation		
Minimum fresh air		10	litres / s person
Heat recovery			
CP/BP building scenarios variations			
CONSTRUCTION			
External walls	as described in Chapter 4		
Airtightness	constant rate	0,6	ac/h

Energy simulations have been carried out with the building simulation tool: Design Builder, version 5.0.2.003; integrating Energy Plus version 8.5..

A.5.3 Energy and economy assessment results

List of simulations

AAF BUILDING SCENARIO	PV TECHNOLOGY	PERFORMANCE	STORAGE	CAPACITY kWh
1A	*Market-ready*		No battery	
	OPAQUE MONOCRYSTALLINE	21%	Battery	90
	High-Performance		No battery	
	OPAQUE TANDEM-PEROVSKITE	28%	Battery	110
1B	*Market-ready*		No battery	
	TRANSLUCENT MONOCRYSTALLINE	14%	Battery	5
	High-Performance		No battery	
	TRANSLUCENT TANDEM-PEROVSKITE	18%	Battery	10
1C	*Market-ready*		No battery	
	TRANSPARENT THIN-FILM	3%	Battery	-
	High-Performance		No battery	
	TRANSPARENT THIN-FILM	5%	Battery	5
2A	*Market-ready*		No battery	
	OPAQUE MONOCRYSTALLINE filtered	12%	Battery	40
	High-Performance		No battery	
	OPAQUE TANDEM-PEROVSKITE filtered	18%	Battery	80
2B	*Market-ready*		No battery	
	TRANSLUCENT POLYCRYSTALLINE	12%	Battery	5
	High-Performance		No battery	
	TRANSLUCENT TANDEM-PEROVSKITE	18%	Battery	10
2C	*Market-ready*		No battery	
	TRANSPARENT THIN-FILM	3%	Battery	-
	High-Performance		No battery	
	TRANSPARENT THIN-FILM	5%	Battery	-
3A	*Market-ready*		No battery	
	OPAQUE MONOCRYSTALLINE filtered	12%	Battery	10
	High-Performance		No battery	
	OPAQUE TANDEM-PEROVSKITE filtered	18%	Battery	50
3B	*Market-ready*		No battery	
	TRANSLUCENT DSSC	2%	Battery	-
	High-Performance		No battery	
	TRANSLUCENT THIN-FILM	7%	Battery	-
3C	*Market-ready*		No battery	
	TRANSPARENT THIN-FILM	3%	Battery	-
	High-Performance		No battery	
	TRANSPARENT THIN-FILM	5%	Battery	-
4A	*Market-ready*		No battery	
	OPAQUE MONOCRYSTALLINE	21%	Battery	100
	High-Performance		No battery	
	OPAQUE TANDEM-PEROVSKITE	28%	Battery	110
4B	*Market-ready*		No battery	
	TRANSLUCENT POLYCRYSTALLINE	12%	Battery	5
	High-Performance		No battery	
	TRANSLUCENT TANDEM-PEROVSKITE	18%	Battery	5
4C	*Market-ready*		No battery	
	TRANSPARENT THIN-FILM	3%	Battery	-
	High-Performance		No battery	
	TRANSPARENT THIN-FILM	5%	Battery	-

* Battery scenarios with no battery incorporated: discarded for higer battery $ costs than $ benefits

Building scenario 1A

MR: opaque Monocrystalline 21%
HP: opaque Tandem-Perovskite 28%

O P E R A T I O N A L   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

Performance

FINAL ENERGY

Building's Energy Demand	119424	kWh /yr
Total Energy Generation	97392	kWh /yr
Nominal Power of the BIPV installatior	17,3	kWp
Building's compactness index	1,0	
Building's Energy demand per m²	42	kWh/m² yr
Buildings Energy generation per m²	34	kWh/m² yr
Façade surface yield (per m² façade)	118	kWh/m² yr

No Battery Scenario

Self-Sufficiency Rate	33%	
Self-Consumption Rate	41%	
Total Energy Export	57458	kWh
Energy economy to CP	42%	
Energy economy to BP	39%	

Battery Scenario

Battery Size	90	kWh
Self-Sufficiency Rate	48%	
Self-Consumption Rate	66%	
Total Energy Export	33036	kWh
Energy economy to CP	60%	
Energy economy to BP	57%	

Total Self-Consumption Scenario

Self-Sufficiency Rate	82%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	84%	
Energy economy to BP	83%	

H I G H - P E R F O R M A N C E

Performance

FINAL ENERGY

Building's Energy Demand	119424	kWh /yr
Total Energy Generation	129855	kWh /yr
Nominal Power of the BIPV installatior	23,1	kWp
Building's compactness index	1,0	
Building's Energy demand per m²	42	kWh/m² yr
Buildings Energy generation per m²	46	kWh/m² yr
Façade surface yield (per m² façade)	157	kWh/m² yr

No Battery Scenario

Self-Sufficiency Rate	37%	
Self-Consumption Rate	34%	
Total Energy Export	85760	kWh
Energy economy to CP	45%	
Energy economy to BP	42%	

Battery Scenario

Battery Size	110	kWh
Self-Sufficiency Rate	57%	
Self-Consumption Rate	58%	
Total Energy Export	55038	kWh
Energy economy to CP	67%	
Energy economy to BP	66%	

Total Self-Consumption Scenario

Self-Sufficiency Rate	109%	
Self-Consumption Rate	92%	
Total Energy Export	10431	kWh
Energy economy to CP	100%	
Energy economy to BP	100%	

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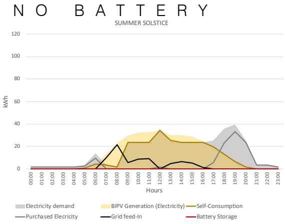

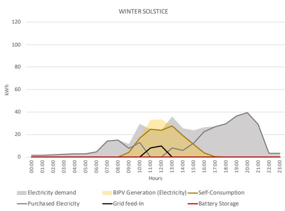

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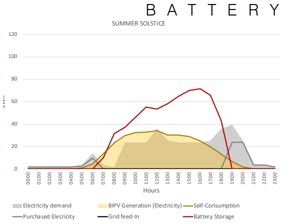

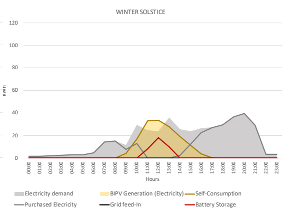

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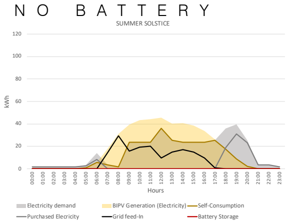

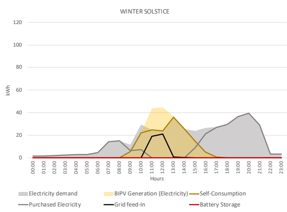

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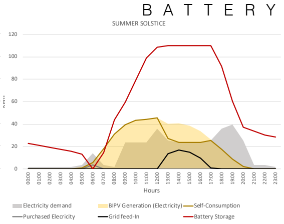
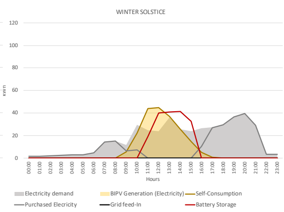




E M B O D I E D   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

PRIMARY ENERGY

SIA 2040 Limit Values	30	9
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	32,31	7,70
BP	23,91	5,40
AAF	31,42	7,39
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	36,30	8,76
BP	27,90	6,47
AAF	35,41	8,46
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	40,00	9,71
BP	31,59	7,41
AAF	31,42	7,39

H I G H - P E R F O R M A N C E

SIA 2040 Limit Values	30	9
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	32,31	7,70
BP	23,91	5,40
AAF	29,57	7,19
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	36,30	8,76
BP	27,90	6,47
AAF	33,56	8,25
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	38,15	9,50
BP	29,74	7,21
AAF	29,57	7,19

COMBINED ENERGY EFFICIENCY

MARKET-READY

PRIMARY ENERGY

Impact Payback Time

No Battery Scenario

	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	946575	247795
Annual Impact Savings	100633	4073
PBT (Years)	**9,4**	**60,8**

Battery Scenario

	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	950877	248785
Annual Impact Savings	162175	6564
PBT (Years)	**5,9**	**37,9**

Total Self-Consumption Scenario

	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	946575	247795
Annual Impact Savings	245427	9934
PBT (Years)	**3,9**	**24,9**

HIGH-PERFORMANCE

PRIMARY ENERGY

Impact Payback Time

No Battery Scenario

	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	718649	222431
Annual Impact Savings	111119	4498
PBT (Years)	**6,5**	**49,5**

Battery Scenario

	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	723907	223641
Annual Impact Savings	188539	7631
PBT (Years)	**3,8**	**29,3**

Total Self-Consumption Scenario

	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	718649	222431
Annual Impact Savings	327236	13245
PBT (Years)	**2,2**	**16,8**

Anual environmental impact

Market-ready

	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
SIA 2040 Combined Limit Values	90	12
BASE SCENARIO		
CP	153,38	12,60
BP	138,55	10,04
AAF	50,95	8,18
Battery impact per building ERA	1,51	0,35
AAF with Battery	52,46	8,53
BAPV ROOF SCENARIO		
CP	109,80	11,74
BP	94,96	9,18
AAF	7,36	7,32
BAPV FAÇADE SCENARIO		
CP	74,75	11,12
BP	59,92	8,56
AAF	50,95	8,18

High-performance

	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
SIA 2040 Combined Limit Values	90	12
BASE SCENARIO		
CP	153,38	12,60
BP	138,55	10,04
AAF	20,32	6,81
Battery impact per building ERA	1,85	0,43
AAF with Battery	22,17	7,24
BAPV ROOF SCENARIO		
CP	109,80	11,74
BP	94,96	9,18
AAF	-23,26	5,95
BAPV FAÇADE SCENARIO		
CP	44,13	9,75
BP	29,30	7,19
AAF	20,32	6,81

ECONOMIC EFFICIENCY

Life Cycle Cost (LCC)

Initial investment

	Façade initial Investment cost per m²	Totals
CP	311,90 CHF	356 537 CHF
BP	460,67 CHF	526 589 CHF
AAF	635,11 CHF	725 998 CHF

	Building construction cost per m²	Totals
CP	2 161 CHF	6 143 116 CHF
BP	2 226 CHF	6 330 173 CHF
AAF	2 303 CHF	6 549 522 CHF

Market-ready

30-year investment period	LCC
CP	8 260 541 CHF
BP	8 435 043 CHF
AAF	8 227 278 CHF

Battery cost (subsidies included)	60 500,00 CHF	
Energy purchase reduction associated	73 967,44 CHF	*NPV formula over battery lifetime
Earnings (NPV)	12 826,13 CHF	

High-performance

30-year investment period	LCC
CP	8 260 541 CHF
BP	8 435 043 CHF
AAF	8 154 429 CHF

Battery cost (subsidies included)	73 500,00 CHF	
Energy purchase reduction associated	93 050,30 CHF	*NPV formula over battery lifetime
Earnings (NPV)	18 619,33 CHF	

Net Present Value (NPV)

Market-ready

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	5 900 918 CHF	7 309 244 CHF
CP + BAPV ROOF	6 392 316 CHF	7 795 207 CHF
BP	6 947 124 CHF	8 386 290 CHF
BP + BAPV ROOF	7 437 537 CHF	8 871 268 CHF
AAF	9 201 299 CHF	10 657 268 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	6 180 477 CHF	6 955 862 CHF
BP	6 485 270 CHF	7 277 635 CHF
AAF	7 525 980 CHF	8 327 596 CHF

High-performance

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	5 900 918 CHF	7 309 244 CHF
CP + BAPV ROOF	6 392 316 CHF	7 795 207 CHF
BP	6 947 124 CHF	8 386 290 CHF
BP + BAPV ROOF	7 437 537 CHF	8 871 268 CHF
AAF	9 407 226 CHF	10 863 194 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	6 180 477 CHF	6 955 862 CHF
BP	6 485 270 CHF	7 277 635 CHF
AAF	7 632 111 CHF	8 433 726 CHF

Internal Rate of Return (IRR)

Market-ready

30-year investment period	**Unlevered IRR**	**Levered IRR**
CP	3,1%	7,6%
CP + BAPV ROOF	3,3%	8,0%
BP	3,4%	7,9%
BP + BAPV ROOF	3,6%	8,2%
AAF	4,1%	8,8%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	6,3%	13,5%
BP	6,4%	13,6%
AAF	7,1%	14,7%

High-performance

30-year investment period	**Unlevered IRR**	**Levered IRR**
CP	3,1%	7,6%
CP + BAPV ROOF	3,3%	8,0%
BP	3,4%	7,9%
BP + BAPV ROOF	3,6%	8,2%
AAF	4,1%	8,9%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	6,3%	13,5%
BP	6,4%	13,6%
AAF	7,2%	14,8%

Discounted Payback (DPB)

Market-ready

DPB	Un-levered	Levered
CP	25	13
BP	24	13
AAF	22	12

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	10	3
AAF to BP	years to have higher cummulated revenue	6	10

High-performance

DPB	Un-levered	Levered
CP	25	13
BP	24	13
AAF	22	12

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	9	3
AAF to BP	years to have higher cummulated revenue	5	9

Building scenario 1B

MR: translucent Monocrystalline 14%
HP: translucent Tandem-Perovskite 18%

O P E R A T I O N A L   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

Performance

FINAL ENERGY

Building's Energy Demand	116075	kWh /yr
Total Energy Generation	28746	kWh /yr
Nominal Power of the BIPV installatior	5,1	kWp
Building's compactness index	1,0	
Building's Energy demand per m²	41	kWh/m² yr
Buildings Energy generation per m²	10	kWh/m² yr
Façade surface yield (per m² façade)	76	kWh/m² yr
No Battery Scenario		
Self-Sufficiency Rate	16%	
Self-Consumption Rate	64%	
Total Energy Export	10290	kWh
Energy economy to CP	27%	
Energy economy to BP	22%	
Battery Scenario		
Battery Size	5	kWh
Self-Sufficiency Rate	17%	
Self-Consumption Rate	71%	
Total Energy Export	8416	kWh
Energy economy to CP	28%	
Energy economy to BP	24%	
Total Self-Consumption Scenario		
Self-Sufficiency Rate	25%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	34%	
Energy economy to BP	30%	

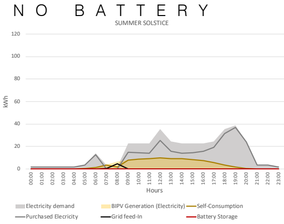
H I G H - P E R F O R M A N C E

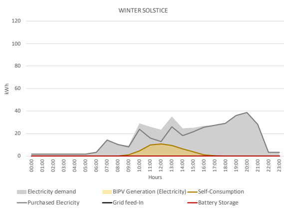
Performance

FINAL ENERGY

Building's Energy Demand	116075	kWh /yr
Total Energy Generation	38328	kWh /yr
Nominal Power of the BIPV installatior	6,9	kWp
Building's compactness index	1,0	
Building's Energy demand per m²	41	kWh/m² yr
Buildings Energy generation per m²	13	kWh/m² yr
Façade surface yield (per m² façade)	102	kWh/m² yr
No Battery Scenario		
Self-Sufficiency Rate	20%	
Self-Consumption Rate	60%	
Total Energy Export	15231	kWh
Energy economy to CP	30%	
Energy economy to BP	26%	
Battery Scenario		
Battery Size	10	kWh
Self-Sufficiency Rate	22%	
Self-Consumption Rate	68%	
Total Energy Export	12135	kWh
Energy economy to CP	32%	
Energy economy to BP	28%	
Total Self-Consumption Scenario		
Self-Sufficiency Rate	33%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	42%	
Energy economy to BP	38%	

N O   B A T T E R Y





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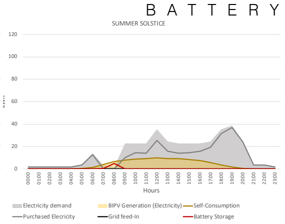

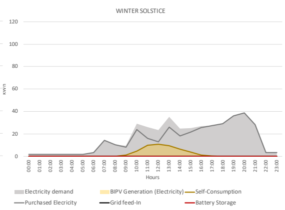

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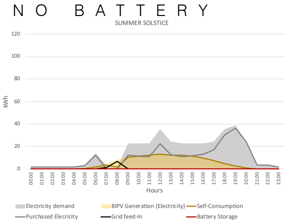
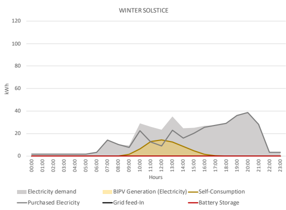
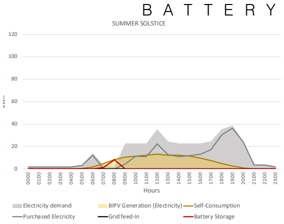
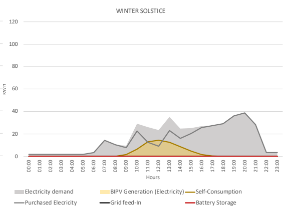




B A T T E R Y





E M B O D I E D   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

PRIMARY ENERGY

SIA 2040 Limit Values	30	9
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	30,96	7,33
BP	23,22	5,25
AAF	24,67	5,63
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	34,95	8,39
BP	27,21	6,31
AAF	28,67	6,70
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	32,14	7,64
BP	24,40	5,56
AAF	24,67	5,63

H I G H - P E R F O R M A N C E

SIA 2040 Limit Values	30	9
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	30,96	7,33
BP	23,22	5,25
AAF	24,40	5,60
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	34,95	8,39
BP	27,21	6,31
AAF	28,39	6,67
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	31,87	7,61
BP	24,13	5,52
AAF	24,40	5,60

C O M B I N E D   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

PRIMARY ENERGY
Impact Payback Time

No Battery Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	193305	50707
Annual Impact Savings	46510	1883
PBT (Years)	**4,2**	**26,9**

Battery Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	193544	50762
Annual Impact Savings	51233	2074
PBT (Years)	**3,8**	**24,5**

Total Self-Consumption Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	193305	50707
Annual Impact Savings	72441	2932
PBT (Years)	**2,7**	**17,3**

H I G H - P E R F O R M A N C E

PRIMARY ENERGY
Impact Payback Time

No Battery Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	146215	45466
Annual Impact Savings	58204	2356
PBT (Years)	**2,5**	**19,3**

Battery Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	146693	45576
Annual Impact Savings	66009	2672
PBT (Years)	**2,2**	**17,1**

Total Self-Consumption Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	146215	45466
Annual Impact Savings	96588	3910
PBT (Years)	**1,5**	**11,6**

Anual environmental impact

Market-Ready

SIA 2040 Combined Limit Values	90	12
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	148,77	12,10
BP	134,33	9,74
AAF	102,07	8,76
Battery impact per building ERA	0,08	0,02
AAF with Battery	102,16	8,78
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	105,19	11,24
BP	90,74	8,88
AAF	58,49	7,91
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	124,48	11,37
BP	110,03	9,02
AAF	102,07	8,76

High-Performance

SIA 2040 Combined Limit Values	90	12
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	148,77	12,10
BP	134,33	9,74
AAF	93,30	8,39
Battery impact per building ERA	0,17	0,04
AAF with Battery	93,47	8,43
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	105,19	11,24
BP	90,74	8,88
AAF	49,72	7,53
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	115,71	11,00
BP	101,26	8,65
AAF	93,30	8,39

E C O N O M I C   E F F I C I E N C Y

Life Cycle Cost (LCC)

Initial investment

	Façade initial Investment cost per m²	Totals
CP	311,90 CHF	234 240 CHF
BP	460,67 CHF	345 961 CHF
AAF	666,24 CHF	500 349 CHF

	Building construction cost per m²	Totals
CP	2 188 CHF	6 221 945 CHF
BP	2 231 CHF	6 344 838 CHF
AAF	2 291 CHF	6 514 665 CHF

Market-Ready

30-year investment period	LCC
CP	8 330 541 CHF
BP	8 429 069 CHF
AAF	8 451 977 CHF

Battery cost (subsidies included)	4 750,00 CHF	
Energy purchase reduction associated	5 676,20 CHF	*NPV formula over battery lifetime
Earnings (NPV)	882,10 CHF	

High-Performance

30-year investment period	LCC
CP	8 330 541 CHF
BP	8 429 069 CHF
AAF	8 417 052 CHF

Battery cost (subsidies included)	8 500,00 CHF	
Energy purchase reduction associated	9 380,01 CHF	*NPV formula over battery lifetime
Earnings (NPV)	838,11 CHF	

Net Present Value (NPV)

Market-Ready

30-year investment period	Unlevered NPV	Levered NPV
CP	5 861 863 CHF	7 283 185 CHF
CP + BAPV ROOF	6 352 957 CHF	7 768 845 CHF
BP	7 041 313 CHF	8 482 896 CHF
BP + BAPV ROOF	7 531 164 CHF	8 967 313 CHF
AAF	8 692 103 CHF	10 161 644 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	6 106 314 CHF	6 888 854 CHF
BP	6 514 301 CHF	7 307 997 CHF
AAF	7 166 528 CHF	7 975 616 CHF

High-Performance

30-year investment period	Unlevered NPV	Levered NPV
CP	5 861 863 CHF	7 283 185 CHF
CP + BAPV ROOF	6 352 957 CHF	7 768 845 CHF
BP	7 041 313 CHF	8 482 896 CHF
BP + BAPV ROOF	7 531 164 CHF	8 967 313 CHF
AAF	8 763 666 CHF	10 233 207 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	6 106 314 CHF	6 888 854 CHF
BP	6 514 301 CHF	7 307 997 CHF
AAF	7 217 486 CHF	8 026 574 CHF

Internal Rate of Return (IRR)

Market-Ready

30-year investment period	Unlevered IRR	Levered IRR
CP	3,1%	7,5%
CP + BAPV ROOF	3,3%	7,9%
BP	3,4%	7,9%
BP + BAPV ROOF	3,6%	8,2%
AAF	3,9%	8,4%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	6,2%	13,3%
BP	6,4%	13,6%
AAF	6,8%	14,2%

High-Performance

30-year investment period	Unlevered IRR	Levered IRR
CP	3,1%	7,5%
CP + BAPV ROOF	3,3%	7,9%
BP	3,4%	7,9%
BP + BAPV ROOF	3,6%	8,2%
AAF	3,9%	8,5%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	6,2%	13,3%
BP	6,4%	13,6%
AAF	6,8%	14,2%

Discounted Payback (DPB)

Market-Ready

DPB	Un-levered	Levered
CP	26	13
BP	24	13
AAF	23	12

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	12	8
AAF to BP	years to have higher cummulated revenue	11	12

High-Performance

DPB	Un-levered	Levered
CP	26	13
BP	24	13
AAF	23	12

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	12	7
AAF to BP	years to have higher cummulated revenue	11	12

Building scenario 1C

MR: transparent Thin-Film 3%
HP: transparent Thin-Film 5%

O P E R A T I O N A L   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

Performance

FINAL ENERGY

Building's Energy Demand	113299	kWh /yr
Total Energy Generation	18056	kWh /yr
Nominal Power of the BIPV installatior	0,8	kWp
Building's compactness index	1,1	
Building's Energy demand per m²	43	kWh/m² yr
Buildings Energy generation per m²	7	kWh/m² yr
Façade surface yield (per m² façade)	66	kWh/m² yr
No Battery Scenario		
Self-Sufficiency Rate	11%	
Self-Consumption Rate	69%	
Total Energy Export	5660	kWh
Energy economy to CP	25%	
Energy economy to BP	20%	
Battery Scenario		
Battery Size	0	kWh
Self-Sufficiency Rate	-	
Self-Consumption Rate	-	
Total Energy Export	-	kWh
Energy economy to CP	-	
Energy economy to BP	-	
Total Self-Consumption Scenario		
Self-Sufficiency Rate	16%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	29%	
Energy economy to BP	24%	

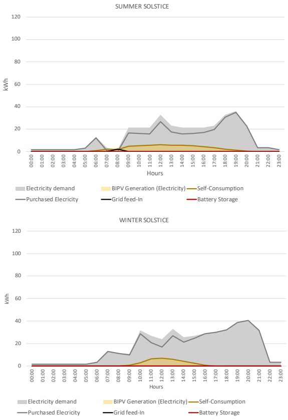
H I G H - P E R F O R M A N C E

Performance

FINAL ENERGY

Building's Energy Demand	113299	kWh /yr
Total Energy Generation	30094	kWh /yr
Nominal Power of the BIPV installatior	1,4	kWp
Building's compactness index	1,1	
Building's Energy demand per m²	43	kWh/m² yr
Buildings Energy generation per m²	11	kWh/m² yr
Façade surface yield (per m² façade)	111	kWh/m² yr
No Battery Scenario		
Self-Sufficiency Rate	16%	
Self-Consumption Rate	62%	
Total Energy Export	11434	kWh
Energy economy to CP	30%	
Energy economy to BP	25%	
Battery Scenario		
Battery Size	5	kWh
Self-Sufficiency Rate	18%	
Self-Consumption Rate	68%	
Total Energy Export	9617	kWh
Energy economy to CP	31%	
Energy economy to BP	26%	
Total Self-Consumption Scenario		
Self-Sufficiency Rate	27%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	38%	
Energy economy to BP	34%	

N O   B A T T E R Y



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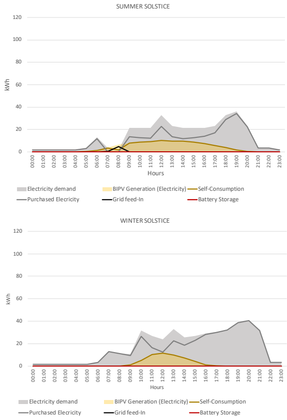
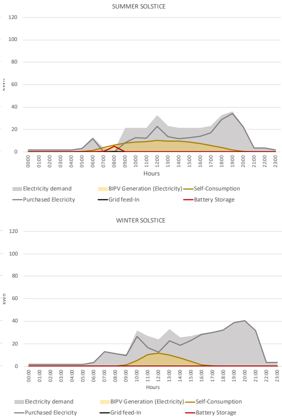


B A T T E R Y



E M B O D I E D   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

PRIMARY ENERGY

SIA 2040 Limit Values	30	9
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	30,71	7,26
BP	23,09	5,22
AAF	24,30	5,51
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	35,05	8,42
BP	27,43	6,38
AAF	28,64	6,67
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	31,37	7,41
BP	23,76	5,37
AAF	24,30	5,51

H I G H - P E R F O R M A N C E

SIA 2040 Limit Values	30	9
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	30,71	7,26
BP	23,09	5,22
AAF	24,26	5,50
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	35,05	8,42
BP	27,43	6,38
AAF	28,60	6,66
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	31,33	7,40
BP	23,72	5,36
AAF	24,26	5,50

C O M B I N E D   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

PRIMARY ENERGY

Impact Payback Time — **No Battery Scenario**

	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	38032	9976
Annual Impact Savings	31240	1264
PBT (Years)	**1,2**	**7,9**

Total Self-Consumption Scenario

	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	38032	9976
Annual Impact Savings	45502	1842
PBT (Years)	**0,8**	**5,4**

H I G H - P E R F O R M A N C E

PRIMARY ENERGY

Impact Payback Time — **No Battery Scenario**

	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	31799	8341
Annual Impact Savings	47024	1903
PBT (Years)	**0,7**	**4,4**

Battery Scenario

	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	32038	8396
Annual Impact Savings	51603	2089
PBT (Years)	**0,6**	**4,0**

Total Self-Consumption Scenario

	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	31799	8341
Annual Impact Savings	75837	3070
PBT (Years)	**0,4**	**2,7**

Anual environmental impact

Market-ready

	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
SIA 2040 Combined Limit Values	90	12
BASE SCENARIO		
CP	160,04	12,50
BP	144,51	10,13
AAF	116,00	9,23
Battery impact per building ERA	0,00	0,00
AAF with Battery	116,00	9,23
BAPV ROOF SCENARIO		
CP	116,80	11,73
BP	101,27	9,37
AAF	72,76	8,46
BAPV FAÇADE SCENARIO		
CP	143,32	11,95
BP	127,79	9,58
AAF	116,00	9,23

High-performance

	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
SIA 2040 Combined Limit Values	90	12
BASE SCENARIO		
CP	160,04	12,50
BP	144,51	10,13
AAF	104,37	8,75
Battery impact per building ERA	0,09	0,02
AAF with Battery	104,47	8,77
BAPV ROOF SCENARIO		
CP	116,80	11,73
BP	101,27	9,37
AAF	61,13	7,98
BAPV FAÇADE SCENARIO		
CP	131,69	11,47
BP	116,16	9,10
AAF	104,37	8,75

E C O N O M I C   E F F I C I E N C Y

Life Cycle Cost (LCC)

Initial investment

Market-ready

	Façade initial Investment cost per m²	Totals
CP	311,90 CHF	285 080 CHF
BP	460,67 CHF	421 050 CHF
AAF	547,34 CHF	500 270 CHF

30-year investment period	LCC
CP	8 117 352 CHF
BP	8 242 993 CHF
AAF	8 192 047 CHF

Battery cost (subsidies included)	- CHF	
Energy purchase reduction associated Earnings (NPV)	0,00 CHF	*NPV formula over battery lifetime
	0,00 CHF	

High-performance

	Building construction cost per m²	Totals
CP	2 304 CHF	6 030 602 CHF
BP	2 361 CHF	6 180 169 CHF
AAF	2 395 CHF	6 267 311 CHF

30-year investment period	LCC
CP	8 117 352 CHF
BP	8 242 993 CHF
AAF	8 146 668 CHF

Battery cost (subsidies included)	4 750,00 CHF	
Energy purchase reduction associated Earnings (NPV)	5 503,40 CHF	*NPV formula over battery lifetime
	717,52 CHF	

Net Present Value (NPV)

Market-ready

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	3 827 613 CHF	5 217 389 CHF
CP + BAPV ROOF	4 316 920 CHF	5 701 262 CHF
BP	5 088 138 CHF	6 502 573 CHF
BP + BAPV ROOF	5 575 904 CHF	6 984 904 CHF
AAF	7 375 217 CHF	8 803 980 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	4 597 259 CHF	5 362 431 CHF
BP	5 019 957 CHF	5 798 706 CHF
AAF	5 974 723 CHF	6 761 360 CHF

High-performance

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	3 827 613 CHF	5 217 389 CHF
CP + BAPV ROOF	4 316 920 CHF	5 701 262 CHF
BP	5 088 138 CHF	6 502 573 CHF
BP + BAPV ROOF	5 575 904 CHF	6 984 904 CHF
AAF	7 466 316 CHF	8 895 078 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	4 597 259 CHF	5 362 431 CHF
BP	5 019 957 CHF	5 798 706 CHF
AAF	6 040 960 CHF	6 827 597 CHF

Internal Rate of Return (IRR)

Market-ready

30-year investment period	**Unlevered IRR**	**Levered IRR**
CP	2,2%	6,0%
CP + BAPV ROOF	2,5%	6,4%
BP	2,7%	6,6%
BP + BAPV ROOF	2,9%	7,0%
AAF	3,4%	7,6%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	5,0%	11,4%
BP	5,2%	11,7%
AAF	5,9%	12,8%

High-performance

30-year investment period	**Unlevered IRR**	**Levered IRR**
CP	2,2%	6,0%
CP + BAPV ROOF	2,5%	6,4%
BP	2,7%	6,6%
BP + BAPV ROOF	2,9%	7,0%
AAF	3,5%	7,7%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	5,0%	11,4%
BP	5,2%	11,7%
AAF	6,0%	12,9%

Discounted Payback (DPB)

Market-ready

DPB	Un-levered	Levered
CP	31	15
BP	29	15
AAF	25	14

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	10	4
AAF to BP	years to have higher cummulated revenue	7	10

High-performance

DPB	Un-levered	Levered
CP	31	15
BP	29	15
AAF	25	13

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	9	4
AAF to BP	years to have higher cummulated revenue	6	9

Building scenario 2A

MR: opaque Monocrystalline filtered 12%
HP: opaque Tandem-Perovskite filtered 18%

O P E R A T I O N A L   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

Performance

FINAL ENERGY

Building's Energy Demand	113151	kWh /yr
Total Energy Generation	54790	kWh /yr
Nominal Power of the BIPV installatior	10,1	kWp
Building's compactness index	1,1	
Building's Energy demand per m²	43	kWh/m² yr
Buildings Energy generation per m²	21	kWh/m² yr
Façade surface yield (per m² façade)	65	kWh/m² yr

No Battery Scenario

Self-Sufficiency Rate	26%	
Self-Consumption Rate	54%	
Total Energy Export	25202	kWh
Energy economy to CP	38%	
Energy economy to BP	34%	

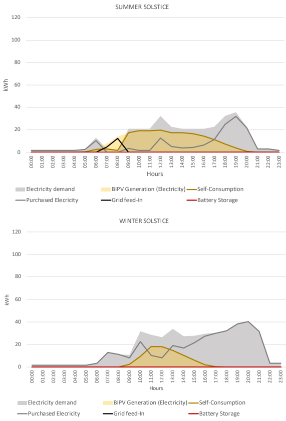
Battery Scenario

Battery Size	40	kWh
Self-Sufficiency Rate	32%	
Self-Consumption Rate	73%	
Total Energy Export	14700	kWh
Energy economy to CP	46%	
Energy economy to BP	42%	

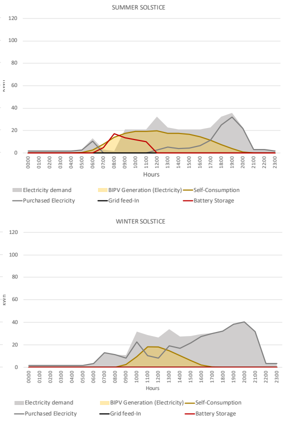
Total Self-Consumption Scenario

Self-Sufficiency Rate	48%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	57%	
Energy economy to BP	54%	

N O   B A T T E R Y



B A T T E R Y



H I G H - P E R F O R M A N C E

Performance

FINAL ENERGY

Building's Energy Demand	113151	kWh /yr
Total Energy Generation	83098	kWh /yr
Nominal Power of the BIPV installatior	15,3	kWp
Building's compactness index	1,1	
Building's Energy demand per m²	43	kWh/m² yr
Buildings Energy generation per m²	32	kWh/m² yr
Façade surface yield (per m² façade)	99	kWh/m² yr

No Battery Scenario

Self-Sufficiency Rate	32%	
Self-Consumption Rate	43%	
Total Energy Export	47226	kWh
Energy economy to CP	43%	
Energy economy to BP	39%	

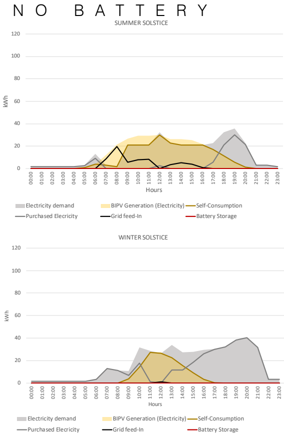
Battery Scenario

Battery Size	80	kWh
Self-Sufficiency Rate	45%	
Self-Consumption Rate	69%	
Total Energy Export	25990	kWh
Energy economy to CP	59%	
Energy economy to BP	56%	

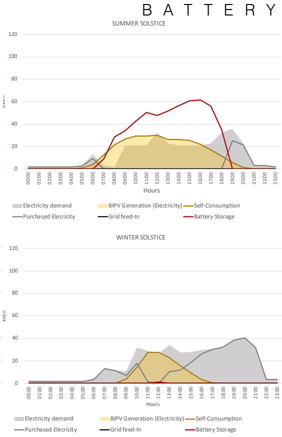
Total Self-Consumption Scenario

Self-Sufficiency Rate	73%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	78%	
Energy economy to BP	76%	

N O   B A T T E R Y



B A T T E R Y



E M B O D I E D   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

PRIMARY ENERGY

SIA 2040 Limit Values	30	9
BASE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	32,58	7,77
BP	24,05	5,43
AAF	32,32	7,63
BAPV ROOF SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	36,92	8,93
BP	28,38	6,59
AAF	36,66	8,79
BAPV FAÇADE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	41,12	10,01
BP	32,58	7,67
AAF	32,32	7,63

H I G H - P E R F O R M A N C E

SIA 2040 Limit Values	30	9
BASE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	32,58	7,77
BP	24,05	5,43
AAF	30,26	7,40
BAPV ROOF SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	36,92	8,93
BP	28,38	6,59
AAF	34,60	8,56
BAPV FAÇADE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	39,06	9,78
BP	30,53	7,44
AAF	30,26	7,40

C O M B I N E D   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

PRIMARY ENERGY
Impact Payback Time

No Battery Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	1001561	262190
Annual Impact Savings	74563	3018
PBT (Years)	**13,4**	**86,9**

Battery Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	1003473	262630
Annual Impact Savings	101027	4089
PBT (Years)	**9,9**	**64,2**

Total Self-Consumption Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	1001561	262190
Annual Impact Savings	138071	5589
PBT (Years)	**7,3**	**46,9**

H I G H - P E R F O R M A N C E

PRIMARY ENERGY
Impact Payback Time

No Battery Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	760394	235351
Annual Impact Savings	90398	3659
PBT (Years)	**8,4**	**64,3**

Battery Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	764218	236231
Annual Impact Savings	143912	5825
PBT (Years)	**5,3**	**40,6**

Total Self-Consumption Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	760394	235351
Annual Impact Savings	209408	8476
PBT (Years)	**3,6**	**27,8**

Anual environmental impact

Market-ready

	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
SIA 2040 Combined Limit Values	90	12
BASE SCENARIO		
CP	163,16	13,06
BP	146,08	10,37
AAF	88,51	9,90
Battery impact per building ERA	0,73	0,17
AAF with Battery	89,24	10,07
BAPV ROOF SCENARIO		
CP	119,92	12,29
BP	102,84	9,60
AAF	45,27	9,13
BAPV FAÇADE SCENARIO		
CP	118,94	13,16
BP	101,86	10,47
AAF	88,51	9,90

High-performance

	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
SIA 2040 Combined Limit Values	90	12
BASE SCENARIO		
CP	163,16	13,06
BP	146,08	10,37
AAF	59,20	8,57
Battery impact per building ERA	1,46	0,34
AAF with Battery	60,66	8,91
BAPV ROOF SCENARIO		
CP	119,92	12,29
BP	102,84	9,60
AAF	15,96	7,80
BAPV FAÇADE SCENARIO		
CP	89,63	11,82
BP	72,55	9,14
AAF	59,20	8,57

E C O N O M I C   E F F I C I E N C Y

Life Cycle Cost (LCC)

Initial investment

	Façade initial Investment cost per m²	Totals
CP	311,90 CHF	351 828 CHF
BP	460,67 CHF	519 633 CHF
AAF	633,43 CHF	714 509 CHF

	Building construction cost per m²	Totals
CP	2 288 CHF	5 987 579 CHF
BP	2 358 CHF	6 172 165 CHF
AAF	2 440 CHF	6 386 528 CHF

Market-ready

30-year investment period	LCC
CP	8 075 062 CHF
BP	8 237 407 CHF
AAF	8 118 417 CHF

Battery cost (subsidies included)	28 000,00 CHF	
Energy purchase reduction associated	31 806,84 CHF	*NPV formula over battery lifetime
Earnings (NPV)	3 625,56 CHF	

High-performance

30-year investment period	LCC
CP	8 075 062 CHF
BP	8 237 407 CHF
AAF	8 042 587 CHF

Battery cost (subsidies included)	54 000,00 CHF	
Energy purchase reduction associated	64 318,42 CHF	*NPV formula over battery lifetime
Earnings (NPV)	9 827,07 CHF	

Net Present Value (NPV)

Market-ready

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	3 626 871 CHF	5 009 554 CHF
CP + BAPV ROOF	4 116 641 CHF	5 493 889 CHF
BP	4 960 044 CHF	6 373 160 CHF
BP + BAPV ROOF	5 448 030 CHF	6 855 711 CHF
AAF	7 577 715 CHF	9 006 480 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	4 543 995 CHF	5 305 262 CHF
BP	4 971 739 CHF	5 749 761 CHF
AAF	6 121 883 CHF	6 908 521 CHF

High-performance

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	3 626 871 CHF	5 009 554 CHF
CP + BAPV ROOF	4 116 641 CHF	5 493 889 CHF
BP	4 960 044 CHF	6 373 160 CHF
BP + BAPV ROOF	5 448 030 CHF	6 855 711 CHF
AAF	7 767 271 CHF	9 196 036 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	4 543 995 CHF	5 305 262 CHF
BP	4 971 739 CHF	5 749 761 CHF
AAF	6 232 211 CHF	7 018 850 CHF

Internal Rate of Return (IRR)

Market-ready

30-year investment period	**Unlevered IRR**	**Levered IRR**
CP	2,1%	5,9%
CP + BAPV ROOF	2,4%	6,4%
BP	2,6%	6,5%
BP + BAPV ROOF	2,8%	6,9%
AAF	3,5%	7,8%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	4,9%	11,3%
BP	5,2%	11,7%
AAF	6,1%	13,0%

High-performance

30-year investment period	**Unlevered IRR**	**Levered IRR**
CP	2,1%	5,9%
CP + BAPV ROOF	2,4%	6,4%
BP	2,6%	6,5%
BP + BAPV ROOF	2,8%	6,9%
AAF	3,6%	7,9%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	4,9%	11,3%
BP	5,2%	11,7%
AAF	6,2%	13,2%

Discounted Payback (DPB)

Market-ready

DPB	Un-levered	Levered
CP	31	15
BP	29	15
AAF	25	13

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	10	4
AAF to BP	years to have higher cummulated revenue	6	10

High-performance

DPB	Un-levered	Levered
CP	31	15
BP	29	15
AAF	25	13

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	9	3
AAF to BP	years to have higher cummulated revenue	5	9

Building scenario 2B

MR: translucent Polycrystalline 12%
HP: translucent Tandem-Perovskite 18%

O P E R A T I O N A L   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

Performance

FINAL ENERGY

Building's Energy Demand	122731	kWh /yr
Total Energy Generation	28185	kWh /yr
Nominal Power of the BIPV installatior	4,2	kWp
Building's compactness index	1,0	
Building's Energy demand per m²	43	kWh/m² yr
Buildings Energy generation per m²	10	kWh/m² yr
Façade surface yield (per m² façade)	79	kWh/m² yr

No Battery Scenario

Self-Sufficiency Rate	14%	
Self-Consumption Rate	62%	
Total Energy Export	10639	kWh
Energy economy to CP	24%	
Energy economy to BP	19%	

Battery Scenario

Battery Size	5	kWh
Self-Sufficiency Rate	16%	
Self-Consumption Rate	68%	
Total Energy Export	8909	kWh
Energy economy to CP	25%	
Energy economy to BP	21%	

Total Self-Consumption Scenario

Self-Sufficiency Rate	23%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	32%	
Energy economy to BP	27%	

H I G H - P E R F O R M A N C E

Performance

FINAL ENERGY

Building's Energy Demand	122731	kWh /yr
Total Energy Generation	43843	kWh /yr
Nominal Power of the BIPV installatior	6,5	kWp
Building's compactness index	1,0	
Building's Energy demand per m²	43	kWh/m² yr
Buildings Energy generation per m²	15	kWh/m² yr
Façade surface yield (per m² façade)	123	kWh/m² yr

No Battery Scenario

Self-Sufficiency Rate	19%	
Self-Consumption Rate	54%	
Total Energy Export	19952	kWh
Energy economy to CP	29%	
Energy economy to BP	24%	

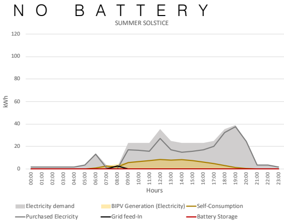
Battery Scenario

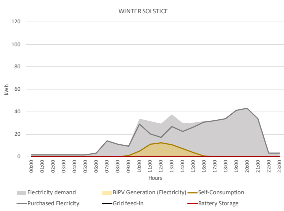
Battery Size	10	kWh
Self-Sufficiency Rate	22%	
Self-Consumption Rate	62%	
Total Energy Export	16612	kWh
Energy economy to CP	31%	
Energy economy to BP	27%	

Total Self-Consumption Scenario

Self-Sufficiency Rate	36%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	43%	
Energy economy to BP	39%	

N O   B A T T E R Y





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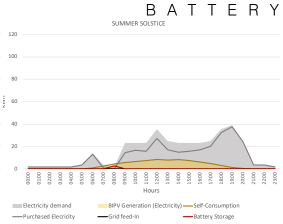

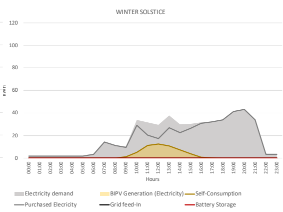

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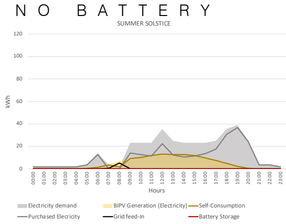

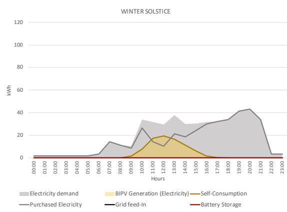

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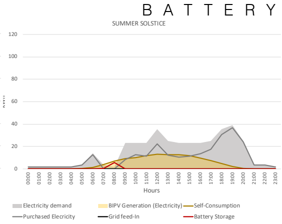
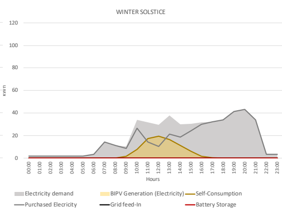




E M B O D I E D   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

PRIMARY ENERGY

SIA 2040 Limit Values	30	9
BASE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	30,89	7,31
BP	23,19	5,24
AAF	24,42	5,56
BAPV ROOF SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	34,89	8,38
BP	27,18	6,31
AAF	28,41	6,63
BAPV FAÇADE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	31,77	7,54
BP	24,06	5,47
AAF	24,42	5,56

H I G H - P E R F O R M A N C E

SIA 2040 Limit Values	30	9
BASE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	30,89	7,31
BP	23,19	5,24
AAF	24,29	5,56
BAPV ROOF SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	34,89	8,38
BP	27,18	6,31
AAF	28,28	6,63
BAPV FAÇADE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	31,64	7,54
BP	23,93	5,47
AAF	24,29	5,56

C O M B I N E D   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

PRIMARY ENERGY

Impact Payback Time	No Battery Scenario	
	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	139915	36670
Annual Impact Savings	44214	1790
PBT (Years)	**3,2**	**20,5**

	Battery Scenario	
	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	140154	36725
Annual Impact Savings	48576	1966
PBT (Years)	**2,9**	**18,7**

	Total Self-Consumption Scenario	
	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	139915	36670
Annual Impact Savings	71026	2875
PBT (Years)	**2,0**	**12,8**

H I G H - P E R F O R M A N C E

PRIMARY ENERGY

Impact Payback Time	No Battery Scenario	
	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	117545	36551
Annual Impact Savings	60205	2437
PBT (Years)	**2,0**	**15,0**

	Battery Scenario	
	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	118023	36661
Annual Impact Savings	68622	2778
PBT (Years)	**1,7**	**13,2**

	Total Self-Consumption Scenario	
	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	117545	36551
Annual Impact Savings	110485	4472
PBT (Years)	**1,1**	**8,2**

Anual environmental impact

Market-ready

SIA 2040 Combined Limit Values	90	12
BASE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	153,45	12,27
BP	138,71	9,92
AAF	108,21	8,95
Battery impact per building ERA	0,08	0,02
AAF with Battery	108,30	8,97
BAPV ROOF SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	109,87	11,41
BP	95,12	9,06
AAF	64,63	8,10
BAPV FAÇADE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	129,35	11,49
BP	114,60	9,13
AAF	108,21	8,95

High-performance

SIA 2040 Combined Limit Values	90	12
BASE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	153,45	12,27
BP	138,71	9,92
AAF	94,20	8,39
Battery impact per building ERA	0,17	0,04
AAF with Battery	94,37	8,43
BAPV ROOF SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	109,87	11,41
BP	95,12	9,06
AAF	50,62	7,53
BAPV FAÇADE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	115,34	10,92
BP	100,59	8,57
AAF	94,20	8,39

E C O N O M I C   E F F I C I E N C Y

Life Cycle Cost (LCC)

Initial investment

	Façade initial Investment cost per m²	Totals
CP	311,90 CHF	259 816 CHF
BP	460,67 CHF	383 736 CHF
AAF	633,35 CHF	527 584 CHF

	Building construction cost per m²	Totals
CP	2 182 CHF	6 205 459 CHF
BP	2 230 CHF	6 341 771 CHF
AAF	2 286 CHF	6 500 003 CHF

Market-ready

30-year investment period	LCC
CP	8 342 252 CHF
BP	8 454 148 CHF
AAF	8 477 461 CHF

Battery cost (subsidies included)	4 750,00 CHF	
Energy purchase reduction associated	5 242,51 CHF	*NPV formula over battery lifetime
Earnings (NPV)	469,06 CHF	

High-performance

30-year investment period	LCC
CP	8 342 252 CHF
BP	8 454 148 CHF
AAF	8 424 730 CHF

Battery cost (subsidies included)	8 500,00 CHF	
Energy purchase reduction associated	10 117,04 CHF	*NPV formula over battery lifetime
Earnings (NPV)	1 540,03 CHF	

Net Present Value (NPV)

Market-ready

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	6 111 040 CHF	7 529 644 CHF
CP + BAPV ROOF	6 602 378 CHF	8 015 547 CHF
BP	7 339 567 CHF	8 780 645 CHF
BP + BAPV ROOF	7 829 624 CHF	9 265 267 CHF
AAF	8 704 078 CHF	10 171 202 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	6 223 566 CHF	7 004 610 CHF
BP	6 642 453 CHF	7 435 871 CHF
AAF	7 178 677 CHF	7 986 435 CHF

High-performance

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	6 111 040 CHF	7 529 644 CHF
CP + BAPV ROOF	6 602 378 CHF	8 015 547 CHF
BP	7 339 567 CHF	8 780 645 CHF
BP + BAPV ROOF	7 829 624 CHF	9 265 267 CHF
AAF	8 817 564 CHF	10 284 687 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	6 223 566 CHF	7 004 610 CHF
BP	6 642 453 CHF	7 435 871 CHF
AAF	7 255 548 CHF	8 063 305 CHF

Internal Rate of Return (IRR)

Market-ready

30-year investment period	**Unlevered IRR**	**Levered IRR**
CP	3,2%	7,6%
CP + BAPV ROOF	3,4%	8,0%
BP	3,5%	8,0%
BP + BAPV ROOF	3,7%	8,4%
AAF	3,9%	8,5%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	6,3%	13,5%
BP	6,5%	13,8%
AAF	6,8%	14,2%

High-performance

30-year investment period	**Unlevered IRR**	**Levered IRR**
CP	3,2%	7,6%
CP + BAPV ROOF	3,4%	8,0%
BP	3,5%	8,0%
BP + BAPV ROOF	3,7%	8,4%
AAF	3,9%	8,5%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	6,3%	13,5%
BP	6,5%	13,8%
AAF	6,8%	14,3%

Discounted Payback (DPB)

Market-ready

DPB	Un-levered	Levered
CP	25	13
BP	24	12
AAF	23	12

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	13	8
AAF to BP	years to have higher cummulated revenue	12	13

High-performance

DPB	Un-levered	Levered
CP	25	13
BP	24	12
AAF	23	12

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	12	7
AAF to BP	years to have higher cummulated revenue	11	12

Building scenario 2C

MR: transparent Thin-Film 3%
HP: transparent Thin-Film 5%

O P E R A T I O N A L   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

Performance

FINAL ENERGY

Building's Energy Demand	118890	kWh /yr
Total Energy Generation	3415	kWh /yr
Nominal Power of the BIPV installatior	0,8	kWp
Building's compactness index	1,0	
Building's Energy demand per m²	42	kWh/m² yr
Buildings Energy generation per m²	1	kWh/m² yr
Façade surface yield (per m² façade)	13	kWh/m² yr
No Battery Scenario		
Self-Sufficiency Rate	3%	
Self-Consumption Rate	100%	
Total Energy Export	1	kWh
Energy economy to CP	14%	
Energy economy to BP	9%	
Battery Scenario		
Battery Size	0	kWh
Self-Sufficiency Rate	-	
Self-Consumption Rate	-	
Total Energy Export	-	kWh
Energy economy to CP	-	
Energy economy to BP	-	
Total Self-Consumption Scenario		
Self-Sufficiency Rate	3%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	14%	
Energy economy to BP	9%	

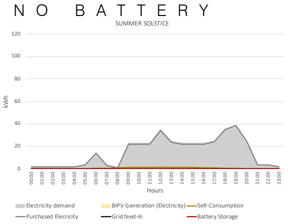
H I G H - P E R F O R M A N C E

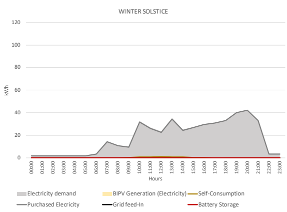
Performance

FINAL ENERGY

Building's Energy Demand	118890	kWh /yr
Total Energy Generation	5692	kWh /yr
Nominal Power of the BIPV installatior	1,3	kWp
Building's compactness index	1,0	
Building's Energy demand per m²	42	kWh/m² yr
Buildings Energy generation per m²	2	kWh/m² yr
Façade surface yield (per m² façade)	22	kWh/m² yr
No Battery Scenario		
Self-Sufficiency Rate	5%	
Self-Consumption Rate	94%	
Total Energy Export	340	kWh
Energy economy to CP	15%	
Energy economy to BP	10%	
Battery Scenario		
Battery Size	0	kWh
Self-Sufficiency Rate	-	
Self-Consumption Rate	-	
Total Energy Export	-	kWh
Energy economy to CP	-	
Energy economy to BP	-	
Total Self-Consumption Scenario		
Self-Sufficiency Rate	5%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	15%	
Energy economy to BP	11%	

N O   B A T T E R Y





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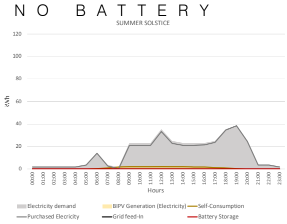
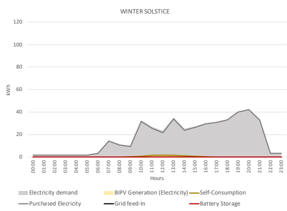




E M B O D I E D   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

PRIMARY ENERGY

SIA 2040 Limit Values	30	9
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	30,60	7,23
BP	23,04	5,21
AAF	24,09	5,48
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	34,59	8,30
BP	27,03	6,27
AAF	28,09	6,55
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	31,03	7,35
BP	23,47	5,33
AAF	24,09	5,48

H I G H - P E R F O R M A N C E

SIA 2040 Limit Values	30	9
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	30,60	7,23
BP	23,04	5,21
AAF	24,06	5,48
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	34,59	8,30
BP	27,03	6,27
AAF	28,06	6,54
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	31,00	7,34
BP	23,44	5,32
AAF	24,06	5,48

C O M B I N E D   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

PRIMARY ENERGY

Impact Payback Time	No Battery Scenario	
	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	30394	7973
Annual Impact Savings	8604	348
PBT (Years)	**3,5**	**22,9**

Total Self-Consumption Scenario		
	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	30394	7973
Annual Impact Savings	8607	348
PBT (Years)	**3,5**	**22,9**

H I G H - P E R F O R M A N C E

PRIMARY ENERGY

Impact Payback Time	No Battery Scenario	
	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	25413	6666
Annual Impact Savings	13487	546
PBT (Years)	**1,9**	**12,2**

Total Self-Consumption Scenario		
	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	25413	6666
Annual Impact Savings	14345	581
PBT (Years)	**1,8**	**11,5**

Anual environmental impact

Market-ready

SIA 2040 Combined Limit Values	90	12
BASE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	149,20	12,03
BP	135,46	9,76
AAF	126,44	9,63
Battery impact per building ERA	0,00	0,00
AAF with Battery	126,44	9,63
BAPV ROOF SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	105,61	11,17
BP	91,87	8,90
AAF	82,85	8,77
BAPV FAÇADE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	146,60	12,03
BP	132,86	9,75
AAF	126,44	9,63

High-performance

SIA 2040 Combined Limit Values	90	12
BASE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	149,20	12,03
BP	135,46	9,76
AAF	124,39	9,54
Battery impact per building ERA	0,00	0,00
AAF with Battery	124,39	9,54
BAPV ROOF SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	105,61	11,17
BP	91,87	8,90
AAF	80,80	8,68
BAPV FAÇADE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	144,55	11,94
BP	130,81	9,66
AAF	124,39	9,54

E C O N O M I C   E F F I C I E N C Y

Life Cycle Cost (LCC)

Initial investment

	Façade initial Investment cost per m²	Totals
CP	311,90 CHF	320 949 CHF
BP	460,67 CHF	474 027 CHF
AAF	504,78 CHF	519 423 CHF

	Building construction cost per m²	Totals
CP	2 169 CHF	6 166 055 CHF
BP	2 228 CHF	6 334 440 CHF
AAF	2 245 CHF	6 384 376 CHF

Market-ready

30-year investment period	LCC
CP	8 271 006 CHF
BP	8 425 572 CHF
AAF	8 419 422 CHF

Battery cost (subsidies included)	- CHF	
Energy purchase reduction associated	0,00 CHF	*NPV formula over battery lifetime
Earnings (NPV)	0,00 CHF	

High-performance

30-year investment period	LCC
CP	8 271 006 CHF
BP	8 425 572 CHF
AAF	8 408 425 CHF

Battery cost (subsidies included)	- CHF	
Energy purchase reduction associated	0,00 CHF	*NPV formula over battery lifetime
Earnings (NPV)	0,00 CHF	

Net Present Value (NPV)

Market-ready

30-year investment period	Unlevered NPV	Levered NPV
CP	6 269 172 CHF	7 681 280 CHF
CP + BAPV ROOF	6 759 307 CHF	8 165 980 CHF
BP	7 287 797 CHF	8 727 666 CHF
BP + BAPV ROOF	7 777 087 CHF	9 211 522 CHF
AAF	8 653 911 CHF	10 101 974 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	6 319 152 CHF	7 096 619 CHF
BP	6 625 962 CHF	7 418 714 CHF
AAF	7 179 991 CHF	7 977 254 CHF

High-performance

30-year investment period	Unlevered NPV	Levered NPV
CP	6 269 172 CHF	7 681 280 CHF
CP + BAPV ROOF	6 759 307 CHF	8 165 980 CHF
BP	7 287 797 CHF	8 727 666 CHF
BP + BAPV ROOF	7 777 087 CHF	9 211 522 CHF
AAF	8 673 052 CHF	10 121 115 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	6 319 152 CHF	7 096 619 CHF
BP	6 625 962 CHF	7 418 714 CHF
AAF	7 196 091 CHF	7 993 354 CHF

Internal Rate of Return (IRR)

Market-ready

30-year investment period	Unlevered IRR	Levered IRR
CP	3,2%	7,7%
CP + BAPV ROOF	3,5%	8,1%
BP	3,5%	8,0%
BP + BAPV ROOF	3,7%	8,4%
AAF	3,9%	8,5%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	6,4%	13,7%
BP	6,5%	13,8%
AAF	6,8%	14,3%

High-performance

30-year investment period	Unlevered IRR	Levered IRR
CP	3,2%	7,7%
CP + BAPV ROOF	3,5%	8,1%
BP	3,5%	8,0%
BP + BAPV ROOF	3,7%	8,4%
AAF	3,9%	8,5%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	6,4%	13,7%
BP	6,5%	13,8%
AAF	6,9%	14,3%

Discounted Payback (DPB)

Market-ready

DPB	Un-levered	Levered
CP	25	12
BP	24	12
AAF	23	12

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	12	5
AAF to BP	years to have higher cummulated revenue	7	12

High-performance

DPB	Un-levered	Levered
CP	25	12
BP	24	12
AAF	23	12

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	12	5
AAF to BP	years to have higher cummulated revenue	7	12

Building scenario 3A

MR: opaque Monocrystalline filtered 12%
HP: opaque Tandem-Perovskite filtered 18%

O P E R A T I O N A L   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

Performance

FINAL ENERGY

Building's Energy Demand	120187	kWh /yr
Total Energy Generation	43450	kWh /yr
Nominal Power of the BIPV installatior	6,7	kWp
Building's compactness index	1,0	
Building's Energy demand per m²	42	kWh/m² yr
Buildings Energy generation per m²	15	kWh/m² yr
Façade surface yield (per m² façade)	78	kWh/m² yr

No Battery Scenario

Self-Sufficiency Rate	20%	
Self-Consumption Rate	55%	
Total Energy Export	19476	kWh
Energy economy to CP	30%	
Energy economy to BP	26%	

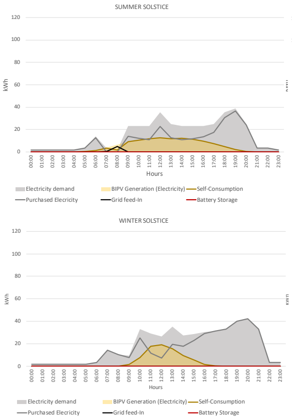
Battery Scenario

Battery Size	10	kWh
Self-Sufficiency Rate	22%	
Self-Consumption Rate	63%	
Total Energy Export	16137	kWh
Energy economy to CP	33%	
Energy economy to BP	29%	

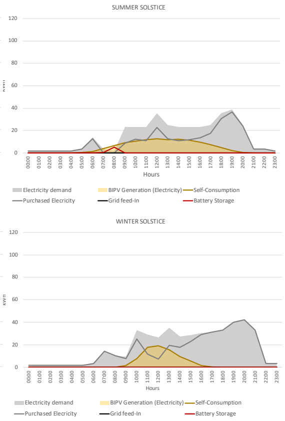
Total Self-Consumption Scenario

Self-Sufficiency Rate	36%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	45%	
Energy economy to BP	41%	

N O   B A T T E R Y



B A T T E R Y



H I G H - P E R F O R M A N C E

Performance

FINAL ENERGY

Building's Energy Demand	120187	kWh /yr
Total Energy Generation	65899	kWh /yr
Nominal Power of the BIPV installatior	10,2	kWp
Building's compactness index	1,0	
Building's Energy demand per m²	42	kWh/m² yr
Buildings Energy generation per m²	23	kWh/m² yr
Façade surface yield (per m² façade)	118	kWh/m² yr

No Battery Scenario

Self-Sufficiency Rate	25%	
Self-Consumption Rate	46%	
Total Energy Export	35442	kWh
Energy economy to CP	35%	
Energy economy to BP	31%	

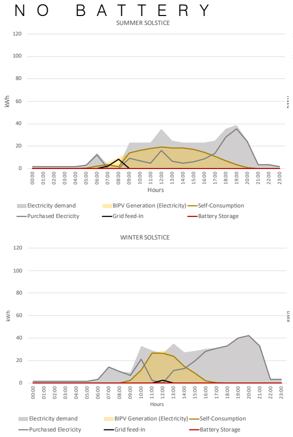
Battery Scenario

Battery Size	50	kWh
Self-Sufficiency Rate	32%	
Self-Consumption Rate	66%	
Total Energy Export	22179	kWh
Energy economy to CP	45%	
Energy economy to BP	41%	

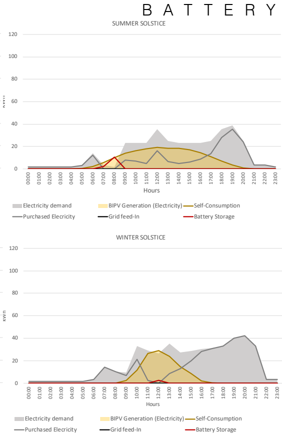
Total Self-Consumption Scenario

Self-Sufficiency Rate	55%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	61%	
Energy economy to BP	58%	

N O   B A T T E R Y



B A T T E R Y



E M B O D I E D   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

PRIMARY ENERGY

SIA 2040 Limit Values	30	9
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	31,50	7,48
BP	23,50	5,31
AAF	27,04	6,25
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	35,50	8,54
BP	27,49	6,38
AAF	31,03	7,32
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	35,00	8,39
BP	27,00	6,22
AAF	27,04	6,25

H I G H - P E R F O R M A N C E

SIA 2040 Limit Values	30	9
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	31,50	7,48
BP	23,50	5,31
AAF	26,20	6,16
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	35,50	8,54
BP	27,49	6,38
AAF	30,20	7,22
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	34,16	8,30
BP	26,16	6,13
AAF	26,20	6,16

C O M B I N E D   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

PRIMARY ENERGY
Impact Payback Time

No Battery Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	587368	154075
Annual Impact Savings	60415	2445
PBT (Years)	**9,7**	**63,0**

Battery Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	587846	154185
Annual Impact Savings	68830	2786
PBT (Years)	**8,5**	**55,3**

Total Self-Consumption Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	587368	154075
Annual Impact Savings	109494	4432
PBT (Years)	**5,4**	**34,8**

H I G H - P E R F O R M A N C E

PRIMARY ENERGY
Impact Payback Time

No Battery Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	444282	138151
Annual Impact Savings	76753	3107
PBT (Years)	**5,8**	**44,5**

Battery Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	446672	138701
Annual Impact Savings	110176	4459
PBT (Years)	**4,1**	**31,1**

Total Self-Consumption Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	444282	138151
Annual Impact Savings	166067	6722
PBT (Years)	**2,7**	**20,6**

Anual environmental impact

Market-ready

SIA 2040 Combined Limit Values	90	12
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	154,19	12,44
BP	139,11	9,99
AAF	95,05	9,00
Battery impact per building ERA	0,17	0,04
AAF with Battery	95,22	9,04
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	110,60	11,58
BP	95,53	9,13
AAF	51,47	8,14
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	119,18	11,80
BP	104,10	9,35
AAF	95,05	9,00

High-performance

SIA 2040 Combined Limit Values	90	12
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	154,19	12,44
BP	139,11	9,99
AAF	74,32	8,11
Battery impact per building ERA	0,84	0,19
AAF with Battery	75,16	8,30
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	110,60	11,58
BP	95,53	9,13
AAF	30,73	7,25
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	98,44	10,90
BP	83,37	8,45
AAF	74,32	8,11

E C O N O M I C   E F F I C I E N C Y

Life Cycle Cost (LCC)

Initial investment

	Façade initial Investment cost per m²	Totals
CP	311,90 CHF	259 816 CHF
BP	460,67 CHF	383 736 CHF
AAF	719,42 CHF	599 279 CHF

	Building construction cost per m²	Totals
CP	2 182 CHF	6 205 459 CHF
BP	2 230 CHF	6 341 771 CHF
AAF	2 314 CHF	6 578 868 CHF

Market-ready

30-year investment period	LCC
CP	8 343 057 CHF
BP	8 454 774 CHF
AAF	8 501 712 CHF

Battery cost (subsidies included)	8 500,00 CHF	
Energy purchase reduction associated	10 113,85 CHF	*NPV formula over battery lifetime
Earnings (NPV)	1 537,00 CHF	

High-performance

30-year investment period	LCC
CP	8 343 057 CHF
BP	8 454 774 CHF
AAF	8 435 906 CHF

Battery cost (subsidies included)	34 500,00 CHF	
Energy purchase reduction associated	40 171,07 CHF	*NPV formula over battery lifetime
Earnings (NPV)	5 401,02 CHF	

Net Present Value (NPV)

Market-ready

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	5 639 783 CHF	7 058 388 CHF
CP + BAPV ROOF	6 131 199 CHF	7 544 368 CHF
BP	6 873 756 CHF	8 314 834 CHF
BP + BAPV ROOF	7 363 868 CHF	8 799 511 CHF
AAF	8 719 426 CHF	10 199 545 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	6 024 625 CHF	6 805 669 CHF
BP	6 445 812 CHF	7 239 229 CHF
AAF	7 156 678 CHF	7 971 590 CHF

High-performance

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	5 639 783 CHF	7 058 388 CHF
CP + BAPV ROOF	6 131 199 CHF	7 544 368 CHF
BP	6 873 756 CHF	8 314 834 CHF
BP + BAPV ROOF	7 363 868 CHF	8 799 511 CHF
AAF	8 874 291 CHF	10 354 410 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	6 024 625 CHF	6 805 669 CHF
BP	6 445 812 CHF	7 239 229 CHF
AAF	7 252 493 CHF	8 067 405 CHF

Internal Rate of Return (IRR)

Market-ready

30-year investment period	**Unlevered IRR**	**Levered IRR**
CP	3,0%	7,4%
CP + BAPV ROOF	3,2%	7,8%
BP	3,4%	7,8%
BP + BAPV ROOF	3,6%	8,2%
AAF	3,9%	8,4%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	6,1%	13,3%
BP	6,3%	13,6%
AAF	6,7%	14,1%

High-performance

30-year investment period	**Unlevered IRR**	**Levered IRR**
CP	3,0%	7,4%
CP + BAPV ROOF	3,2%	7,8%
BP	3,4%	7,8%
BP + BAPV ROOF	3,6%	8,2%
AAF	3,9%	8,5%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	6,1%	13,3%
BP	6,3%	13,6%
AAF	6,8%	14,2%

Discounted Payback (DPB)

Market-ready

DPB	Un-levered	Levered
CP	26	13
BP	25	13
AAF	23	12

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	13	9
AAF to BP	years to have higher cummulated revenue	13	13

High-performance

DPB	Un-levered	Levered
CP	26	13
BP	25	13
AAF	23	12

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	12	8
AAF to BP	years to have higher cummulated revenue	12	12

Building scenario 3B

MR: translucent DSSC 2%
HP: translucent Thin-Film 7%

O P E R A T I O N A L   E N E R G Y   E F F I C I E N C Y

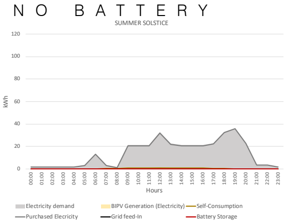
M A R K E T - R E A D Y

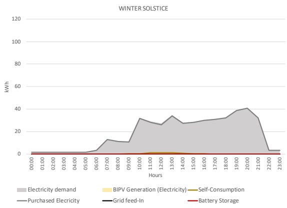
Performance

FINAL ENERGY

Building's Energy Demand	114324	kWh /yr
Total Energy Generation	2807	kWh /yr
Nominal Power of the BIPV installatior	0,5	kWp
Building's compactness index	1,1	
Building's Energy demand per m²	44	kWh/m² yr
Buildings Energy generation per m²	1	kWh/m² yr
Façade surface yield (per m² façade)	13	kWh/m² yr
No Battery Scenario		
Self-Sufficiency Rate	2%	
Self-Consumption Rate	99%	
Total Energy Export	27	kWh
Energy economy to CP	18%	
Energy economy to BP	12%	
Battery Scenario		
Battery Size	0	kWh
Self-Sufficiency Rate	-	
Self-Consumption Rate	-	
Total Energy Export	-	kWh
Energy economy to CP	-	
Energy economy to BP	-	
Total Self-Consumption Scenario		
Self-Sufficiency Rate	2%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	18%	
Energy economy to BP	12%	

N O   B A T T E R Y





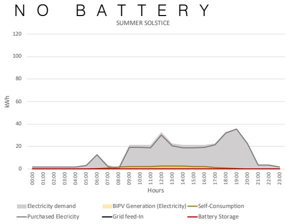
H I G H - P E R F O R M A N C E

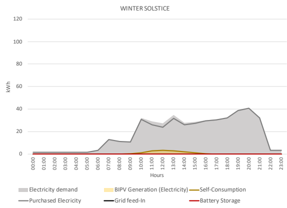
Performance

FINAL ENERGY

Building's Energy Demand	114324	kWh /yr
Total Energy Generation	8188	kWh /yr
Nominal Power of the BIPV installatior	1,5	kWp
Building's compactness index	1,1	
Building's Energy demand per m²	44	kWh/m² yr
Buildings Energy generation per m²	3	kWh/m² yr
Façade surface yield (per m² façade)	39	kWh/m² yr
No Battery Scenario		
Self-Sufficiency Rate	6%	
Self-Consumption Rate	81%	
Total Energy Export	1536	kWh
Energy economy to CP	21%	
Energy economy to BP	15%	
Battery Scenario		
Battery Size	0	kWh
Self-Sufficiency Rate	-	
Self-Consumption Rate	-	
Total Energy Export	-	kWh
Energy economy to CP	-	
Energy economy to BP	-	
Total Self-Consumption Scenario		
Self-Sufficiency Rate	7%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	22%	
Energy economy to BP	16%	

N O   B A T T E R Y





E M B O D I E D   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

PRIMARY ENERGY

SIA 2040 Limit Values	30	9
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	30,50	7,20
BP	22,99	5,19
AAF	24,40	5,53
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	34,84	8,36
BP	27,32	6,35
AAF	28,74	6,69
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	31,11	7,34
BP	23,60	5,33
AAF	24,40	5,53

H I G H - P E R F O R M A N C E

SIA 2040 Limit Values	30	9
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	30,50	7,20
BP	22,99	5,19
AAF	24,42	5,54
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	34,84	8,36
BP	27,32	6,35
AAF	28,75	6,69
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	31,13	7,35
BP	23,62	5,34
AAF	24,42	5,54

C O M B I N E D   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

PRIMARY ENERGY

Impact Payback Time — **No Battery Scenario**

	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	15068	3952
Annual Impact Savings	7007	284
PBT (Years)	**2,2**	**13,9**

Total Self-Consumption Scenario

	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	15068	3952
Annual Impact Savings	7074	286
PBT (Years)	**2,1**	**13,8**

H I G H - P E R F O R M A N C E

PRIMARY ENERGY

Impact Payback Time — **No Battery Scenario**

	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	18021	4727
Annual Impact Savings	16764	679
PBT (Years)	**1,1**	**7,0**

Total Self-Consumption Scenario

	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	18021	4727
Annual Impact Savings	20634	835
PBT (Years)	**0,9**	**5,7**

Anual environmental impact

Market-ready

	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
SIA 2040 Combined Limit Values	90	12
BASE SCENARIO		
CP	161,08	12,49
BP	145,02	10,13
AAF	131,77	9,88
Battery impact per building ERA	0,00	0,00
AAF with Battery	131,77	9,88
BAPV ROOF SCENARIO		
CP	117,84	11,72
BP	101,78	9,37
AAF	88,53	9,11
BAPV FAÇADE SCENARIO		
CP	158,99	12,52
BP	142,93	10,16
AAF	131,77	9,88

High-performance

	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
SIA 2040 Combined Limit Values	90	12
BASE SCENARIO		
CP	161,08	12,49
BP	145,02	10,13
AAF	126,61	9,67
Battery impact per building ERA	0,00	0,00
AAF with Battery	126,61	9,67
BAPV ROOF SCENARIO		
CP	117,84	11,72
BP	101,78	9,37
AAF	83,37	8,90
BAPV FAÇADE SCENARIO		
CP	153,83	12,31
BP	137,77	9,96
AAF	126,61	9,67

E C O N O M I C   E F F I C I E N C Y

Life Cycle Cost (LCC)

Initial investment

Market-ready

	Façade initial Investment cost per m²	Totals
CP	311,90 CHF	351 828 CHF
BP	460,67 CHF	519 633 CHF
AAF	495,62 CHF	559 062 CHF

30-year investment period	LCC
CP	8 075 062 CHF
BP	8 237 407 CHF
AAF	8 201 284 CHF

Battery cost (subsidies included)	- CHF	
Energy purchase reduction associated	0,00 CHF	*NPV formula over battery lifetime
Earnings (NPV)	0,00 CHF	

High-performance

	Building construction cost per m²	Totals
CP	2 288 CHF	5 987 579 CHF
BP	2 358 CHF	6 172 165 CHF
AAF	2 375 CHF	6 215 537 CHF

30-year investment period	LCC
CP	8 075 062 CHF
BP	8 237 407 CHF
AAF	8 177 436 CHF

Battery cost (subsidies included)	- CHF	
Energy purchase reduction associated	0,00 CHF	*NPV formula over battery lifetime
Earnings (NPV)	0,00 CHF	

Net Present Value (NPV)

Market-ready

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	3 832 846 CHF	5 215 528 CHF
CP + BAPV ROOF	4 322 615 CHF	5 699 863 CHF
BP	5 166 019 CHF	6 579 134 CHF
BP + BAPV ROOF	5 654 004 CHF	7 061 685 CHF
AAF	7 318 302 CHF	8 738 530 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	4 630 947 CHF	5 392 213 CHF
BP	5 058 690 CHF	5 836 712 CHF
AAF	5 946 870 CHF	6 728 808 CHF

High-performance

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	3 832 846 CHF	5 215 528 CHF
CP + BAPV ROOF	4 322 615 CHF	5 699 863 CHF
BP	5 166 019 CHF	6 579 134 CHF
BP + BAPV ROOF	5 654 004 CHF	7 061 685 CHF
AAF	7 361 848 CHF	8 782 077 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	4 630 947 CHF	5 392 213 CHF
BP	5 058 690 CHF	5 836 712 CHF
AAF	5 981 748 CHF	6 763 687 CHF

Internal Rate of Return (IRR)

Market-ready

30-year investment period	**Unlevered IRR**	**Levered IRR**
CP	2,2%	6,1%
CP + BAPV ROOF	2,5%	6,5%
BP	2,7%	6,6%
BP + BAPV ROOF	2,9%	7,0%
AAF	3,4%	7,6%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	5,0%	11,5%
BP	5,3%	11,8%
AAF	6,0%	12,8%

High-performance

30-year investment period	**Unlevered IRR**	**Levered IRR**
CP	2,2%	6,1%
CP + BAPV ROOF	2,5%	6,5%
BP	2,7%	6,6%
BP + BAPV ROOF	2,9%	7,0%
AAF	3,5%	7,7%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	5,0%	11,5%
BP	5,3%	11,8%
AAF	6,0%	12,9%

Discounted Payback (DPB)

Market-ready

DPB	Un-levered	Levered
CP	31	15
BP	28	15
AAF	25	14

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	10	4
AAF to BP	years to have higher cummulated revenue	5	10

High-performance

DPB	Un-levered	Levered
CP	31	15
BP	28	15
AAF	25	13

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	10	3
AAF to BP	years to have higher cummulated revenue	5	10

Building scenario 3C

MR: transparent Thin-Film 3%
HP: transparent Thin-Film 5%

O P E R A T I O N A L   E N E R G Y   E F F I C I E N C Y

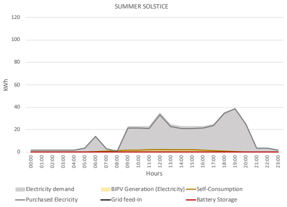
M A R K E T - R E A D Y

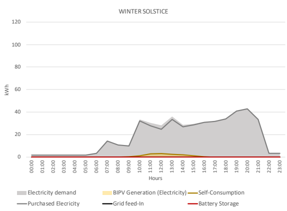
Performance

FINAL ENERGY

Building's Energy Demand	121973	kWh /yr
Total Energy Generation	7349	kWh /yr
Nominal Power of the BIPV installatior	1,0	kWp
Building's compactness index	1,0	
Building's Energy demand per m²	43	kWh/m² yr
Buildings Energy generation per m²	3	kWh/m² yr
Façade surface yield (per m² façade)	22	kWh/m² yr
No Battery Scenario		
Self-Sufficiency Rate	5%	
Self-Consumption Rate	84%	
Total Energy Export	1143	kWh
Energy economy to CP	16%	
Energy economy to BP	11%	
Battery Scenario		
Battery Size	0	kWh
Self-Sufficiency Rate	-	
Self-Consumption Rate	-	
Total Energy Export	-	kWh
Energy economy to CP	-	
Energy economy to BP	-	
Total Self-Consumption Scenario		
Self-Sufficiency Rate	6%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	17%	
Energy economy to BP	12%	

N O   B A T T E R Y





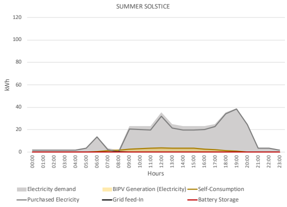
H I G H - P E R F O R M A N C E

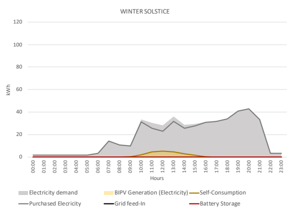
Performance

FINAL ENERGY

Building's Energy Demand	121973	kWh /yr
Total Energy Generation	12248	kWh /yr
Nominal Power of the BIPV installatior	1,7	kWp
Building's compactness index	1,0	
Building's Energy demand per m²	43	kWh/m² yr
Buildings Energy generation per m²	4	kWh/m² yr
Façade surface yield (per m² façade)	37	kWh/m² yr
No Battery Scenario		
Self-Sufficiency Rate	7%	
Self-Consumption Rate	75%	
Total Energy Export	3104	kWh
Energy economy to CP	18%	
Energy economy to BP	13%	
Battery Scenario		
Battery Size	0	kWh
Self-Sufficiency Rate	-	
Self-Consumption Rate	-	
Total Energy Export	-	kWh
Energy economy to CP	-	
Energy economy to BP	-	
Total Self-Consumption Scenario		
Self-Sufficiency Rate	10%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	21%	
Energy economy to BP	16%	

N O   B A T T E R Y





E M B O D I E D   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

PRIMARY ENERGY

SIA 2040 Limit Values	30	9
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	30,83	7,29
BP	23,15	5,23
AAF	23,97	5,45
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	34,82	8,36
BP	27,15	6,30
AAF	27,96	6,51
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	31,26	7,40
BP	23,58	5,34
AAF	23,97	5,45

H I G H - P E R F O R M A N C E

SIA 2040 Limit Values	30	9
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	30,83	7,29
BP	23,15	5,23
AAF	23,91	5,43
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	34,82	8,36
BP	27,15	6,30
AAF	27,90	6,50
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	31,20	7,39
BP	23,52	5,33
AAF	23,91	5,43

C O M B I N E D   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

PRIMARY ENERGY
Impact Payback Time

No Battery Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	63300	16604
Annual Impact Savings	15638	633
PBT (Years)	**4,0**	**26,2**

Total Self-Consumption Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	63300	16604
Annual Impact Savings	18519	750
PBT (Years)	**3,4**	**22,2**

H I G H - P E R F O R M A N C E

PRIMARY ENERGY
Impact Payback Time

No Battery Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	52926	13883
Annual Impact Savings	23042	933
PBT (Years)	**2,3**	**14,9**

Total Self-Consumption Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	52926	13883
Annual Impact Savings	30865	1249
PBT (Years)	**1,7**	**11,1**

Anual environmental impact

Market-Ready

	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
SIA 2040 Combined Limit Values	90	12
BASE SCENARIO		
CP	153,38	12,25
BP	138,67	9,91
AAF	125,56	9,56
Battery impact per building ERA	0,00	0,00
AAF with Battery	125,56	9,56
BAPV ROOF SCENARIO		
CP	109,80	11,39
BP	95,09	9,05
AAF	81,97	8,70
BAPV FAÇADE SCENARIO		
CP	147,30	12,10
BP	132,58	9,75
AAF	125,56	9,56

High-Performance

	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
SIA 2040 Combined Limit Values	90	12
BASE SCENARIO		
CP	153,38	12,25
BP	138,67	9,91
AAF	121,15	9,37
Battery impact per building ERA	0,00	0,00
AAF with Battery	121,15	9,37
BAPV ROOF SCENARIO		
CP	109,80	11,39
BP	95,09	9,05
AAF	77,57	8,51
BAPV FAÇADE SCENARIO		
CP	142,89	11,91
BP	128,18	9,56
AAF	121,15	9,37

E C O N O M I C   E F F I C I E N C Y

Life Cycle Cost (LCC)

Initial investment

	Façade initial Investment cost per m²	Totals
CP	311,90 CHF	259 816 CHF
BP	460,67 CHF	383 736 CHF
AAF	624,01 CHF	519 798 CHF

	Building construction cost per m²	Totals
CP	2 182 CHF	6 205 459 CHF
BP	2 230 CHF	6 341 771 CHF
AAF	2 283 CHF	6 491 440 CHF

Market-Ready

30-year investment period	LCC
CP	8 342 204 CHF
BP	8 454 121 CHF
AAF	8 543 566 CHF

Battery cost (subsidies included)	- CHF	
Energy purchase reduction associated	0,00 CHF	*NPV formula over battery lifetime
Earnings (NPV)	0,00 CHF	

High-Performance

30-year investment period	LCC
CP	8 342 204 CHF
BP	8 454 121 CHF
AAF	8 523 714 CHF

Battery cost (subsidies included)	- CHF	
Energy purchase reduction associated	0,00 CHF	*NPV formula over battery lifetime
Earnings (NPV)	0,00 CHF	

Net Present Value (NPV)

Market-Ready

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	5 979 449 CHF	7 398 053 CHF
CP + BAPV ROOF	6 470 786 CHF	7 883 956 CHF
BP	7 207 323 CHF	8 648 401 CHF
BP + BAPV ROOF	7 697 379 CHF	9 133 022 CHF
AAF	8 555 366 CHF	10 021 079 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	6 168 015 CHF	6 949 059 CHF
BP	6 586 626 CHF	7 380 044 CHF
AAF	7 072 011 CHF	7 878 992 CHF

High-Performance

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	5 979 449 CHF	7 398 053 CHF
CP + BAPV ROOF	6 470 786 CHF	7 883 956 CHF
BP	7 207 323 CHF	8 648 401 CHF
BP + BAPV ROOF	7 697 379 CHF	9 133 022 CHF
AAF	8 593 545 CHF	10 059 257 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	6 168 015 CHF	6 949 059 CHF
BP	6 586 626 CHF	7 380 044 CHF
AAF	7 101 012 CHF	7 907 993 CHF

Internal Rate of Return (IRR)

Market-Ready

30-year investment period	**Unlevered IRR**	**Levered IRR**
CP	3,1%	7,6%
CP + BAPV ROOF	3,3%	7,9%
BP	3,5%	8,0%
BP + BAPV ROOF	3,7%	8,3%
AAF	3,8%	8,4%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	6,2%	13,4%
BP	6,4%	13,7%
AAF	6,7%	14,1%

High-Performance

30-year investment period	**Unlevered IRR**	**Levered IRR**
CP	3,1%	7,6%
CP + BAPV ROOF	3,3%	7,9%
BP	3,5%	8,0%
BP + BAPV ROOF	3,7%	8,3%
AAF	3,8%	8,4%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	6,2%	13,4%
BP	6,4%	13,7%
AAF	6,7%	14,1%

Discounted Payback (DPB)

Market-Ready

DPB	Un-levered	Levered
CP	25	13
BP	24	12
AAF	23	12

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	13	9
AAF to BP	years to have higher cummulated revenue	13	13

High-Performance

DPB	Un-levered	Levered
CP	25	13
BP	24	12
AAF	23	12

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	13	9
AAF to BP	years to have higher cummulated revenue	12	13

Building scenario 4A

MR: opaque Monocrystalline 21%
HP: opaque Tandem-Perovskite 28%

OPERATIONAL ENERGY EFFICIENCY

MARKET-READY

Performance

FINAL ENERGY

Building's Energy Demand	113558	kWh /yr
Total Energy Generation	117150	kWh /yr
Nominal Power of the BIPV installatior	23,7	kWp
Building's compactness index	1,1	
Building's Energy demand per m²	43	kWh/m² yr
Buildings Energy generation per m²	45	kWh/m² yr
Façade surface yield (per m² façade)	104	kWh/m² yr
No Battery Scenario		
Self-Sufficiency Rate	36%	
Self-Consumption Rate	34%	
Total Energy Export	76824	kWh
Energy economy to CP	47%	
Energy economy to BP	43%	
Battery Scenario		
Battery Size	100	kWh
Self-Sufficiency Rate	55%	
Self-Consumption Rate	58%	
Total Energy Export	49110	kWh
Energy economy to CP	67%	
Energy economy to BP	64%	
Total Self-Consumption Scenario		
Self-Sufficiency Rate	103%	
Self-Consumption Rate	97%	
Total Energy Export	3592	kWh
Energy economy to CP	100%	
Energy economy to BP	100%	

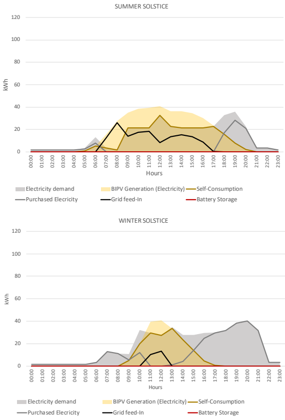
HIGH-PERFORMANCE

Performance

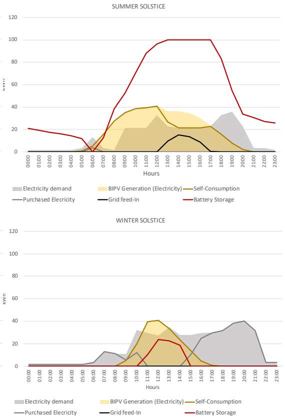
FINAL ENERGY

Building's Energy Demand	113558	kWh /yr
Total Energy Generation	156200	kWh /yr
Nominal Power of the BIPV installatior	31,6	kWp
Building's compactness index	1,1	
Building's Energy demand per m²	43	kWh/m² yr
Buildings Energy generation per m²	60	kWh/m² yr
Façade surface yield (per m² façade)	138	kWh/m² yr
No Battery Scenario		
Self-Sufficiency Rate	39%	
Self-Consumption Rate	28%	
Total Energy Export	112192	kWh
Energy economy to CP	49%	
Energy economy to BP	46%	
Battery Scenario		
Battery Size	110	kWh
Self-Sufficiency Rate	61%	
Self-Consumption Rate	48%	
Total Energy Export	80725	kWh
Energy economy to CP	72%	
Energy economy to BP	70%	
Total Self-Consumption Scenario		
Self-Sufficiency Rate	138%	
Self-Consumption Rate	73%	
Total Energy Export	42642	kWh
Energy economy to CP	100%	
Energy economy to BP	100%	

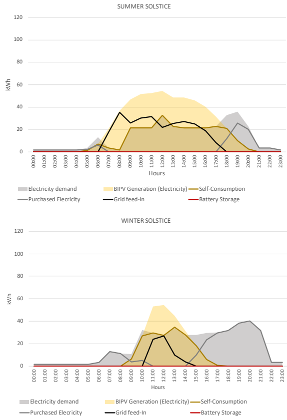
NO BATTERY



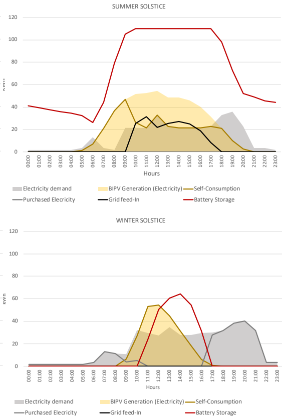
BATTERY



NO BATTERY



BATTERY



EMBODIED ENERGY EFFICIENCY

MARKET-READY

PRIMARY ENERGY

SIA 2040 Limit Values	30	9
BASE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	33,52	8,03
BP	24,52	5,54
AAF	35,20	8,38
BAPV ROOF SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	37,86	9,18
BP	28,86	6,70
AAF	39,54	9,54
BAPV FAÇADE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	44,94	11,02
BP	35,94	8,53
AAF	35,20	8,38

HIGH-PERFORMANCE

SIA 2040 Limit Values	30	9
BASE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	33,52	8,03
BP	24,52	5,54
AAF	32,45	8,08
BAPV ROOF SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	37,86	9,18
BP	28,86	6,70
AAF	36,79	9,23
BAPV FAÇADE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	42,19	10,71
BP	33,19	8,22
AAF	32,45	8,08

C O M B I N E D   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

PRIMARY ENERGY

Impact Payback Time	No Battery Scenario	
	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	1793249	469439
Annual Impact Savings	101620	4113
PBT (Years)	**17,6**	**114,1**

	Battery Scenario	
	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	1798029	470539
Annual Impact Savings	171459	6940
PBT (Years)	**10,5**	**67,8**

	Total Self-Consumption Scenario	
	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	1793249	469439
Annual Impact Savings	295217	11949
PBT (Years)	**6,1**	**39,3**

H I G H - P E R F O R M A N C E

PRIMARY ENERGY

Impact Payback Time	No Battery Scenario	
	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	1361451	421386
Annual Impact Savings	110900	4489
PBT (Years)	**12,3**	**93,9**

	Battery Scenario	
	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	1366709	422596
Annual Impact Savings	190196	7698
PBT (Years)	**7,2**	**54,9**

	Total Self-Consumption Scenario	
	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	1361451	421386
Annual Impact Savings	393623	15932
PBT (Years)	**3,5**	**26,4**

Anual environmental impact

Market-Ready

SIA 2040 Combined Limit Values	90	12
BASE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	165,45	13,37
BP	147,52	10,52
AAF	31,74	8,24
Battery impact per building ERA	1,83	0,42
AAF with Battery	33,57	8,66
BAPV ROOF SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	122,21	12,60
BP	104,28	9,75
AAF	-11,50	7,47
BAPV FAÇADE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	64,07	11,79
BP	46,15	8,94
AAF	31,74	8,24

High-Performance

SIA 2040 Combined Limit Values	90	12
BASE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	165,45	13,37
BP	147,52	10,52
AAF	-8,60	6,41
Battery impact per building ERA	2,01	0,46
AAF with Battery	-6,60	6,88
BAPV ROOF SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	122,21	12,60
BP	104,28	9,75
AAF	-51,84	5,65
BAPV FAÇADE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	23,72	9,96
BP	5,80	7,11
AAF	-8,60	6,41

E C O N O M I C   E F F I C I E N C Y

Life Cycle Cost (LCC)

Initial investment

	Façade initial Investment cost per m²	Totals
CP	311,90 CHF	351 828 CHF
BP	460,67 CHF	519 633 CHF
AAF	612,30 CHF	690 675 CHF

30-year investment period	LCC
CP	8 083 135 CHF
BP	8 243 185 CHF
AAF	7 916 956 CHF

Battery cost (subsidies included)	67 000,00 CHF	
Energy purchase reduction associated	83 938,53 CHF	*NPV formula over battery lifetime
Earnings (NPV)	16 131,94 CHF	

	Building construction cost per m²	Totals
CP	2 288 CHF	5 987 579 CHF
BP	2 358 CHF	6 172 165 CHF
AAF	2 430 CHF	6 360 311 CHF

30-year investment period	LCC
CP	8 083 135 CHF
BP	8 243 185 CHF
AAF	7 837 021 CHF

Battery cost (subsidies included)	73 500,00 CHF	
Energy purchase reduction associated	103 049,25 CHF	*NPV formula over battery lifetime
Earnings (NPV)	28 142,14 CHF	

Net Present Value (NPV)

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	3 451 837 CHF	4 834 520 CHF
CP + BAPV ROOF	3 942 218 CHF	5 319 466 CHF
BP	4 855 087 CHF	6 268 203 CHF
BP + BAPV ROOF	5 343 548 CHF	6 751 229 CHF
AAF	8 035 301 CHF	9 454 627 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	4 470 104 CHF	5 231 371 CHF
BP	4 927 431 CHF	5 705 453 CHF
AAF	6 404 133 CHF	7 185 574 CHF

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	3 451 837 CHF	4 834 520 CHF
CP + BAPV ROOF	3 934 751 CHF	5 311 999 CHF
BP	4 855 087 CHF	6 268 203 CHF
BP + BAPV ROOF	5 335 931 CHF	6 743 612 CHF
AAF	8 252 235 CHF	9 671 561 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	4 470 104 CHF	5 231 371 CHF
BP	4 927 431 CHF	5 705 453 CHF
AAF	6 477 430 CHF	7 258 871 CHF

Internal Rate of Return (IRR)

30-year investment period	**Unlevered IRR**	**Levered IRR**
CP	2,1%	5,8%
CP + BAPV ROOF	2,3%	6,3%
BP	2,6%	6,5%
BP + BAPV ROOF	2,8%	6,9%
AAF	3,7%	8,1%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	4,9%	11,2%
BP	5,2%	11,6%
AAF	6,3%	13,5%

30-year investment period	**Unlevered IRR**	**Levered IRR**
CP	2,1%	5,8%
CP + BAPV ROOF	2,3%	6,3%
BP	2,6%	6,5%
BP + BAPV ROOF	2,8%	6,8%
AAF	3,8%	8,2%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	4,9%	11,2%
BP	5,2%	11,6%
AAF	6,4%	13,6%

Discounted Payback (DPB)

DPB	Un-levered	Levered
CP	31	15
BP	29	15
AAF	24	13

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	7	1
AAF to BP	years to have higher cummulated revenue	2	7

DPB	Un-levered	Levered
CP	31	15
BP	29	15
AAF	24	13

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	7	1
AAF to BP	years to have higher cummulated revenue	2	7

Building scenario 4B

MR: translucent Polycrystalline 12%
HP: translucent Tandem-Perovskite 18%

O P E R A T I O N A L   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

Performance

FINAL ENERGY

Building's Energy Demand	120815	kWh /yr
Total Energy Generation	15963	kWh /yr
Nominal Power of the BIPV installatior	2,9	kWp
Building's compactness index	1,0	
Building's Energy demand per m²	42	kWh/m² yr
Buildings Energy generation per m²	6	kWh/m² yr
Façade surface yield (per m² façade)	65	kWh/m² yr

No Battery Scenario

Self-Sufficiency Rate	10%	
Self-Consumption Rate	72%	
Total Energy Export	4468	kWh
Energy economy to CP	19%	
Energy economy to BP	14%	

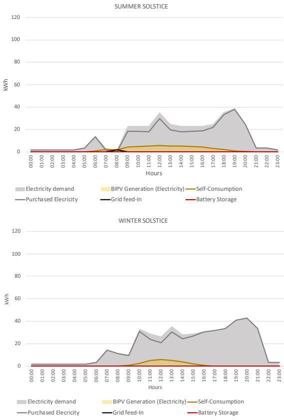
Battery Scenario

Battery Size	5	kWh
Self-Sufficiency Rate	11%	
Self-Consumption Rate	84%	
Total Energy Export	2578	kWh
Energy economy to CP	20%	
Energy economy to BP	16%	

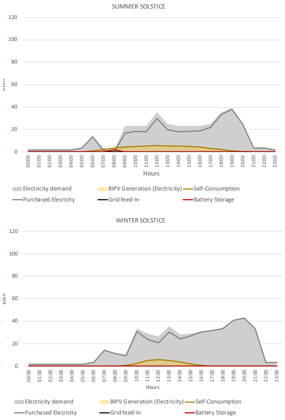
Total Self-Consumption Scenario

Self-Sufficiency Rate	13%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	22%	
Energy economy to BP	18%	

N O   B A T T E R Y



B A T T E R Y



H I G H - P E R F O R M A N C E

Performance

FINAL ENERGY

Building's Energy Demand	120815	kWh /yr
Total Energy Generation	24832	kWh /yr
Nominal Power of the BIPV installatior	4,4	kWp
Building's compactness index	1,0	
Building's Energy demand per m²	42	kWh/m² yr
Buildings Energy generation per m²	9	kWh/m² yr
Façade surface yield (per m² façade)	102	kWh/m² yr

No Battery Scenario

Self-Sufficiency Rate	14%	
Self-Consumption Rate	66%	
Total Energy Export	8450	kWh
Energy economy to CP	22%	
Energy economy to BP	18%	

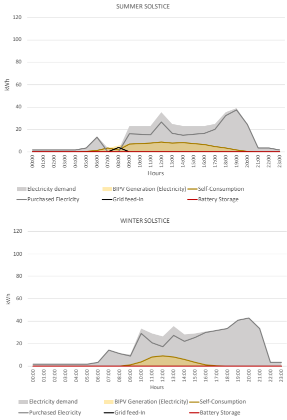
Battery Scenario

Battery Size	5	kWh
Self-Sufficiency Rate	15%	
Self-Consumption Rate	74%	
Total Energy Export	6451	kWh
Energy economy to CP	24%	
Energy economy to BP	20%	

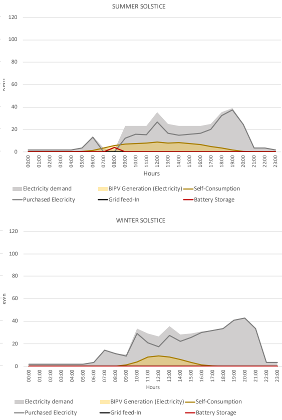
Total Self-Consumption Scenario

Self-Sufficiency Rate	21%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	29%	
Energy economy to BP	25%	

N O   B A T T E R Y



B A T T E R Y



E M B O D I E D   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

PRIMARY ENERGY

SIA 2040 Limit Values	30	9
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	30,55	7,22
BP	23,01	5,20
AAF	24,24	5,52
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	34,55	8,28
BP	27,01	6,27
AAF	28,23	6,59
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	31,12	7,37
BP	23,58	5,36
AAF	24,24	5,52

H I G H - P E R F O R M A N C E

SIA 2040 Limit Values	30	9
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	30,55	7,22
BP	23,01	5,20
AAF	24,19	5,52
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	34,55	8,28
BP	27,01	6,27
AAF	28,18	6,59
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	31,07	7,37
BP	23,53	5,36
AAF	24,19	5,52

C O M B I N E D   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

PRIMARY ENERGY

Impact Payback Time

No Battery Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	52393	13731
Annual Impact Savings	28970	1173
PBT (Years)	**1,8**	**11,7**

Battery Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	52632	13786
Annual Impact Savings	33731	1365
PBT (Years)	**1,6**	**10,1**

Total Self-Consumption Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	52393	13731
Annual Impact Savings	40228	1628
PBT (Years)	**1,3**	**8,4**

H I G H - P E R F O R M A N C E

PRIMARY ENERGY

Impact Payback Time

No Battery Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	44016	13687
Annual Impact Savings	41283	1671
PBT (Years)	**1,1**	**8,2**

Battery Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	44255	13742
Annual Impact Savings	46321	1875
PBT (Years)	**1,0**	**7,3**

Total Self-Consumption Scenario	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	44016	13687
Annual Impact Savings	62577	2533
PBT (Years)	**0,7**	**5,4**

Anual environmental impact

Market-Ready

	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
SIA 2040 Combined Limit Values	90	12
BASE SCENARIO		
CP	149,74	12,04
BP	135,92	9,77
AAF	117,16	9,28
Battery impact per building ERA	0,08	0,02
AAF with Battery	117,25	9,30
BAPV ROOF SCENARIO		
CP	106,15	11,18
BP	92,33	8,91
AAF	73,58	8,42
BAPV FAÇADE SCENARIO		
CP	136,16	11,62
BP	122,33	9,35
AAF	117,16	9,28

High-Performance

	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
SIA 2040 Combined Limit Values	90	12
BASE SCENARIO		
CP	149,74	12,04
BP	135,92	9,77
AAF	109,25	8,97
Battery impact per building ERA	0,08	0,02
AAF with Battery	109,34	8,98
BAPV ROOF SCENARIO		
CP	106,15	11,18
BP	92,33	8,91
AAF	65,67	8,11
BAPV FAÇADE SCENARIO		
CP	128,25	11,31
BP	114,43	9,03
AAF	109,25	8,97

E C O N O M I C   E F F I C I E N C Y

Life Cycle Cost (LCC)

Initial investment

	Façade initial Investment cost per m²	Totals
CP	311,90 CHF	325 940 CHF
BP	460,67 CHF	481 398 CHF
AAF	497,51 CHF	519 900 CHF

	Building construction cost per m²	Totals
CP	2 167 CHF	6 162 838 CHF
BP	2 228 CHF	6 333 842 CHF
AAF	2 242 CHF	6 376 194 CHF

Market-Ready

30-year investment period	LCC
CP	8 271 081 CHF
BP	8 428 010 CHF
AAF	8 368 444 CHF

Battery cost (subsidies included)	4 750,00 CHF	
Energy purchase reduction associated	5 722,98 CHF	*NPV formula over battery lifetime
Earnings (NPV)	926,65 CHF	

High-Performance

30-year investment period	LCC
CP	8 271 081 CHF
BP	8 428 010 CHF
AAF	8 334 063 CHF

Battery cost (subsidies included)	4 750,00 CHF	
Energy purchase reduction associated	6 055,70 CHF	*NPV formula over battery lifetime
Earnings (NPV)	1 243,53 CHF	

Net Present Value (NPV)

Market-Ready

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	6 495 260 CHF	7 906 837 CHF
CP + BAPV ROOF	6 985 529 CHF	8 391 672 CHF
BP	7 530 978 CHF	8 970 748 CHF
BP + BAPV ROOF	8 020 329 CHF	9 454 665 CHF
AAF	8 763 033 CHF	10 209 748 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	6 416 948 CHF	7 194 123 CHF
BP	6 729 059 CHF	7 521 756 CHF
AAF	7 267 046 CHF	8 063 567 CHF

High-Performance

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	6 495 260 CHF	7 906 837 CHF
CP + BAPV ROOF	6 985 529 CHF	8 391 672 CHF
BP	7 530 978 CHF	8 970 748 CHF
BP + BAPV ROOF	8 020 329 CHF	9 454 665 CHF
AAF	8 830 904 CHF	10 277 619 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	6 416 948 CHF	7 194 123 CHF
BP	6 729 059 CHF	7 521 756 CHF
AAF	7 317 246 CHF	8 113 767 CHF

Internal Rate of Return (IRR)

Market-Ready

30-year investment period	**Unlevered IRR**	**Levered IRR**
CP	3,3%	7,9%
CP + BAPV ROOF	3,5%	8,2%
BP	3,6%	8,1%
BP + BAPV ROOF	3,8%	8,5%
AAF	4,0%	8,6%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	6,4%	13,8%
BP	6,5%	13,9%
AAF	6,9%	14,4%

High-Performance

30-year investment period	**Unlevered IRR**	**Levered IRR**
CP	3,3%	7,9%
CP + BAPV ROOF	3,5%	8,2%
BP	3,6%	8,1%
BP + BAPV ROOF	3,8%	8,5%
AAF	4,0%	8,7%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	6,4%	13,8%
BP	6,5%	13,9%
AAF	7,0%	14,5%

Discounted Payback (DPB)

Market-Ready

DPB	Un-levered	Levered
CP	24	12
BP	24	12
AAF	23	12

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	12	4
AAF to BP	years to have higher cummulated revenue	6	12

High-Performance

DPB	Un-levered	Levered
CP	24	12
BP	24	12
AAF	23	12

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time	Un-levered	Levered
AAF to CP	11	3
AAF to BP	5	11

Building scenario 4C

MR: transparent Thin-Film 3%
HP: transparent Thin-Film 5%

O P E R A T I O N A L   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

Performance

FINAL ENERGY

Building's Energy Demand	119896	kWh /yr
Total Energy Generation	5356	kWh /yr
Nominal Power of the BIPV installatior	0,3	kWp
Building's compactness index	1,0	
Building's Energy demand per m²	42	kWh/m² yr
Buildings Energy generation per m²	2	kWh/m² yr
Façade surface yield (per m² façade)	51	kWh/m² yr
No Battery Scenario		
Self-Sufficiency Rate	4%	
Self-Consumption Rate	92%	
Total Energy Export	441	kWh
Energy economy to CP	17%	
Energy economy to BP	12%	
Battery Scenario		
Battery Size	0	kWh
Self-Sufficiency Rate	-	
Self-Consumption Rate	-	
Total Energy Export	-	kWh
Energy economy to CP	-	
Energy economy to BP	-	
Total Self-Consumption Scenario		
Self-Sufficiency Rate	4%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	17%	
Energy economy to BP	12%	

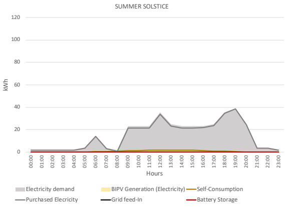
H I G H - P E R F O R M A N C E

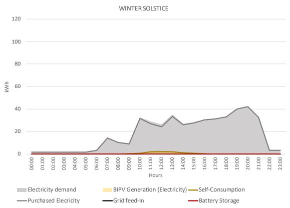
Performance

FINAL ENERGY

Building's Energy Demand	119896	kWh /yr
Total Energy Generation	8927	kWh /yr
Nominal Power of the BIPV installatior	0,5	kWp
Building's compactness index	1,0	
Building's Energy demand per m²	42	kWh/m² yr
Buildings Energy generation per m²	3	kWh/m² yr
Façade surface yield (per m² façade)	85	kWh/m² yr
No Battery Scenario		
Self-Sufficiency Rate	6%	
Self-Consumption Rate	81%	
Total Energy Export	1653	kWh
Energy economy to CP	19%	
Energy economy to BP	14%	
Battery Scenario		
Battery Size	0	kWh
Self-Sufficiency Rate	-	
Self-Consumption Rate	-	
Total Energy Export	-	kWh
Energy economy to CP	-	
Energy economy to BP	-	
Total Self-Consumption Scenario		
Self-Sufficiency Rate	7%	
Self-Consumption Rate	100%	
Total Energy Export	-	kWh
Energy economy to CP	20%	
Energy economy to BP	15%	

N O   B A T T E R Y





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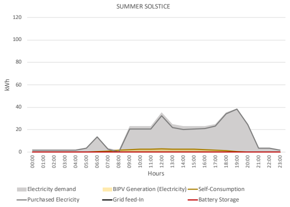
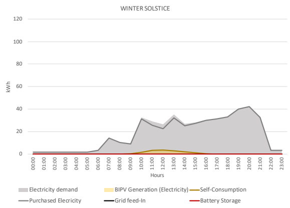




E M B O D I E D   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

PRIMARY ENERGY

SIA 2040 Limit Values	30	9
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	30,13	7,10
BP	22,80	5,15
AAF	23,78	5,40
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	34,13	8,17
BP	26,79	6,22
AAF	27,78	6,47
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	30,38	7,17
BP	23,04	5,22
AAF	23,78	5,40

H I G H - P E R F O R M A N C E

SIA 2040 Limit Values	30	9
BASE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	30,13	7,10
BP	22,80	5,15
AAF	23,78	5,40
BAPV ROOF SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	34,13	8,17
BP	26,79	6,22
AAF	27,77	6,47
BAPV FAÇADE SCENARIO	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	30,37	7,17
BP	23,04	5,22
AAF	23,78	5,40

C O M B I N E D   E N E R G Y   E F F I C I E N C Y

M A R K E T - R E A D Y

PRIMARY ENERGY

Impact Payback Time	**No Battery Scenario**	
	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	6219	1631
Annual Impact Savings	12386	501
PBT (Years)	**0,5**	**3,3**

	Total Self-Consumption Scenario	
	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	6219	1631
Annual Impact Savings	13497	546
PBT (Years)	**0,5**	**3,0**

H I G H - P E R F O R M A N C E

PRIMARY ENERGY

Impact Payback Time	**No Battery Scenario**	
	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	5199	1364
Annual Impact Savings	18329	742
PBT (Years)	**0,3**	**1,8**

	Total Self-Consumption Scenario	
	NRPE (kwh)	GWP (kg CO2 eq)
Total lifespan active elements impact	5199	1364
Annual Impact Savings	22495	911
PBT (Years)	**0,2**	**1,5**

Anual environmental impact

Market-Ready

SIA 2040 Combined Limit Values	90	12
BASE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	152,69	12,06
BP	138,32	9,83
AAF	125,30	9,51
Battery impact per building ERA	0,00	0,00
AAF with Battery	125,30	9,51
BAPV ROOF SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	109,11	11,20
BP	94,73	8,97
AAF	81,71	8,65
BAPV FAÇADE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	148,19	11,94
BP	133,81	9,71
AAF	125,30	9,51

High-Performance

SIA 2040 Combined Limit Values	90	12
BASE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	152,69	12,06
BP	138,32	9,83
AAF	122,13	9,38
Battery impact per building ERA	0,00	0,00
AAF with Battery	122,13	9,38
BAPV ROOF SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	109,11	11,20
BP	94,73	8,97
AAF	78,54	8,52
BAPV FAÇADE SCENARIO		
	NRPE (kwh/m² yr)	GWP (kg CO2 eq/m² yr)
CP	145,02	11,81
BP	130,64	9,58
AAF	122,13	9,38

E C O N O M I C   E F F I C I E N C Y

Life Cycle Cost (LCC)

Initial investment

	Façade initial Investment cost per m²	Totals
CP	311,90 CHF	259 816 CHF
BP	460,67 CHF	383 736 CHF
AAF	458,29 CHF	381 757 CHF

	Building construction cost per m²	Totals
CP	2 182 CHF	6 205 459 CHF
BP	2 230 CHF	6 341 771 CHF
AAF	2 230 CHF	6 339 595 CHF

Market-Ready

30-year investment period	LCC
CP	8 342 226 CHF
BP	8 454 121 CHF
AAF	8 364 511 CHF

Battery cost (subsidies included)	- CHF	
Energy purchase reduction associated	0,00 CHF	*NPV formula over battery lifetime
Earnings (NPV)	0,00 CHF	

High-Performance

30-year investment period	LCC
CP	8 342 226 CHF
BP	8 454 121 CHF
AAF	8 349 328 CHF

Battery cost (subsidies included)	- CHF	
Energy purchase reduction associated	0,00 CHF	*NPV formula over battery lifetime
Earnings (NPV)	0,00 CHF	

Net Present Value (NPV)

Market-Ready

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	5 614 014 CHF	7 032 618 CHF
CP + BAPV ROOF	6 105 351 CHF	7 518 520 CHF
BP	6 842 576 CHF	8 283 654 CHF
BP + BAPV ROOF	7 332 632 CHF	8 768 275 CHF
AAF	8 724 384 CHF	10 165 064 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	6 013 746 CHF	6 794 791 CHF
BP	6 432 649 CHF	7 226 066 CHF
AAF	7 248 835 CHF	8 042 033 CHF

High-Performance

30-year investment period	**Unlevered NPV**	**Levered NPV**
CP	5 614 014 CHF	7 032 618 CHF
CP + BAPV ROOF	6 105 351 CHF	7 518 520 CHF
BP	6 842 576 CHF	8 283 654 CHF
BP + BAPV ROOF	7 332 632 CHF	8 768 275 CHF
AAF	8 752 776 CHF	10 193 457 CHF
10-year investment period	**Unlevered NPV**	**Levered NPV**
CP	6 013 746 CHF	6 794 791 CHF
BP	6 432 649 CHF	7 226 066 CHF
AAF	7 271 030 CHF	8 064 228 CHF

Internal Rate of Return (IRR)

Market-Ready

30-year investment period	**Unlevered IRR**	**Levered IRR**
CP	3,0%	7,4%
CP + BAPV ROOF	3,2%	7,8%
BP	3,4%	7,8%
BP + BAPV ROOF	3,6%	8,2%
AAF	4,0%	8,6%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	6,1%	13,3%
BP	6,3%	13,6%
AAF	6,9%	14,5%

High-Performance

30-year investment period	**Unlevered IRR**	**Levered IRR**
CP	3,0%	7,4%
CP + BAPV ROOF	3,2%	7,8%
BP	3,4%	7,8%
BP + BAPV ROOF	3,6%	8,2%
AAF	4,0%	8,6%
10-year investment period	**Unlevered IRR**	**Levered IRR**
CP	6,1%	13,3%
BP	6,3%	13,6%
AAF	6,9%	14,5%

Discounted Payback (DPB)

Market-Ready

DPB	Un-levered	Levered
CP	26	13
BP	25	13
AAF	23	12

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time		Un-levered	Levered
AAF to CP	years to have higher cummulated revenue	8	0
AAF to BP	years to have higher cummulated revenue	0	8

High-Performance

DPB	Un-levered	Levered
CP	26	13
BP	25	13
AAF	23	12

*no significant differences between CP and BP with their correspondent BAPV roof vari

Comparative Payback time	Un-levered	Levered
AAF to CP	8	0
AAF to BP	0	8

A.6 Active Housing student competition

1st prize

12 L'ALCHIMISTE

DOS SANTOS | LORENZINI | MAHMOUDI | RICHTERICH

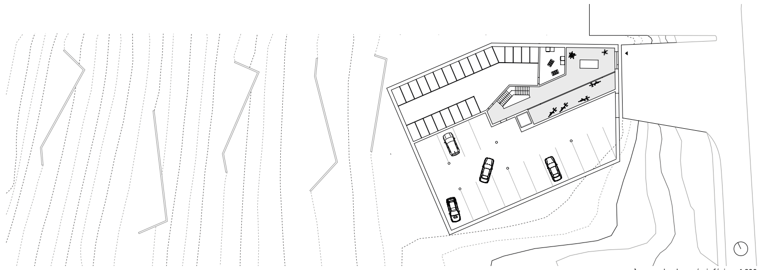
The integration of the project into the urban context is based on the desire to distinguish itself from the neighbouring villas by limiting its footprint. This clear architectural strategy concentrates all the building functions in a single monolithic building freeing enough ground space to design a public park.

The resulting volume is defined by its context and a geometric approach that considers the solar trajectory. Higher than its neighbouring villas, it relates to the large building scale of the EPFL campus.

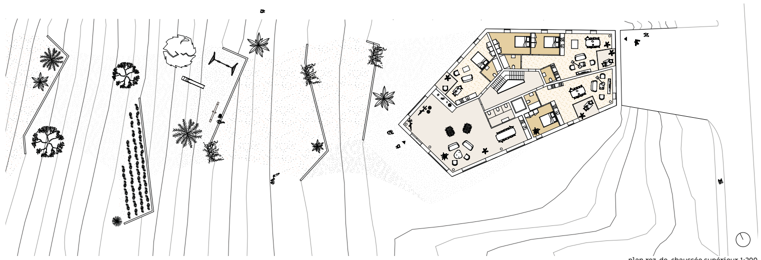
The façade morphologies – 3 active façades facing south, south-east and south-west and 2 non-active façades on the north side – incorporate loggias providing quality exterior spaces to the apartments whereas remaining consistent with the monolithic character of the building.

The jury praised the quality of the façades that highlight the material: the BIPV / dummy panels of two different dimensions that are arranged in the form of scales. BIPV panels are tilted to 80° improving its energy output and the façade's visual expression.

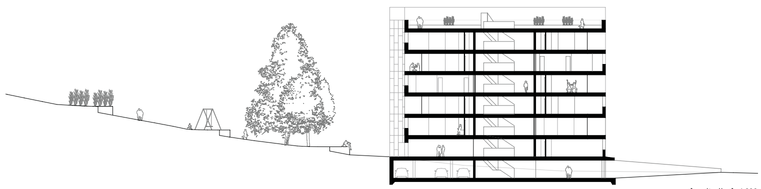
The façades emphasize the monolith composition: the basement, the main body of the building with six floors and the crowning with a winter garden. The AAF is incorporated into the main body of the buildings integrating widows and loggias with a remarkable façade unity [LAST 2019].



plan rez-de-chaussée inférieur 1:200



plan rez-de-chaussée supérieur 1:200

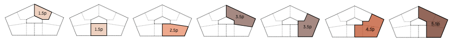


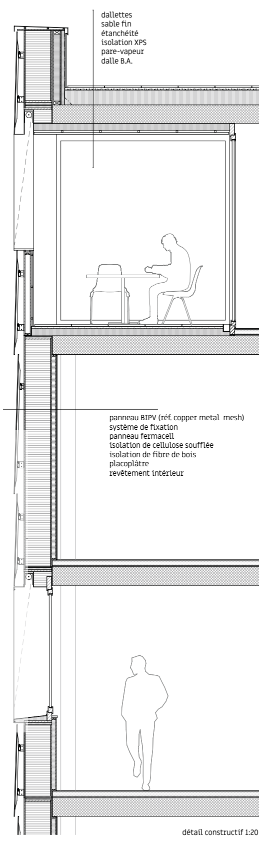
coupe longitudinale 1:200

LAST / Sustainable is beautiful
Sébastien Lorenzini, Gregory Dos Santos, Tobias Richtercih, Nordine Mahmoudi

plan type **B** 1:100

plan type **C** 1:100





détail constructif 1:20

tableau des surfaces

surface totale (SPD)	**2560 m²**
surface dédiée aux habitations (SPD)	**2072 m²**

plan type **A**: 2x3.5 pièces + 2x2.5
plan type **B**: 1x5.5 pièces + 2x1.5 pièces + 1x3 pièces
plan type **C**: 1x4.5 pièces + 1x2.5 pièces + 1x3.5 pièces + 1x1.5 pièces

variation typologique proposée

2x plan type A
2x plan type B →
2x plan type C

1.5 pièces = 6
2.5 pièces = 6
3.5 pièces = 7*
4.5 pièces = 2
5.5 pièces = 2

total 2072m²

** 8 normalement, mais suite à la suppression d'un 3.5 pièces au rez-de-chaussée supérieur pour la création de l'espace commun il en reste 7.*

LAST / Sustainable is beautiful
Sébastien Lorenzini, Gregory Dos Santos, Tobias Richtercih, Nordine Mahmoudi

2nd prize ex-aequo

11 LE CUBARRE D'ECUBLENS

JUNGEN | PENGG | STOSIK

Project number 11 is a building composed of two volumes. At the head of the plot is a five-storey building that aims to create a dialogue with the buildings of the EPFL campus. In the upstream portion of the plot, well integrated with the slope, the low-lying volume of reduced height develops a community space on the roof. This big roof is designed with vegetable gardens and common areas. The housing offers a great variety of typologies with numerous apartments in a duplex with double height living rooms.

The integration of the AAF incorporates active surfaces on the solar-oriented façades meeting the specific requirements of the competition.

Despite these multiple assets, the jury remains reserved on several points, in particular the scale of the building - which seems slightly disproportionate compared to the context despite the relatively low density of the project - and the lack of overall efficiency of the building induced between others by the repetition of the passageways [LAST 2019].

Le Cubarre d'Ecublens

Matthias Pengg, Samy Stosik, Loris Jungen

Forme urbaine

Faisant d'un coté face au campus de l'EPFL, plus particulièrement aux bâtiments du SG, de l'atrium, et du Swiss Tech Convention Center et à l'avenue du Tir-fédéral, et côtoyant d'autre part un paisible quartier de villas, la forme urbaine du *Cubarre* se veut intégrée à la pente et dialoguant avec ces deux contextes radicalement opposés. En effet, il présente une partie haute de cinq niveaux en tête de parcelle ainsi qu'une partie longitudinale s'enfonçant dans la pente et offrant sur sa toiture un espace communautaire de potager et de loisir. De part son intégration, ce bâtiment ne dispose que de peu de parties enterrées, ceci afin de minimiser l'impact sur le terrain et de s'affranchir d'un terrassement massif.

Coursives

L'entier du bâtiment se voit desservi par une unique et généreuse cage d'escalier extérieure, disposant d'un puit de lumière et offrant un parcours architectural avec différentes vues sur le contexte rural du nord de la parcelle. Les coursives se prolongent à partir de ce noyau distributif et permettent l'accès aux appartements de la barre tout en s'insérant dans la pente à leurs extrémités.

Duplex

Les doubles hauteurs conçues dans les séjours du tiers des appartements du projet offrent aux habitants une qualité spatiale toute particulière de par un volume et une lumière naturelle privilégiés. Cette typologie ne compose cependant pas l'entièreté du projet mais apporte une diversification des types de logement dans le projet.

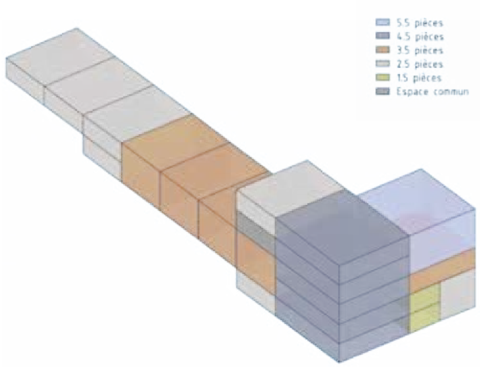
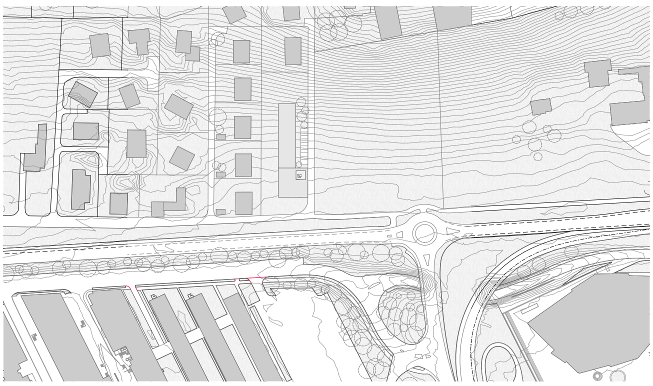
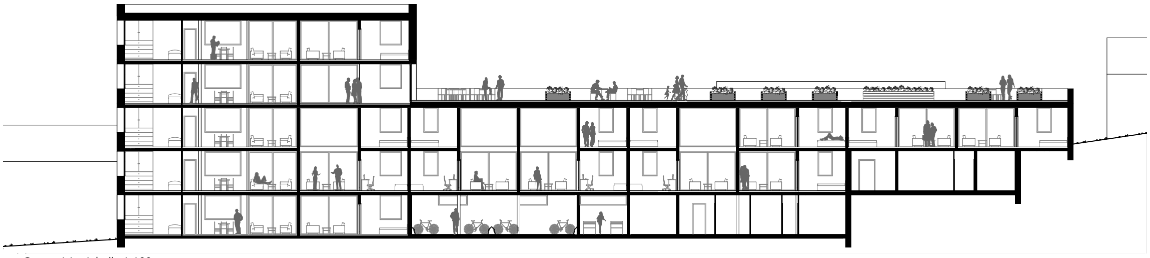


Schéma de mixité

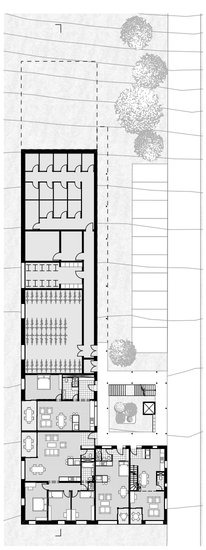
Vue du haut du terrain



Plan de situation - échelle 1:1000

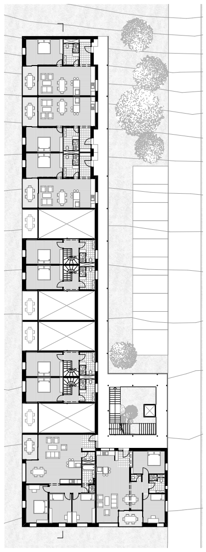


Coupe AA - échelle 1:100

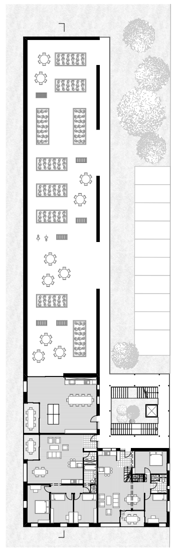


Plan RDC - échelle 1:200

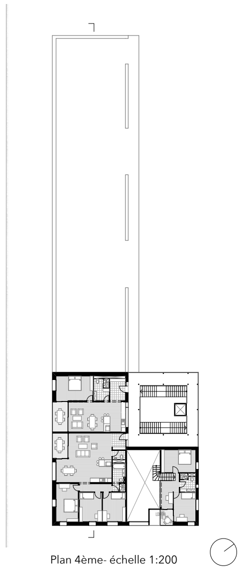
Plan 1er- échelle 1:200



Plan 2ème - échelle 1:200



Plan 3ème - échelle 1:200



Plan 4ème- échelle 1:200

Vue depuis l'avenue du Tir-Fédéral

Typologie duplex 5,5 pièces - échelle 1:100

Typologie duplex 3,5 pièces - échelle 1:100

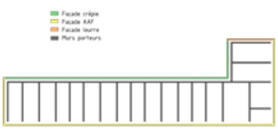


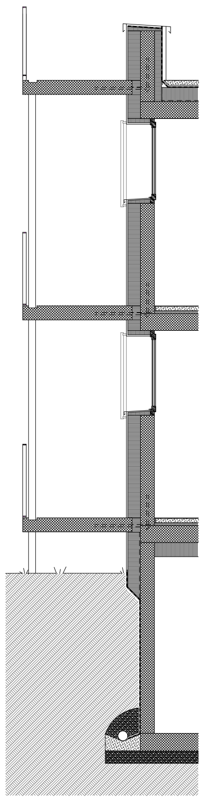
Schéma porteur et AAF

Surface de planche déterminante (SPd) : 2'081 m2

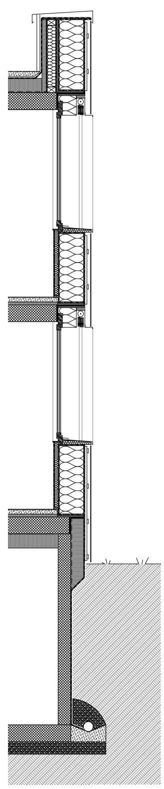
Indice d'utilisation du sol (IUS) : 0,61

Type	Surface hab. nette	Nombre	Total	% du total
1,5 pièces	42 m2	2	2	10%
2,5 pièces duplex	65 m2	1		
2,5 pièces	60 m2	6	7	35%
3,5 pièces duplex	83 m2	4		
3,5 pièces	81 m2	1	5	25%
4,5 pièces	104 m2	5	5	25%
5,5 pièces duplex	126 m2	1	1	5%
		Nbr total appartements :	20	dont 6 duplexs (30%)

Tableau de surfaces



Façade nord crépie - échelle 1:20



Façade sud AAF - échelle 1:20

2nd prize ex-aequo

17 CHRYSALIDE

MULARD | MÜTZENBERG

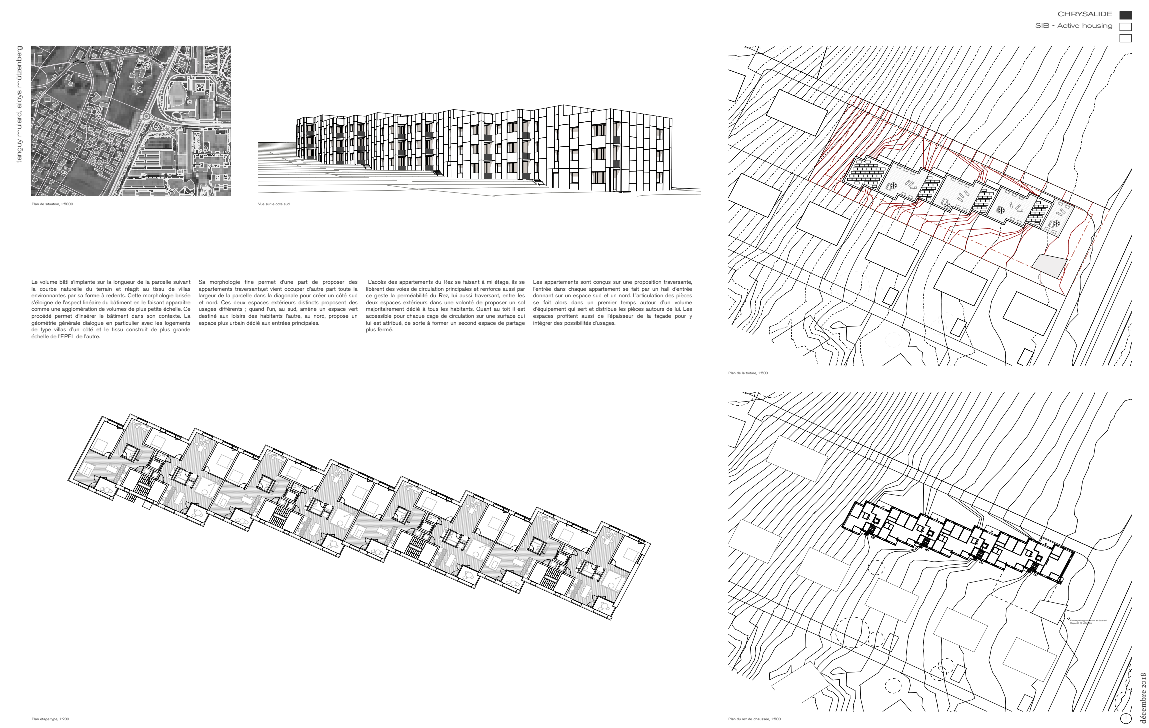
Among the candidates having explored the theme of an elongated building volume as a *bar,* Project number 17 proposes an original and adequate approach. The volume is fractioned with a rhythm consistent with that of the natural terrain, favouring the integration of the project in the irregular slope. The fractioned volume also contributes to the contextualization of the building by providing a smaller scale that dialogues with the surrounding urban fabric.

The jury emphasizes the quality of the apartment typologies and the optimal orientation of their exterior spaces designed as loggias. These loggias allow a spatially interesting link between the living area and the kitchen.

At the ground floor level, a traversing space ensures both the permeability of the building and the continuity between the outdoor spaces defined on either side of the building volume. Each entrance is also accompanied by an exterior hall, set in the natural slope, which reinforces the feeling of *address* and the potential for appropriation by the inhabitants.

This project integrates the AAF in all four façades with different BIPV panel formats as façade cladding.

The jury questions the adequacy of the diagonal inclination of the urban form, the meaning of which seems counterintuitive to the morphological qualities of the site and generates residual external spaces. It is also noted that the location of the vertical circulation cores on the south facade is not very judicious [LAST 2019].



CHRYSALIDE

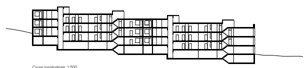
SIB - Active housing

tanguy mulard, aloys mützenberg

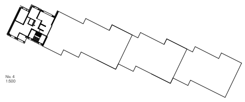
Façade Nord-Est, 1:200

Façade Sud-Est, 1:200

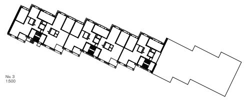
Façade Sud-Ouest, 1:200



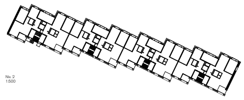
Coupe longitudinale, 1:500



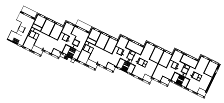
Niv. 4
1:500



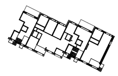
Niv. 3
1:500



Niv. 2
1:500



Niv. 1
1:500



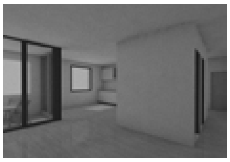
Niv. 0
1:500

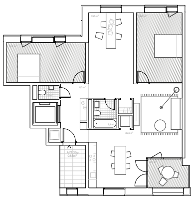
décembre 2018

CHRYSALIDE

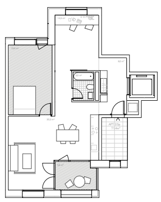
SIB - Active housing

tanguy mulard, aloys mützenberg

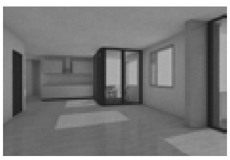


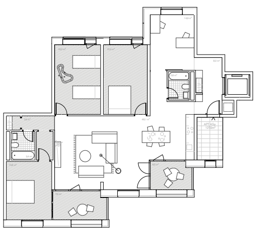


Appartement 3,5p 1:100

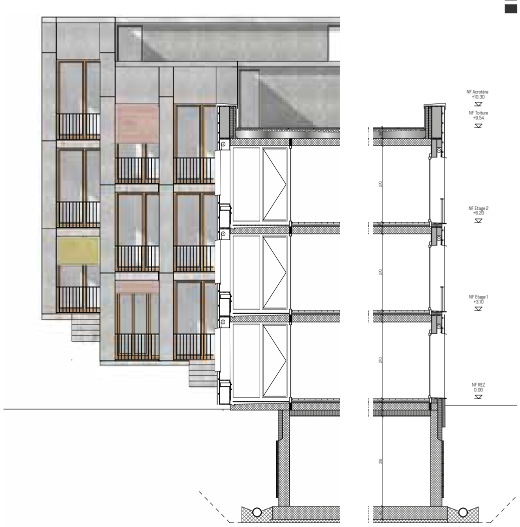


Appartement 2,5p 1:100





Appartement 4,5p 1:100



Appartement 4,5p 1:100

décembre 2018

2nd prize ex-aequo and special prize: Ville d'Ecublens

18 LA-HAUT

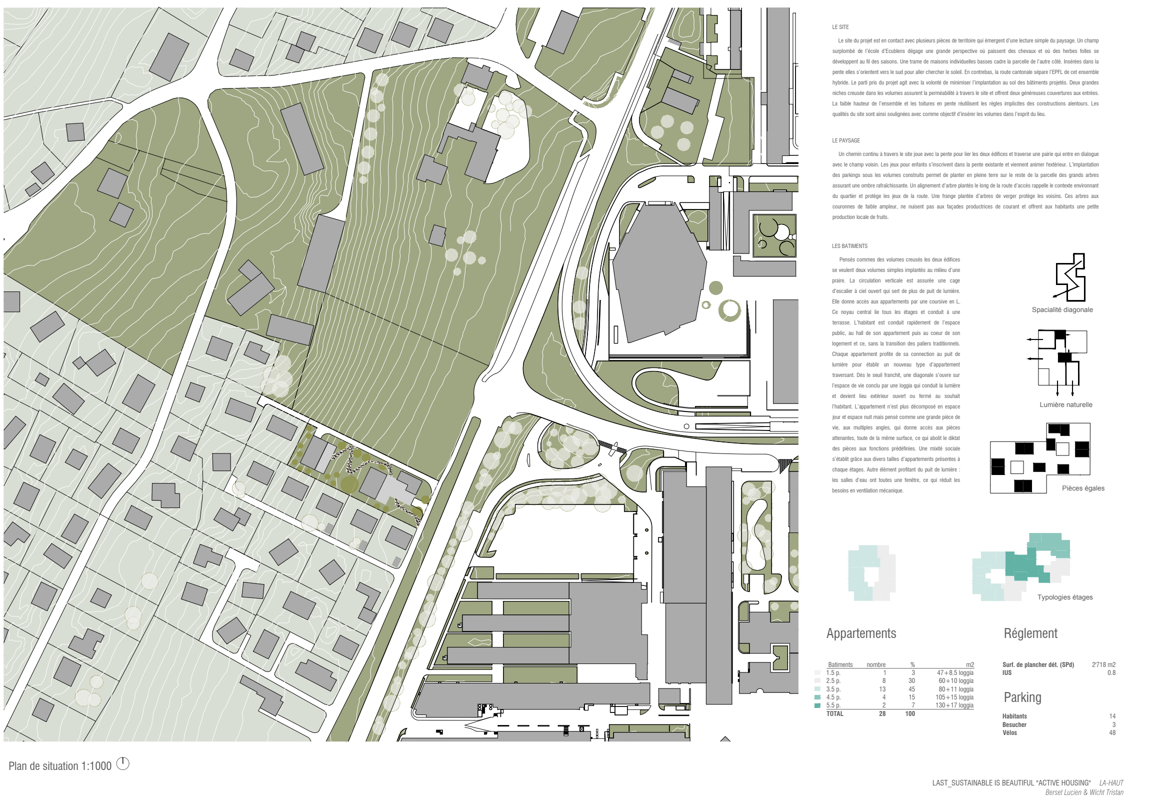
BERSET | WICHT

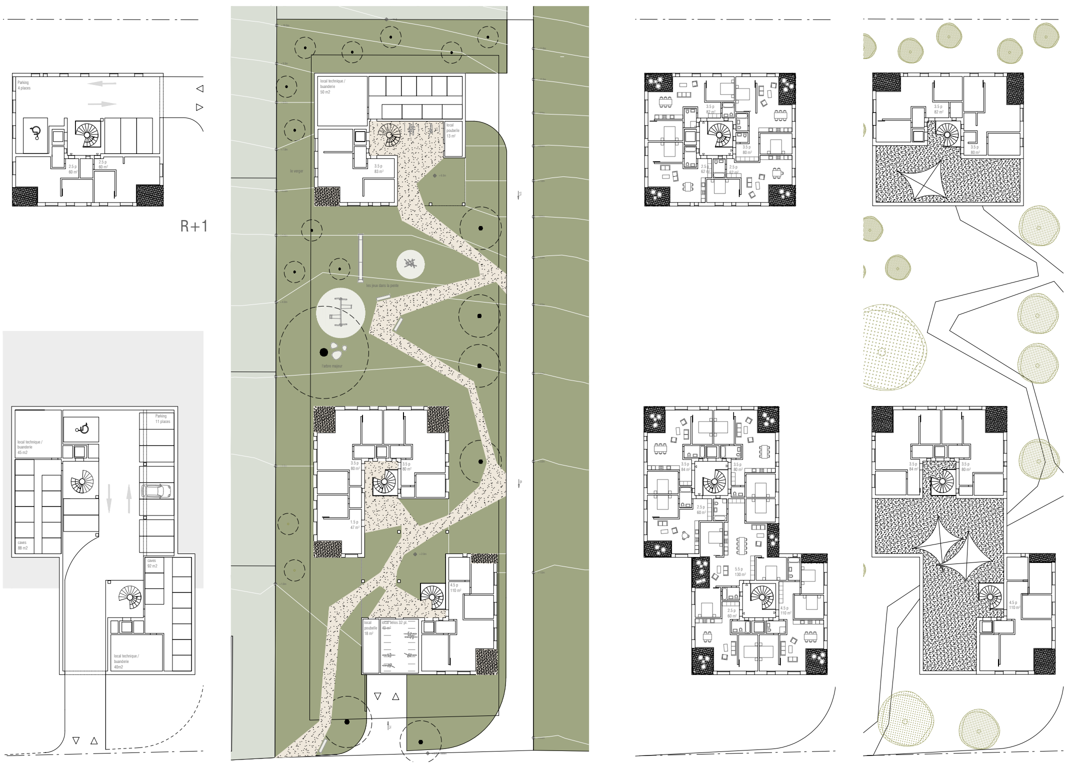
This project proposes a reinterpretation of the *urban villa* by the arrangement of two volumes in the middle of the plot. The design of these two buildings is inspired by the surrounding individual houses – sloped roof and low height – and fit neatly into the natural terrain. The implementation aims not only to minimize the footprint but also to offer quality densification of the plot.

Two large hollow recesses signal the entrances whereas ensuring the permeability of the buildings. Vertical circulation is through *cold* stairwells, benefiting from natural light and ventilation. These distribution cores give access to different apartments and collective roofs. The jury praises the work on housing typologies, which guarantees the quality of life of the inhabitants despite the relatively high density built.

The two volumes are dressed by BIPV and dummy panels according to the orientation of the facade concerned and to the study of the façade composition. The latter incorporates BIPV modules of 285 cm x 60 cm which seems consistent with the characteristics of the AAF constructive system.

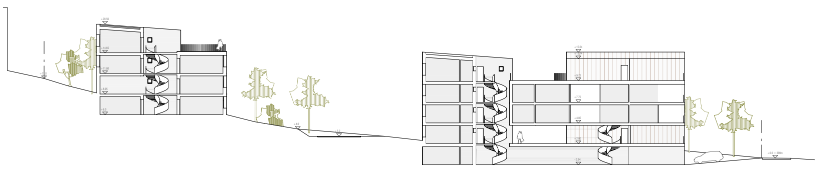
After deliberation, this project is decided to be awarded the *Special Prize City of Ecublens* due to the above-mentioned qualities and because it sketches an urban densification strategy for the site that is less disconcerting for the neighbourhood than the other projects [LAST 2019].





Plan de situation 1:200 R+1 Rdc étage type Terrasse

LAST_SUSTAINABLE IS BEAUTIFUL "ACTIVE HOUSING" *LA-HAUT*
Berset Lucien & Wicht Tristan



Coupe 1:200

façade 1:200

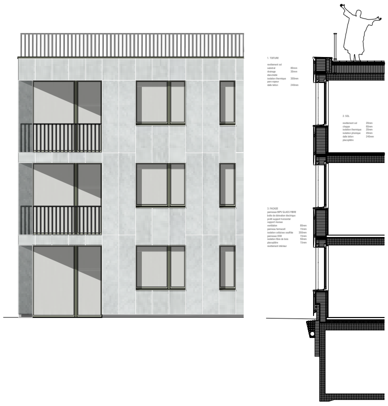
Vue intérieure 5.5p

LA TECHNIQUE

Dans ce projet, le système BIPV est interprété comme une contrainte de façade. Le volume construit s'habille entièrement des panneaux en verre fibré. Légèrement transparents ils laissent apercevoir la technologie qu'ils contiennent et interpellent les habitants. Les parties productrices de cette façade se placent d'elles-même en fonction du rayonnement optimal le reste est recouvert de dummies non productifs. L'intérieur des cages d'escalier et des loggia accueillent elles aussi ce revêtement pour assurer une homogénéité globale, mais aussi pour mettre en lumière, jusqu'au coeur des appartements, ce système innovateur. Le choix d'un module de panneau de 285cm sur 60cm permet un jeu d'ouvertures simples entre les étages.

LES HABITANTS

Dans le projet Là-Haut, l'habitant est mis en contact direct avec un système questionnant le rôle de l'architecture. Intrinsèquement, plus un élément remplit de fonctions plus il est durable. Le rôle de la façade n'est plus uniquement de protéger de l'extérieur ou de représenter son maître d'ouvrage. Le projet essaie de répondre à cette dualité et de proposer quelque-chose en plus à ses occupants ; que ce soit dans l'espace le plus privé de la chambre qui est ouverte à recevoir une grande diversité de fonctions ; dans les pièces de vies, baignées de lumière ; dans un bâtiment innovant pourtant placé au milieu d'une prairie. L'escalier en colimaçon qui mène là-haut devient le coeur de l'habitat nouveau proposé et prolonge l'espace extérieur de chacun jusqu'au sommet des bâtiments.



détail 1:50

Vue extérieure

LAST_SUSTAINABLE IS BEAUTIFUL "ACTIVE HOUSING" *LA-HAUT*
Berset Lucien & Wicht Tristan

10. List of figures and tables

All figures and tables are created by the author unless specified otherwise

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Chapter 5: Quantitative assessment

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Chapter 6: Transfer potential towards architectural practice

FIGURES

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11. Curriculum Vitae

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15.02.1988

EDUCATION

2015-2019	**DOCTORATE OF SCIENCE** Ecole Polytechnique Fédérale de Lausanne (EPFL) Doctoral program: Architecture et sciences de la ville	Lausanne (Switzerland)
2006-2012	**MASTER OF SCIENCE (MSc) and POST-GRADUATE DIPLOMA** Universidad de Navarra School of architecture (ETSAUN) Graduated with honors	Pamplona (Spain)
2010-2012	**MASTER IN LANDSCAPE AND NATURAL ENVIRONMENT** Universidad de Navarra School of architecture (ETSAUN)	Pamplona (Spain)

PROFESSIONAL EXPERIENCE

2015-2019	**Laboratory of Architecture and Sustainable technologies (LAST)** Ecole Polytechnique Fédérale de Lausanne (EPFL) Doctoral-assistant – teaching and research	Lausanne, (Switzerland)
2012-2015	**Richter and Dahl Rocha architectes et associés** Architect, design and construction	Lausanne (Switzerland)
2011-2012	**Francisco Mangado y asociados** Intern, design and architecture competitions	Pamplona (Spain)
2008-2012	**Departamento de elementos** Universidad de Navarra Teacher assistant, Architecture projects department	Pamplona (Spain)
2011 (summer)	**Richter and Dahl Rocha architectes et associés** Intern, design and architecture competitions	Lausanne (Switzerland)
2010 (summer)	**Machado, Silvetti & Associates** Intern, design and construction	Boston (USA)
2009 (summer)	**CLC Arquitectos** Intern, design and construction	Zaragoza (Spain)

ACADEMIC AWARDS

2015 **MASTER THESIS PROJECT_COMPETITION**
Asemas_Finalist

2013 **MASTER THESIS PROJECT _NATIONAL SELECTION**
Spanish biennial_Featured awarded project

2012 **GUARDIAN GLASS SCHOLARSHIP**
Scholarship to attend the *Arquitectura y Sociedad* foundation congress

2011 **INVITATION TO INTERNATIONAL ARCHITECTURE WORKSHOP "MESA"**
National selection

2010 **GLOBAL INTERNSHIP SCHOLARSHIP**
Scholarship to travel abroad and work at an architecture office as an intern

PUBLICATIONS

Conference papers

2019 Itten, R., Stucki, M., Clúa Longás, A., Cattaneo, G., 2019. *Active Façades: Life Cycle Environmental Impacts and Savings of Photovoltaic Power Plants Integrated into the Building Envelope.* Presented at the EU PVSEC 2019, Marseille.

2018 Clúa Longás, A., Lufkin, S., Rey, E., 2018. *Advanced Active Façades: The construction of a full-scale demonstrator for BIPV architectural integration.* Presented at the PLEA 2018, Hong Kong.

2017 Clúa Longás, A., Lufkin, S., Rey, E., 2017. *Towards Advanced Active Façades: Analysis of façade requirements and development of an innovative construction system*. Presented at the PLEA 2017, Edinburgh.

2017 Clúa Longás, A., Lufkin, S., Rey, E., 2017. *Towards Advanced Active Façades. The development and assessment of a new façade concept, which combines passive and active design strategies*. Presented at SDBE 2017, London.

2016 Clúa Longás, A., Lufkin, S., Rey, E., 2016. *Towards a new prospective basis for the design strategies of Active Façades. A research methodology to create guidelines for photovoltaic integration*. Presented at the PLEA 2016, Los Angeles.

Posters

2017 Clúa Longás, A., Lufkin, S., Rey, E., 2017. *Introducing the Advanced Active Façade: Towards near-zero energy buildings, incorporating BIPV expressive issues.* Presented at PVSEC 2017, Amsterdam.

2017 Clúa Longás, A., Lufkin, S., Rey, E., 2017. *Architectural integration of low-carbon technology and Building Integrated Photovoltaics (BIPV): Into the design process of Advanced Active Façades.* Presented at PVTAGUN 2017, Lausanne.

Other papers

2019 Rey, E., Clúa Longás, A., Lufkin, S., 2019. *Un démonstrateur de façade active bas carbone*. Fassade Façade 01–2019, 47–53.

2017 Clúa Longás, A., Lufkin, S., Rey, E., 2017. *Concevoir des façades actives bas carbone*. TRACÉS , cahier spécial, 23–24, 20–22.