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Towards Advanced Active Façades. The development and assessment of a new façade concept, which combines passive and active design strategies.

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Abstract: In Switzerland, as in many European countries, new energy directives focus on decreasing the carbon footprint of buildings by promoting passive and active energy strategies and systems. Among the latter, Building Integrated Photovoltaics (BIPV), which function both as envelope materials and electricity producers, are rapidly improving their performance. However, their potential remains largely unrealised due to diverse barriers. Among them, the poor expressive qualities of many BIPV products are preventing architects from using these systems. In reaction, and with the goal of bridging the gap between technology and designers, a new façade concept has been developed integrating BIPV expressive issues. This is the Advanced Active Façade (AAF) concept, which results from analysing the evolution of façade requirements and solutions over time. The AAF combines passive and active façade design strategies. This is to say; it simultaneously aims to achieve low embodied energy by benefiting from passive low-carbon design strategies, and to generate energy by integrating BIPV technology. The AAF construction system is the direct application of the AAF concept to construction practice. It is a wood-based, self-supporting and demountable façade system, which meets the most exigent insulating targets and is compatible with a wide range of existing BIPV formats and emerging technologies. The development of this system is paired with a series of design strategies which present a variety of scenarios where the AAF concept can be applied. In addition, his concept is assessed regarding its environmental impact, cost and architectural quality.

The AAF construction system and design strategies have provided the basis for realizing a real scale active prototype. Ultimately, the output of the research will provide architects with a system and assessed design strategies to optimize design process of BIPV façades, meeting the new energy directives performance standards.

Keywords: Building Integrated Photovoltaics, Low-carbon façades, Design Strategies, Energy efficiency

Research overview

The European Union is committed to drastically reduce greenhouse gas emissions by 2050: levels should be 80-95% lower when compared to 1990 (Energy Roadmap 2050, 2012). This is why European energy directives are becoming more demanding with regards to performance standards. Switzerland follows the same evolution. Since it decided to gradually withdraw from nuclear power in 2011 (SFOE, 2014), the country undergoes a profound restructuring of its energy system. Its new energy policy establishes that energy consumption from photovoltaic (PV) will represent 20% of the total electricity consumption of the country. Thanks to this energy focus, such technology is becoming more efficient and affordable.

The most innovative offer of PV technology consists in the constructive and architectural integration of PV elements. This technology is named Building Integrated Photovoltaics (BIPV) and have both an architectural function and energy generation capacity.

BIPV permits to reduce material use and initial investment costs when compared to a traditional construction where PV systems are independent and added to the building (Centre Suisse de compétence BIPV, 2015). However, despite this favourable context, BIPV technology is not exploited to the best of its potential. Architects often justify the lack of PV use in their designs with the limited aesthetics of existing BIPV solutions. As a result, a real gap between technology and architecture exists. This evidences that further research is needed in order to bridge this gap between technology and designers.

Targeting bridging this gap, a new facade concept has been developed in order to approach architects to BIPV technology and energy efficiency concepts. This façade is called Advanced Active Façade (AAF) due to the combination of passive and active energy design strategies. The concept is materialized in façade construction system and the correspondent facade design strategies, which can be assessed easily with methods and a language that architects can easily understand. The development of the AAF narrows the gap between technology and designers due to the use of architectural language for communication and a solid assessment, not only based on energy performance but also architectural quality, environmental and economic impact of the facade.

Research approach

In order to deal simultaneously architectural, construction and technological issues, the research approaches the subject based on a reinforced collaboration of product developers, architects and scientist. To fill in the gap between these agents, new design strategies are developed for the composition and construction of active façades.

The work developed in this research focuses on collective residential buildings in the Swiss context. This target is a consequence of a preliminary analysis of BIPV buildings' state of the art world wide (Clua Longas et al., 2015). This analysis showed a scarcity of dwellings among the best-practice selection, which is mainly due to the high cost and lack of knowledge of developers and architects (Farkas and Horvat, 2012). This research will enable architects and the general public to deepen in BIPV façade composition and construction knowledge, as well as motivate them to integrate BIPV in their designs.

The approach of the research is based on the analysis of different factors that affect BIPV façades. These preliminary analyses set a common ground to the already mentioned product developers, architects and scientist, which permits a more efficient collaboration to the development of the AAF concept. The outcome of these preliminary analysis enables the application of the theory to the practice by architectural design. Once there is an architectural product output that can be assessed, different criteria will be evaluated. The criteria will assess architectural features as well as energy performance values. In a fourth step, a real scale prototype has been constructed in order to test and verify different aspects of the façade concept. The presentation of the prototype in a national architecture forum has also introduced the last step: the knowledge transfer phase. This last phase consists mainly in a student competition, which permits testing how architects use and appropriate the design strategies and architecture concepts developed on the research process. Figure 1 shows a schematic research methodology to illustrate the research approach.

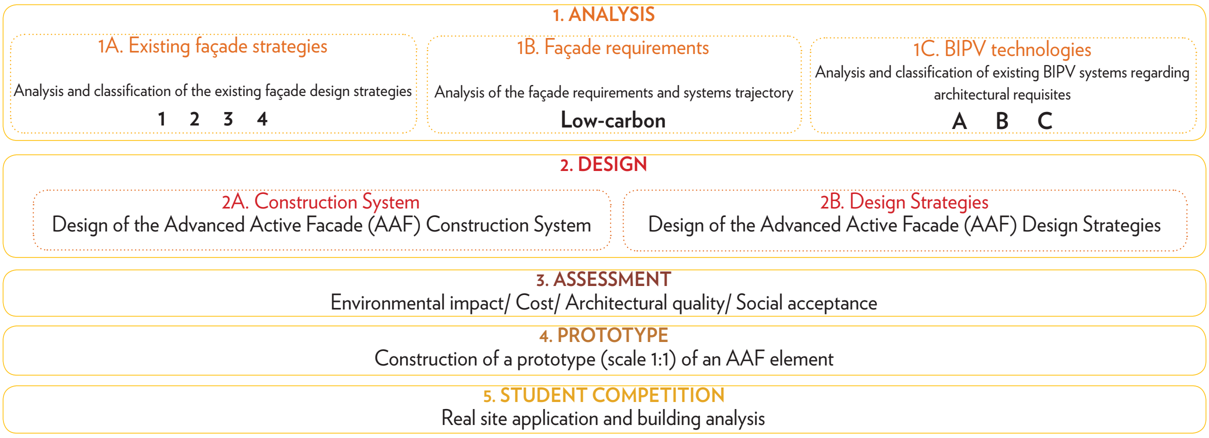

Figure 1. Research methodology in five phases

Research outcome

Following the methodology explained above, the preliminary results of the research can be classified according to the different research phases.

Analysis

The Advanced Active Façade concept is based in three analyses. The first one refers to the Swiss residential building common practice façade composition. Different elements take part in the façade composition process: building's structure, windows, balconies, doors, etc. (Herzog et al., 2004). These element's dimensions determine the subjacent grid or rhythm of the façade composition. The first phase of the research consists in analysing and classifying the existing façade design strategies.

The output of this first phase manifested that existing façade design strategies can be classified: four categories have been the outcome of the analysis (figure 2).

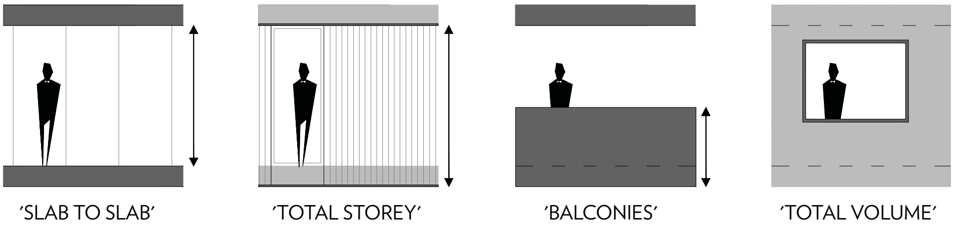

Figure 2. Collective residential buildings' façade design strategies: classification in four groups

The 'Slab to Slab' strategy includes façades were the horizontal structure of the building is apparent and the dimension of the horizontal slab is highlighted on the façade. The 'Total Storey' group gathers façade designs where the building horizontal structure is also expressed, but the resulting dimension is that of the whole storey, which does not show the horizontal slab. The third strategy, 'Balconies', refers to façades where balconies are clearly apparent in a large part of a façade. The consequence is that the balcony dimension predominates in the façade composition. Finally, the 'Total Volume' group includes façades where the structure rhythm and the interior distribution are not apparent. Many buildings present a combination of these four strategies in the same façade or in different ones.

This classification is both useful for architects and product developers. The former can identify easily different façade elements with different dimensions. Then, architects can evaluate which of those will be active and which will not, depending on different energy strategies explained in the ‘Assessment section’. Product developers can find in this classification different dimensions with standardization potential, which will decrease BIPV production costs.

The second analysis carried out on this research refers to the evolution and trajectory of the façade requirements and the solution systems developed to meet those requirements. In the beginning, wood and stone huts façades only needed to protect from the environment. Currently and in the near future, façades need to lower the building’s final energy consumption, they will be required to have a very low embodied energy and to generate energy. These three requirements have find different solutions in façade construction, but there is not yet a widespread façade system that meets all three requirements. This is mainly due to the different professionals and specialist that deal with passive and active energy strategies.

Finally, a third analysis classifies the existing BIPV systems. There is a growing number of different PV technologies as research is rapidly pushing forward this field (Jelle et al., 2012). And BIPV systems have been already classified in many different ways. The originality of our approach is that BIPV façade systems are classified according to its architectural features given that they play an important role as an integral part of the façade (Roberts and Guariento, 2009). Therefore, existing systems have been classified, based on their transparency degree, in three groups (Clua Longas et al., 2017): Opaque, Translucent and Transparent. Different technologies such as monocrystalline, polycrystalline or thin-film can fit in one or more of these categories, depending on their disposition on the BIPV module. This classification is open and welcomes the newest high efficiency modules such as heterojunction technologies, which combines two layers of different crystalline semiconductors, or organic cells, among others.

Design

The previous analyses set the basis for the development of the Advanced Active Façade (AAF) concept, which combines active and passive energy design strategies. It consists on an active BIPV façade, which is combined with highly insulated low-embodied carbon construction. This approach respond to the existing design strategies at the façade composition level, it also meets the latest façade requirements analysed and welcomes a large variety of BIPV systems. The AAF is a concept that can lead to design Nearly Zero Energy Buildings (NZEB) when combined with other passive and active energy building strategies, regarding building services and structure design.

The AAF is designed as a non-structural, self-supporting façade, which guarantees more flexibility in the façade composition compared to other loadbearing options. Based on this concept, the AAF Construction System and the AAF Design Strategies have been developed.

Advanced Active Façade Construction System

The AAF Construction System is the materialisation of the AAF Concept (figure 3). Hence it has a very low thermal transmittance value, follows low-carbon construction principles and integrates BIPV.

In the Swiss context, the most exigent normative regarding building’s insulation is Minergie P. The AAF construction system, with a total of 400 milimeters of two different insulators in two different layers, achieves a 0.1 W/(m^{2}K) thermal transmittance value, which meets also Passive House standards.

The embodied carbon of a building accounts approximately for 30% of the total lifetime carbon footprint from the residential building sector (Lane, 2010). More specifically, façades are responsible for around 16% of the embodied carbon of a building (Cheung and Farnetani, 2015). For this reason, a low-carbon façade construction system can make a significant difference in a building's total carbon footprint.

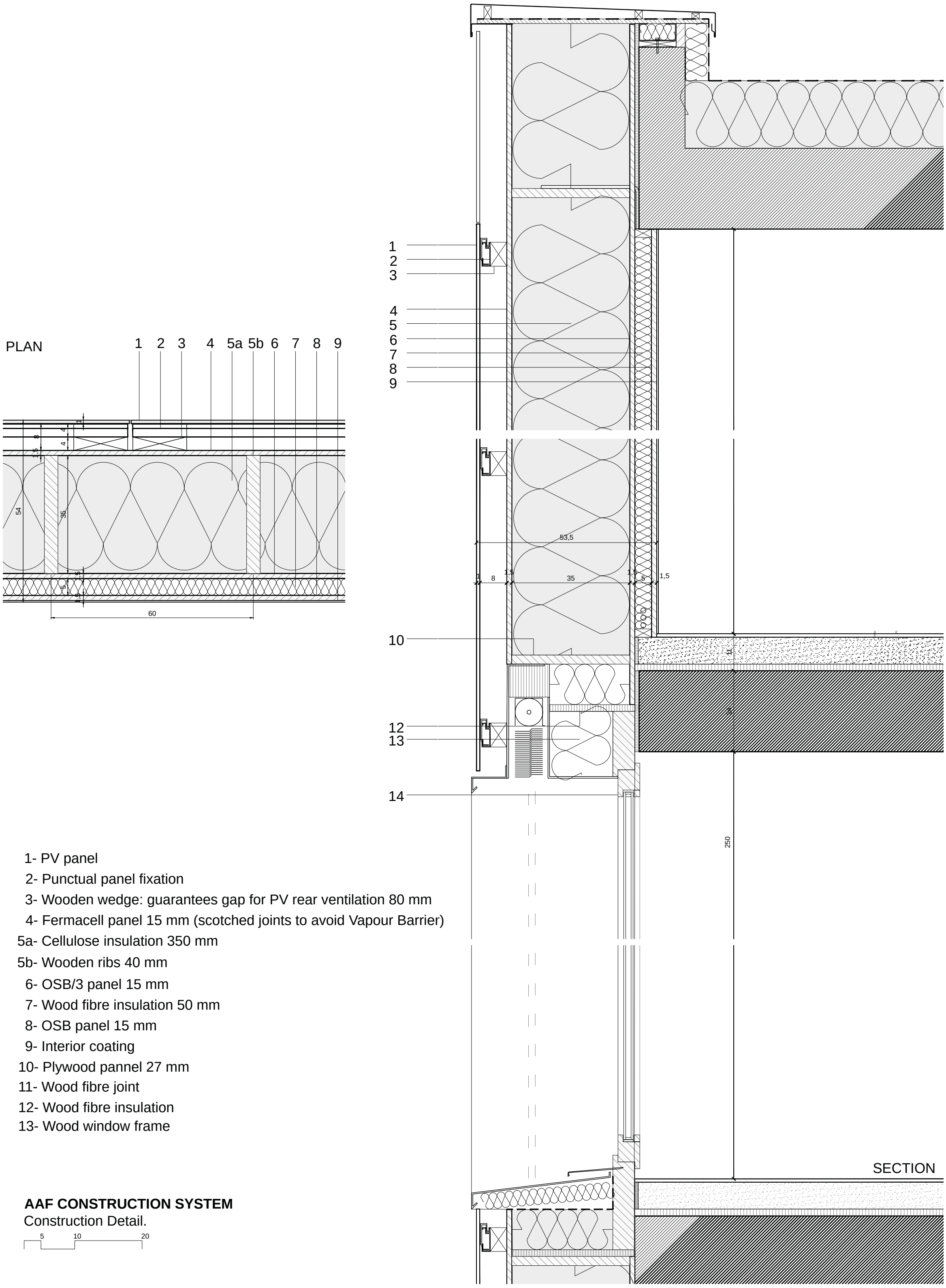

Figure 3. Advanced Active Façade construction system

The AAF construction system (Fig. 3) follows the low-carbon construction principles among we highlight the following: Using of natural, locally-sourced materials; reducing material's amount throughout the entire life cycle; designing the system to be disassembled rather than demolished (this involves the use of bolts instead of adhesives), designing a prefabricated system with low maintenance, designing a recyclable system with reusable materials. These principles have leaded to a light wood-framed prefabricated construction system, with two layers of natural insulation: cellulose and wood fibre.

The integration of BIPV in a façade involves a ventilated façade, with a ventilated chamber of 80-100 millimeters to guarantee the rear ventilation of the BIPV panels (Brinkworth and Sandberg, 2005). Among all sorts of PV panel layering composition, the AAF constructions system integrates glass-glass BIPV panels, which permit a frameless panel composition. Among the fixing options, the system works with invisible ones: one option is the punctual metallic fixations and a second option is the linear metallic fixations, adherer to the rear of the BIPV panels.

Advanced Active Façade Design Strategies

It exists a number of researches which have already studied solar systems integration and have provided composition guidelines: IEA - SHC, 2013, FOSTEr inMED, 2015, Munari Probst et al., 2012. They mainly focus on the functional integration and some construction guidelines. Some of them also propose visual simulations of existing façades and how they can integrate solar systems.

This ongoing research aims to develop a number of scenarios that widely represents common practice in the Swiss context. This will permit every architect, independently from style, land situation or urbanistic constraints, to find solutions or inspiration to BIPV façade composition. In addition, different criteria assessments will permit architects to evaluate themselves the optimal example for their practice.

To develop real scenarios, the 'Standard Swiss Dwelling' has been identified and adapted to a real site in Lausanne. In the context of urban densification, a land with a building in demolition process has been selected in Lausanne. This city has the representative climatic conditions of the "Swiss plateau", where most of the Swiss population lives. The standard building typology and climatic conditions of the site, permit a wider application of the design strategies to particular case studies in the rest of Switzerland and potentially in central and southern Europe.

The Advanced Active Façade design strategies are applied to the 'Standard Swiss Dwelling' in Lausanne. They are the combination of the four existing design strategies ('Slab to Slab', 'Total Storey', 'Balconies' and 'Total Volume') with the three groups of BIPV systems (Opaque, Translucent and Transparent) identified in the analysis phase. This combination results in 12 scenarios which integrate BIPV.

Figure 4 gathers four images which represent four of the twelve real site scenarios. This sample represents all four designs strategies combined with three different BIPV systems. The first AAF design strategy (1A) presents a BIPV system recently developed in Neuchatel by CSEM researches. It has opaque BIPV modules composed by monocrystalline cells and a grey metal mesh filter which gives colour, texture and vibrant reflections to the façade. These modules generate around 120W/m^2. The second design strategy (2B) integrates translucent BIPV modules in sliding panels for solar control purposes on the balconies. These translucent panels generate also 120W/m^2. The third image (3C) has transparent BIPV balconies in its south façade. The transparent thin-film modules generate around 50W/m^2. The fourth image (4A) has opaque high efficiency perovskite modules which generate 270W/m^2.

Figure 4. AAF Design Strategies sample

Assessment

Both the AAF Construction System and the AAF Design Strategies are assessed following different criteria: Environmental impact, social acceptance, architectural quality and cost.

Environmental impact

Regarding environmental impact, the Life Cycle Assessment (LCA) of the AAF construction system has been studied. Its preliminary results have been compared to Swiss common practice construction system LCA, and Swiss best practice LCA (Fig. 5). The AAF construction system presents a remarkable difference regarding the embodied energy of its structure. Although the total embodied energy is higher due to the high embodied energy of BIPV panels, it is largely compensated by the energy that they generate.

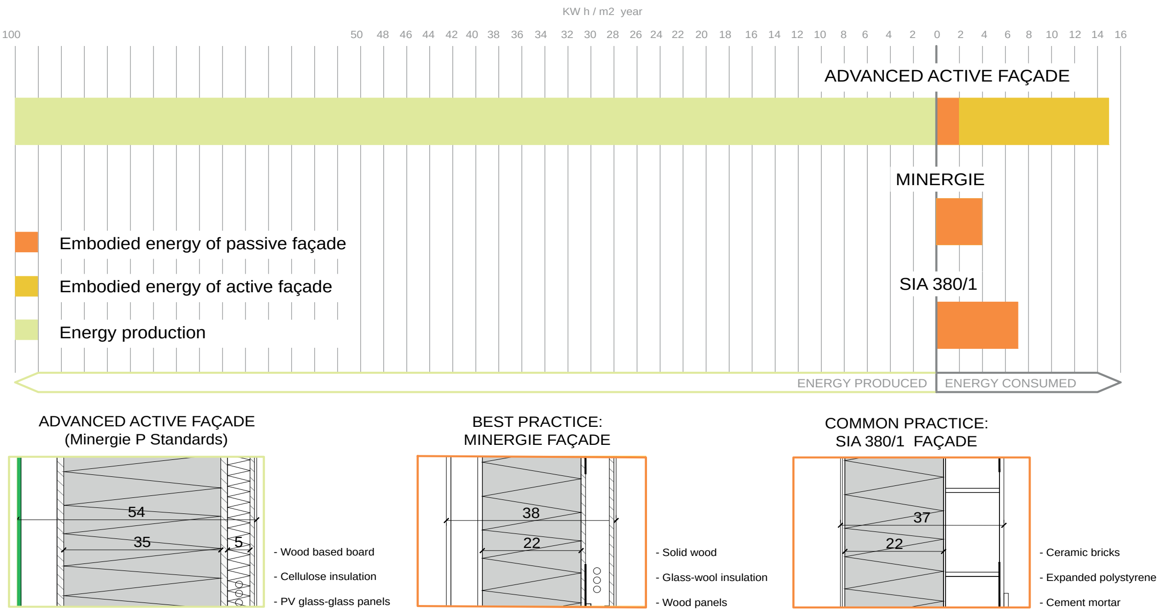

Figure 5. Life Cycle Analysis comparative: Advanced practice: AAF Construction system, Best practice: Minergie facade and Common practice: SIA 380/1 façade

To assess the Environmental impact of the Design strategies, the scenarios have been simulated using a building simulation tool (Design Builder). Different criteria such as total energy generation, self-consumption, self-sufficiency and energy exceed are displayed in the graphics (Fig.6), to provide architects with all the information they might need to target different objectives.

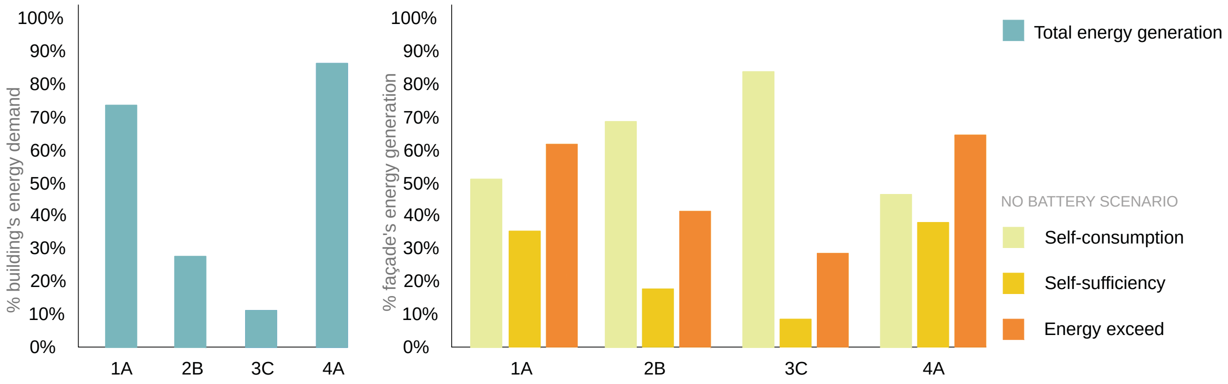

Figure 6. Energy simulation results. Refers to scenarios illustrated in figure 9

When designing a BIPV façade, there are two main active design strategies to consider, regarding energy production. On one hand, when the objective is to maximize the autonomy of the building, the design must prioritize a high self-sufficiency percentage. On the other hand, to minimize the energy injection to the grid, façade design should prioritize a high self-consumption percentage. Figure 7 and 8 illustrates these concepts by showing the example 1A simulations in two different times of the year: January and June.

The areas A and B are the total net electricity demand and generation, respectively. The overlapping part in area C is the PV power that is utilized directly within the building. This is sometimes referred to as the absolute self-consumption. What is most commonly meant by self-consumption, however, is the self-consumed part relative to the total production, which in the simplified nomenclature of Fig X would be: Self-consumption = C / (B+C)

The self-consumed part relative to the total load is also a commonly used metric. Normally we refer to it as self-sufficiency: Self-sufficiency = C / (A+C)

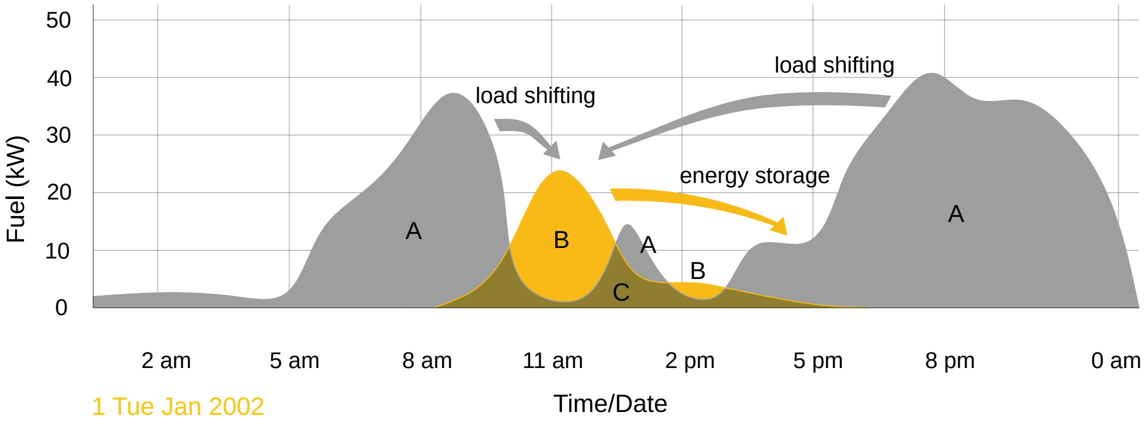

Fig 7: Schematic outline of daily net load (A+C), net generation (B+C) and absolute self-consumption (C) in a building with on-site BIPV (Design Strategy 1A example). It also indicates the function on the two main options (load shifting and energy storage) for increasing the self-consumption. In a winter scenario

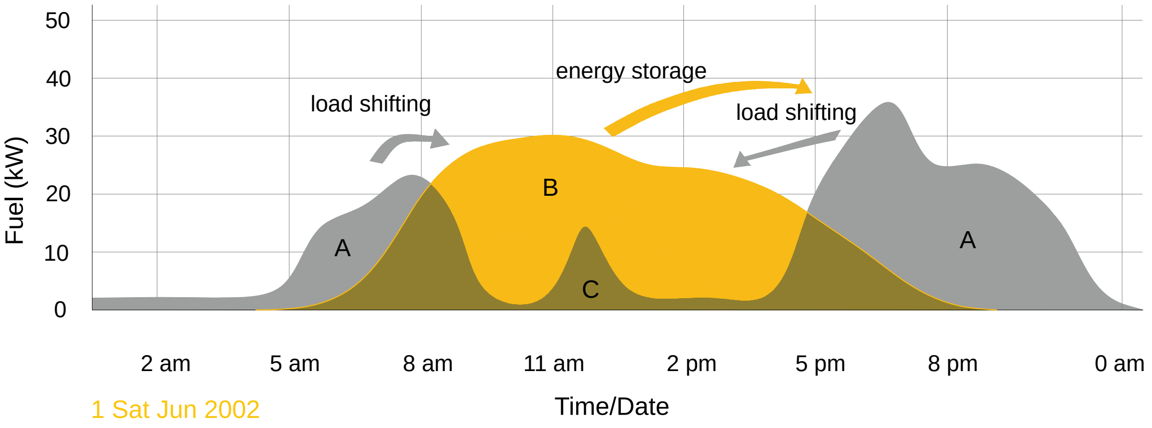

Fig 8: Schematic outline of daily net load (A+C), net generation (B+C) and absolute self-consumption (C) in a building with on-site PV (Design Strategy 1A example). It also indicates the function on the two main options (load shifting and energy storage) for increasing the self-consumption. In a summer scenario

Since the output of PV power is determined by variable meteorological processes, solar generated electricity cannot be reliably dispatched or perfectly forecasted. Additionally, in residential buildings, the PV generation and electricity consumption do not have the same variation profile. As shown in figure 6, this mismatch brings the need to export to the grid a significant part of the locally generated energy, even though energy is later imported from the grid (Vieira et al., 2016). For this reason, the integration of an energy storage system seems interesting to improve the self-consumption of the PV installation. With a storage system, the excess PV electricity during the day is buffered and later used at night. In this way, households equipped with a PV battery system can reduce the energy drawn from the grid and therefore increase their self-sufficiency.

The widely-employed method to improve PV performance is to incorporate batteries. Today it is still expensive for most households but due to its price drop: ca. 14% annually from

2007 to 2014 (Zhang et al., 2015) and its steep learning curve (paired to electric mobility research) it is foreseeable that in a near future all BIPV buildings will count with a battery system.

Social acceptance
In collaboration with ZHAW Zurich University of Applied Sciences, a public survey has been carried out to assess the social acceptance of the AAF design strategies developed. The main conclusion is that most respondents are in favour BIPV integration in Switzerland, and more that 70% percent of the respondents are convinced to use BIPV in their neighbour. It was revealed that the public believes that BIPV use increases the reputation the site and buildings which integrate it. It was also relevant to find out that the public gives more importance to color and design than to efficiency and electricity production. This finding reinforces the reasons and focus of the on-going research which is dealing with BIPV architectural features and expressive issues.

Further assessment regarding architectural quality and cost is currently being developed in collaboration with experienced architects of the Swiss context and façade constructors.

Prototype

Collaborating with BIPV producers, wood façade experts and Swiss façade consultants, a prototype of the AAF façade has recently been constructed. It consists in a demonstrator of the AAF construction system and the latest BIPV panels produced by CSEM (Fig.9). This exercise has permitted to test how professionals from very different backgrounds can work together with a common objective: a successful BIPV façade. This goal, which was stated at the beginning of this paper, is one of the main targets of our research. The prototype design and construction process has also permitted to verify the prefabrication potential of the construction system with the façade constructors. Working with experienced façade consultants has permitted to optimize material quantity, as well as the fixation systems

The CSEM laboratory has handmade the BIPV modules displayed on the prototype. They consist in a frameless encapsulation of regular PV monocrystalline cells, with a superposed metal or glass fibre mesh. This extra layer, integrated in the module structure, gives them texture, colour and dynamic reflections. These architectural qualities open a new horizon for BIPV ventilated facades. However, this extra layer blocks part of the sunlight from the cells, this is why the efficiencies of these panels are slightly lower than regular panels. While a standard BIPV panel has 18% efficiency, these panels' efficiency varies among 9% and 15% depending on the mesh material, density and structure. According to the research team, as cells' performance is improving, we can tolerate some loses in performance in favour of a better expressive quality of the BIPV module. This compromise will motivate more architects to use BIPV in their projects. In other words, eventually there will be modules with a lower production, but in a much bigger number which will lead to higher production.

The prototype was presented in the Ecoparc Forum, held in Neuchatel in September 2017. In this event, topics of solar energy generation in the urban context were discussed. During the presentation, the audience, which was mainly architects and investors manifested a high interest on this new BIPV facade: The Advanced Active Façade. An online survey is being carried out to register feedback and optimize the final AAF construction system and design strategies integrating their comments.

Figure 9. AAF full scale prototype. The prototype design allows to understand its composition and the way BIPV panels can be integrated in a low-carbon façade.

Research preliminary conclusions

With the aim of demonstrating how BIPV can be used as a real construction material in building envelopes, this research proposes a solution that can narrow the gap between technology and architecture. The preliminary results exposed in this paper permit concluding that it is, in fact, possible to integrate different types of BIPV systems into Advanced Active Façade. Firstly, it has been demonstrated how BIPV can be part of the dimensional composition of collective residential housing. The development of this argumentation provides BIPV producers with a series of dimensions and guidelines to consider. This will increase architect's demand and facilitate the BIPV façade composition process. Secondly, collaborating with wood construction experts and façade consultants while developing the construction system, gives the results technical accuracy and reliability. It can be stated that provided with the Advanced Active Façade Design Strategies, architects are enabled to deal with the expressive and aesthetical aspects of their BIPV designs, producing façades fitting the current composition trends in the Swiss context.

The assessment phase demonstrates that regarding environmental impact, the AAF construction system has a lower total embodied energy that any other construction system in the Swiss practice. In addition, the AAF Design Strategies assessment has evidenced that there are different criteria to consider when designing a façade: a building envelope will not be the same if self-consumption is targeted or self-sufficiency shall be maximized. The actual results insinuate the advantages of a BIPV installation while paired with a storage system.

Both LCA and energy demand assessments need further research for simulating building energy performance paired with an energy storage system. To complete the assessment, a collaboration with a BIPV façade constructor will permit to develop an economical comparative of different construction systems generalized in the Swiss context. A prediction comparative will also be provided taking into account the drastic price drops that BIPV and battery storage systems are experiencing.

The next and final step of this research consists in the organization of an international student competition to validate the user-friendliness and convenience of the approach for architects in the practice. This last phase will also initiate the duty of knowledge transfer of our research project.

Acknowledgments

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