Architectural design scenarios with building-integrated photovoltaic solutions in renovation processes:
Case study in Neuchâtel (Switzerland)

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ABSTRACT: In view of the importance of urban renewal processes, building-integrated photovoltaic (BIPV) systems can potentially provide a crucial response to the energy turnaround challenges. Functioning both as envelope material and electricity generator, they can simultaneously reduce the use of fossil fuels and greenhouse gases emissions while providing savings in materials and electricity costs. However, despite continuous technological and economic progress, the assets of BIPV remain undervalued in the current practice. Various obstacles (technology choice, small volumes, lack of information and good examples) tend to increase the costs and reduce the project acceptance. To overcome these barriers, an interdisciplinary research project developed an approach based on four main phases: 1) selection of archetypal residential buildings, 2) detailed analysis of the buildings, 3) development of renewal design scenarios and 4) multi-criteria assessment of each scenario. Focusing on the architectural-scale, this paper presents design strategies with BIPV solutions of a representative case study realized in Neuchâtel (Switzerland). A multi-criteria assessment of the proposed design scenarios allows comparing the different strategies. It highlights the influence of the design decisions on the final performances, helping us to move towards an optimization of the BIPV surfaces in order to maximize self-consumption regarding the building consumption profile.
Keywords: Building-integrated photovoltaics, energy efficiency, renewable energy, sustainable architectural design, urban renewal, renovation strategy, multi-criteria assessment, self-consumption, self-sufficiency, grid feed-in.

INTRODUCTION

One of the top priorities of European countries is to reduce energy consumption and greenhouse effect in the built environment. Many strategies stress the importance of urban renewal processes towards more sustainability in terms of economic, social and environmental impacts. Indeed, there are still huge potential energy savings to be made in European countries in general, and in Switzerland in particular. Most residential buildings were built before 1985 and require large amounts of energy to ensure the minimum indoor thermal comfort (OFS, 2015). In response, recent research works have started considering the large existing building stock, bringing to light the considerable importance of urban renewal strategies for the sustainability of the built environment in the next decades (Riera and Rey, 2013).

In parallel, one of the objectives of the “Energy strategy 2050” is to increase the use of renewal energy. According to the International Energy Agency (IEA), it is possible to cover 1/3 of the annual Swiss demand for electricity using photovoltaics (IEA, 2002). Building-integrated photovoltaic (BIPV) systems therefore provide a crucial response to the challenges of the energy turnaround (SFOE, 2014).

BIPV is a growing and diverse area of research. In particular, it includes research on new products development, modelling, simulation, and assessment of their integration on buildings (Frontini et al., 2012).

RESEARCH OBJECTIVES

Despite all this technological progress, only a small part of the available local potential for BIPV is valorised in urban areas (integration into roof and façades). Diverse types of obstacles limit a large-scale advanced PV integration into urban renewal processes. Most barriers are related to the limited motivation of architectural designers, a restricted knowledge of the BIPV potential and an insufficiency of aesthetically-convincing exemplary buildings (Heinstein et al., 2013).

To address this challenge, urban and architectural design towards increased integration – and therefore increased acceptance – could potentially provide a decisive solution. Although it remains largely disconnected from solar renewable energy issues, it represents a key element towards establishing a systematic link between BIPV and the necessary renewal of the considerable existing building stock.

Therefore, instead of considering BIPV as a technical constraint for designers, we propose a new approach based on the integration of BIPV solutions as a new “raw material” for architectural renewal projects (Aiulfi and Rey, 2010) (Rey, 2014). By prioritizing architectural quality and dialogue with the built environment, it aims at identifying which construction elements can be substituted by PV components giving the most appropriate response to the requirements of the overall design of the renovation. The latter will not only provide technical answers to the same requirements as other parts of the building envelope (water and air tightness, mechanical resistance, etc.), but also generate electricity on-site from a renewable energy source providing the opportunity to self-consume it at the same time. Towards this aim, an ambitious research project entitled ACTIVE INTERFACES (Rey et al., 2015) is currently being developed in order to study in a structured and in-depth manner the technological, spatial, legal and socio-economic parameters related to the development of new adapted solutions, taking into account diverse criteria (energy consumption, electricity production, cost-effectiveness, and Life Cycle Analysis). Crossing over the limits of current practices, this ongoing project aims at designing and assessing BIPV-adapted scenarios embodying different urban renewal strategies in the Swiss context through a multi-criteria evaluation methodology. The present paper is an integral part of this interdisciplinary research project.

Focusing on the architectural scale, it presents detailed architectural design strategies with BIPV solutions for a case study in Neuchâtel. A multi-criteria assessment of the proposed design scenarios allows comparing the different strategies. It highlights the influence of the architectural design decisions on the final performance with respect to the building consumption profile, helping us to move towards a more precise definition of what we mean by implementation of BIPV systems into building renewal design processes.

PROPOSED METHODOLOGY

The methodology involves four main phases: 1) selection of an archetypal residential building; 2) detailed analysis of the building (study of the current status and of the thermal envelope's construction details); 3) development of three architectural renewal scenarios embodying different levels of intervention; 4) multi-criteria assessment of the design scenarios. The description of the methodology is detailed in Aguacil, Lufkin, and Rey (2016).

Phase1: Selection of an archetypal building

We are focusing on Neuchâtel considering that it is representative of the typical middle-size city of the Swiss Plateau. Based on an urban analysis of its building stock, five residential archetypes were identified. The purpose is to select a representative building for each archetype to carry out a series of real case studies. These five archetypes were defined based on the following selection criteria, which are related to the opportunity to implement BIPV elements: i) construction period, ii) urban context (adjacent or isolated building), iii) solar access potential on roof (sloped or flat), iv) and façade (floors), v) heritage level of protection (protected, common or unattractive).

Phase 2: Detailed analysis of the building

The building presented in this paper corresponds to the archetype 4 residential building of the 70's, constructed at the beginning of the oil crisis (1972-1976) (Fig. 1). Consequently, thermal considerations have had a rather small influence on the design of the envelope. It presents eleven-stories, consisting of 52 apartments and 5,263 m^2 of living floor area (Bauer et al., 2013). A study of the construction details is crucial to detect all BIPV integration opportunities in the building envelope (roof and facades). In this case, façades are made with concrete prefabricated elements (Fig. 5a) consisting of: 12 cm of reinforced concrete, 4cm of expanded polystyrene (EPS) insulation, and an exterior facing concrete of varying thickness coated with a crushed stone agglomerate. Openings present double glazing and wood-metal frame. The flat roof is composed by 22 cm of reinforced concrete, 6 cm of EPS insulation, and 5 cm of gravel. In terms of active systems, the building is connected to a central heating covering heating and domestic hot water (DHW) needs.

Figure 1: Building image (current status).

Phase3: Design of architectural renewal scenarios

Following the methodology, we defined five renewal scenarios from an architectural point of view. We started with the analysis of the **E0-Current status** scenario, which provides all the information about the building and reflects its actual situation. The **S0-Baseline** The S0-Baseline scenario -without BIPV strategies- aims at achieving at least the current legal requirements defined by SIA 380/1:2009 (SIA, 2009), in accordance with current practices. The last three design scenarios incorporate BIPV strategies and are defined as follows. **S1-Conservation** (Fig. 2): aims to maintain the expression of the building while improving its energy performance (at least current legal requirements); **S2-Renovation** (Fig. 3): has as purpose to maintain the general expressive lines of the building while reaching high energy performance (at least *Minergie* standard); **S3-Transformation** (Fig. 4): best energy performance and maximum electricity production possible with aesthetic and formal coherence over the whole building (at least "2000WattsSociety" and "Energy strategy 2050") (SIA, 2011) (SFOE, 2014).

Renovation strategies for each scenario

Following the architectural criteria, for **S0** (Fig. 5a), we propose only passive strategies -to reduce energy demand- improving the performance of the envelope by an internal insulation and substitution of windows to achieve the current legal requirements, using the U-value as a main indicator of this performance.

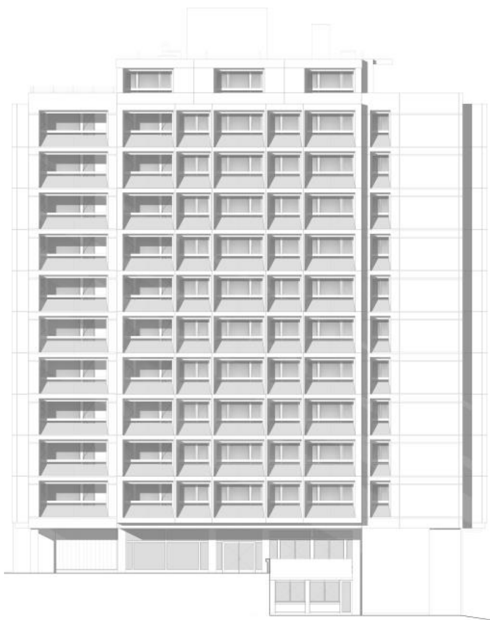

Figure 2: Design scenario S1 (conservation), façade SW.

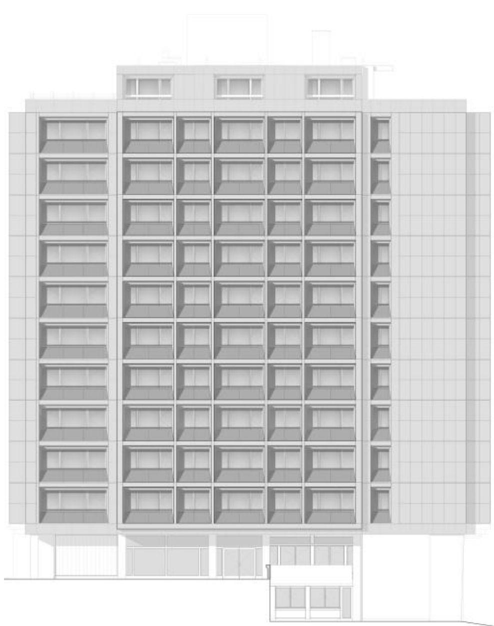

Figure 3: Design scenario S2 (renovation), façade SW.

For **S1** (Fig. 5b), we propose, in addition to the interventions of S0, we propose to cover the roof (250 m^2) and the railing of windows (431 m^2) using BIPV elements, respecting the building's expression (Fig. 2). For **S2** (Fig. 5c), we propose an external insulation façade system including the replacement of existing windows, and placing BIPV elements in the entire roof, the railing of windows and window surroundings (254 m^2), while maintaining the main lines of the building's architectural expression (Fig. 3).

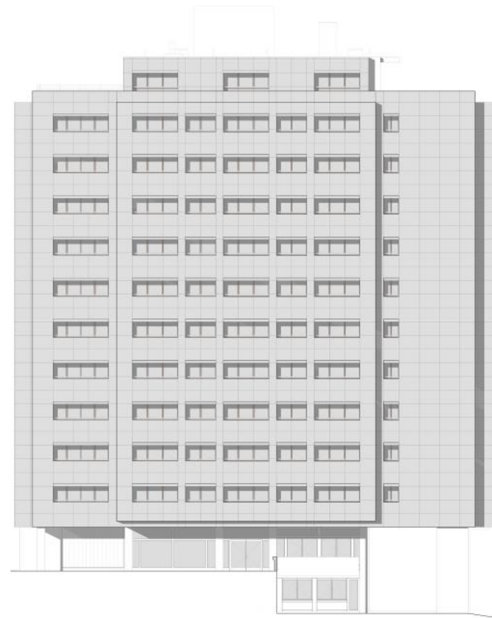

Figure 4: Design scenario S3 (transformation), façade SW.

Finally, for **S3** (Fig. 5d), we propose a prefabricated façade element to plugin directly onto the existing façade, including insulation (ventilated facade), new windows and BIPV elements covering all opaque surfaces (514 m^2) (Fig. 4). In terms of active strategy -to reduce consumption by increasing the HVAC systems performance- we propose to change the original system to reduce the impact in term of GHG emissions due to the type of energy source used. In his case, we propose to substitute the existing oil-boiler by an electricity-based system to increase the self-consumption potential of electricity produced on-site and reduce the consumption thanks to high efficiency air-water heat-pumps.

Phase 4: Definition of assessment indicators

To carry out a multi-criteria evaluation of the design scenarios, five groups of indicators are defined. They assess and compare their performances in terms of a) energy and emissions, b) life cycle analysis, c) photovoltaic generation, d) indoor comfort, and e) global cost-effectiveness. For this paper, we have selected three of them (Table 1) to emphasized the energy performance, self-consumption and the carbon neutrality potential through a Life Cycle Analysis.

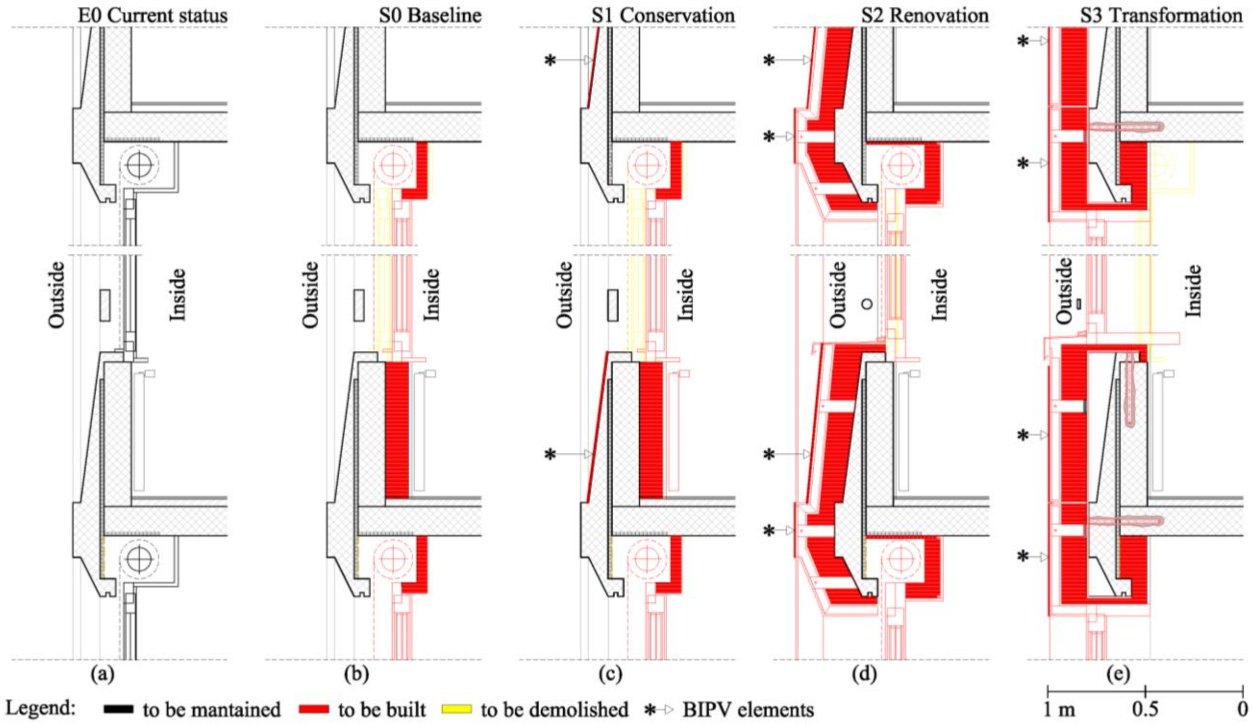

Figure 5: Renovation strategies for each scenario. Detailed section of the main façade.

Table 1: Assessment indicators.

1-Energy and emissions	
- Primary energy consumption	*kWh/m².year*
- Equivalent GHG emissions	*kgCO₂/m².year*
2-Photovoltaic installation	
- Electricity production	*MWh/year*
- Self-consumption potential	*%*
3-LCA-Life Cycle Analysis	
- Embodied energy balance	*MJ/m².year*
- Global warming potential	*kgCO₂/m².year*

A detailed, complete assessment of the remaining indicators is available in Aguacil, Lufkin and Rey (2016).

SIMULATION

The tool used to estimate the assessment criteria related to energy consumption, emissions and photovoltaic production is *DesignBuilder*, based on the *EnergyPlus* simulation engine (DB, 2015). It allows carrying out both hourly and annual simulations. For the cost estimation we used the EPIQR tool (Flourentzou et al., 2000), developed for testing different renewal scenarios and identifying the best performing one(s).

Input data for energy consumption

The U-values for the current status -scenario E0- are defined through a detailed analysis of the exiting envelope (Bauart, 2015). For scenarios S0 and S1, U-values target corresponds to SIA 380/1 requirements (Table 2), and for scenarios S2 and S3 they are the result of the construction detail proposition (Fig. 5).

Table 2: U-value (W/m2K) and ventilation ratio (renov./h).

Scenario	E0	S0	S1	S2	S3
Façade	0.90	0.23	0.23	0.18	0.18
Roof	1.30	0.21	0.21	0.21	0.21
Glazing	2.60	1.30	1.30	1.10	0.85
Vent. (r/h)	2.00	2.00	1.00	0.50	0.50

Input data for photovoltaic installation

The choice of the BIPV components to be used in scenarios S1, S2 and S3 responds to the will of carrying out a rehabilitation which preserves the architectural quality of the building, while compromising as little as possible the level of electricity produced. We have chosen standard panels for the roof (Meyer Burguer, 2016) and BIPV customized elements with frameless panels for the façade (CSEM, 2015). Based on the monocrystalline (sc-Si) technology of cells, an efficiency of 14% is estimated (Cerón et al., 2013). The cost is estimated between 245 and 445 CHF/m² (1,748 and 3,179 CHF/kWp), including inverters, wiring and accessories.

RESULTS

Energy consumption

The heating need target set by the SIA 380/1 for housing, considering an envelope area (Ath) of 3,922m² and a floor area (A_E) of 5,263m² is 38 kWh/m²·year. The target is achieved for the four scenarios (S0, S1, S2 and S3), corresponding to a 53% saving on heating demand. In terms of non-renewable primary energy consumption, scenarios achieve, with respect to the current status scenario E0; -31% (S0), -61% (S1), -78% (S2) and -89% (S3) (Fig. 6). To convert the results from final to primary energy and CO_2 equivalent emissions, we have used coefficients from SIA 380/1:2009 (SIA, 2009): For electricity: 2.970 kWh_{PE}/kWh_{FE} and 0.154 $kgCO_2eq/kWh_{FP}$ electricity); for oil heating 1.690 kWh_{PE}/kWh_{FE} and 0.403 $kgCO_2eq/kWh_{FP}$.

The values obtained for the current situation far exceed the Swiss target value set by SIA2040:2011 based on the "2000WattsSociety" (SIA, 2011), which in this case sets the limit of consumption to 69 kWh/m^2 per year (for electricity, heating and DHW) (Fig. 6). These results show the changes needed to achieve the goals set by the "EnergyStrategy2050" and highlight the importance of strategies to promote urban renewal processes. To achieve this targets, it is crucial to propose mixed strategies composed by passive and active measures to take into account the origin of each energy source. For this reason, we have proposed, in addition to the envelope renovation, a modification of HVAC systems for the scenarios S1, S2 and S3, replacing the existing oil boiler by an air-water heat-pump to increase the self-consumption potential and reduce energy consumption of heating and DHW.

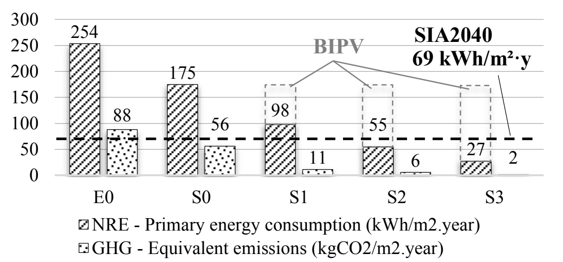

Figure 6: Net energy consumption and emissions.

Photovoltaic installation

The electricity production of the BIPV elements from an irradiation study of each scenario (Fig.7) is 75 (S1), 128 (S2) and 174 (S3) MWh/year.

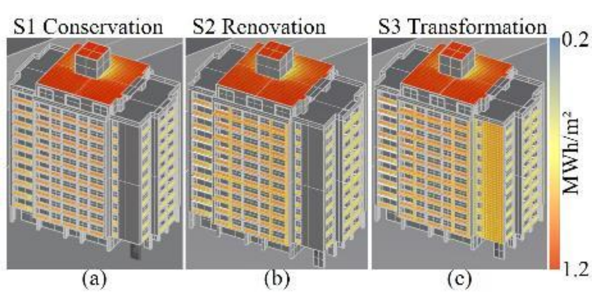

Figure 7: Annual irradiation level for each scenario.

In terms of electricity annual coverage ratio, it represents 16% (S1), 33% (S2) and 48% (S3) of domestic electricity consumption (annual simulation) and 70% (S1), 51% (S2) and 41% (S3) in terms of self-consumption (hourly simulation) of electricity production directly consumed on-site (Fig. 8).

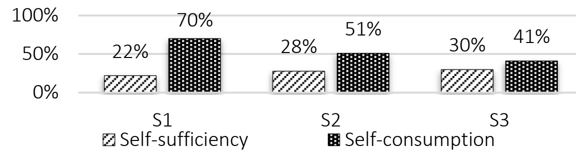

Figure 8: Self-consumption potential.

An example of hourly balance simulation for an average day corresponding to April 21st is shown in Figure 9. It also highlights that for matching the electricity production with the electricity needs, it is essential to install BIPV elements in the specific location (façades) and in a good orientation and inclination (roof). This synchronization effort of electricity production and consumption avoids the overproduction of energy, which eventually has to be absorbed by the grid of the city.

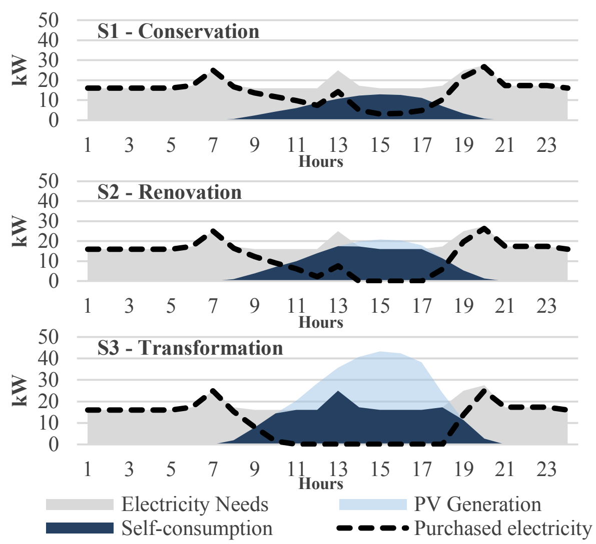

Figure 9: Hourly balance simulation (average day).

Life Cycle Analysis

The results of the LCA assess the entire renovation project of each scenario. They take into account the embodied energy and the greenhouse gas (GHG) emissions of construction materials, BIPV elements and the energy consumed by the use of the building during a life cycle of 30 years. The analysis shows that scenarios S2 and S3 respect the Swiss targets of 310 $MJ/m^2\cdot year$ (in terms of embodied energy) (Fig. 10) and 10 $kgCO_2/m^2\cdot year$ (in terms of GHG emissions) (Fig. 11). It is important to highlight the fact that it was only possible to achieve the Swiss targets - "2000WattsSociety" and "Energy strategy 2050"- (SIA 2011, SFOE 2014) thanks to the change in the type of energy source and the low-emission renovation materials proposed (for S2 and S3) (Table 3), representing key elements toward real carbon neutrality.

Table 3: Impact of main materials used for each renewal scenario, in terms of NRE (MJ/m²·y) and GWP (kgCO₂/m²·y).

Materials	NRE	GWP	S0	S1	S2	S3
Gypsum plasterboard	1.073	0.065	x	x	**x**	
OSB board	**1.303**	**0.060**				**x**
Expanded polystyrene (EPS)	4.373	0.303	x	x		
Expanded polystyrene (recycled)	**0.824**	**0.156**			**x**	**x**
PVC window frame	11.615	0.699	x	x		
Wooden window frame	**4.337**	**0.279**			**x**	**x**
3-IV-IR glazing	3.798	0.256	x	x	**x**	**x**
Particle board	0.824	0.041			**x**	
Cement board with wood particles	**0.165**	**0.020**				**x**
Sawn Timber, air treated	0.078	0.004			**x**	**x**

Calculations have been done with the ECO-BAT application taking into account a service life of 30 years (PV), 20 years (HVAC systems) and 40 years (construction materials) (ECO-BAT, 2015).

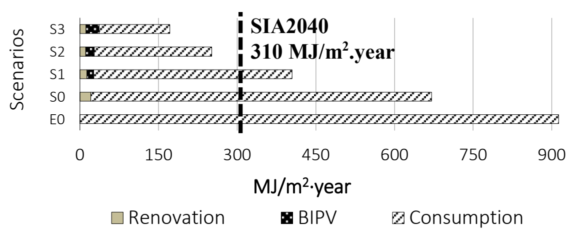

Figure 10: Embodied energy balance (MJ/m².year).

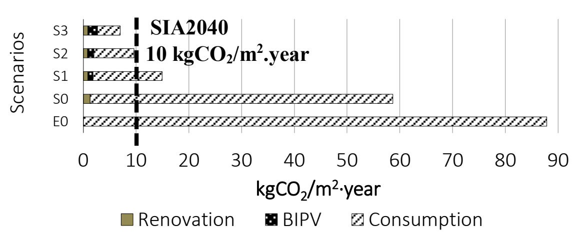

Figure 11: Global Warming Potential (kgCO₂/m².year).

Global cost-effectiveness

The global costs of renewal scenarios correspond to 1,004,400 (S0), 1,403,992 (S1), 1,995,252 (S2) and 2,763,750 (S3) CHF. The difference lies in the different passive strategies and the BIPV elements. The difference lies in the different passive strategies and the BIPV elements. To estimate the global cost-effectiveness, we have considered a horizon of 50 years using the cost-optimal methodology (BPIE, 2013), with 3% of interest rate. To estimate the global cost-effectiveness, we used energy savings and electricity production (including 0.8% of decreasing production per year according to the guaranteed performance of PV elements) (Meyer Burger, 2016), taking into account the sale and purchase price of electricity 0.2 CHF/kWh and 0.1 CHF/kWh for heating oil, tax included. Financial aid to tackle the investment corresponds to 30% of the PV installation cost (Swissgrid, 2015). Using these data, and taking into account maintenance and repair-replacements costs (NREL, 2003) for the BIPV installation, the payback time of each scenario has been calculated using the DCF (discounted cash-flow) methodology by net present value (NPV), leading to 31 (S0), 26 (S1), 25 (S2) and 29 (S3) years, taking into account the real self-consumption with no-battery systems (electricity production consumed on-site by the building). The BIPV strategy thus presents a shorter payback time thanks to the extra revenue generated by the produced electricity.

CONCLUSIONS

Based on the results of the evaluation, it seems clear that energy renovation projects without integration of renewal energy in general and BIPV in particular are no longer an option if we want to achieve the objectives of the "Energy strategy 2050". Today, renovation projects improving the building envelope with a high level of thermal energy performance are necessary, but not sufficient. Compensating buildings' energy consumption by producing electricity on-site has become number one priority. In this sense, by proposing new adapted BIPV solutions for urban renewal processes, the research contributes to advancing architectural design practices in this direction.

At an early stage of the research, the results of this first case study highlight several interesting elements, such as the best cost-effectiveness of the BIPV scenario and the importance of optimizing the location of the active surfaces in order to maximize the self-consumption with respect to the consumption profile of the building. By taking into account a simple passive strategy, 31% (interior insulation) and 61% (exterior insulation) savings of heating are achieved. In this sense, it is possible to achieve more than 89% of total savings by introducing renewal mixed strategies (passive, active and renewable energy systems) (Fig. 6).

Therefore, hourly simulations appear as key to understand the best way to integrate BIPV on existing buildings (facades and roofs) by matching the electricity production with the on-site consumption. This allows us to optimise the installation by minimising the energy injected into the existing grid. This study also allows a first validation of the proposed methodology and opens up perspectives for the upcoming process of finalisation and refinement. Finally, after these various refinements will have been carried out, further phases of the research will consist in applying the methodology to other archetypal buildings. These upcoming case studies will ensure the validation of the finalised methodology and enable the extrapolation of the most performing BIPV renovation strategies at the urban scale. Moreover, these case studies will provide architects, installers and public authorities with a catalogue of innovative and adapted "best practice" solutions for a large-scale advanced BIPV integration into urban renewal processes.

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