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Integrated design strategies for renovation projects with Building-Integrated Photovoltaics towards Low-Carbon Buildings: Two comparative case studies in Neuchâtel (Switzerland)

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Abstract: As tomorrow's cities are already largely built, and as many of their buildings have a low energy performance level, urban renewal processes are essential for the sustainable development of European cities. In this context, Building-Integrated Photovoltaic (BIPV) systems, using innovative PV products as new construction material for façades and roofs, can potentially provide a crucial response for achieving long-term carbon targets. This paper presents an integrated architectural design process for addressing renovation projects. Presented through a comparison of two case studies on archetypal residential buildings from the 1900s and 1970s in Neuchâtel (Switzerland), this approach includes the design of different renovation scenarios integrating passive, active and BIPV strategies. An optimization of the potential BIPV (or active) surfaces based on the annual irradiation threshold is conducted to maximize self-consumption (SC) and self-sufficiency (SS). The scenarios, before and after this optimization-based refinement, are evaluated in terms of Life-Cycle Assessment and Cost. Results demonstrate the importance of the optimization to ensure the cost-effectiveness of the strategy and increase the independence from energy suppliers. The main outcome provides, to architects and engineers, advanced BIPV renovation strategies along with results from a multi-criteria evaluation that are crucial for reaching carbon neutrality.

Keywords: Sustainable architecture, integrated design, renovation, BIPV, self-consumption

Introduction

Many strategies stress the importance of urban renewal processes towards more sustainability (Riera and Rey, 2013). Indeed, there are still considerable potential energy savings to be made in European countries in general, and in Switzerland in particular, where most residential buildings were built before 1985 and require large amounts of energy to ensure the minimum indoor thermal comfort (OFS, 2017). In response, one of the objectives of the "2000 Watt society" (SIA, 2011) – a concept that promotes an annual limit per person of 1 tonne of CO_2 emissions and 2000 W expressed in mean power – is to drastically reduce greenhouse gas (GHG) emissions taking into account the whole life cycle of buildings. Building-Integrated Photovoltaic (BIPV) systems represent a promising solution to the energy turnaround challenges (SFOE, 2017), as it is estimated that PV could cover up to 1/3 of the annual Swiss electricity demand (IEA, 2002).

BIPV is a growing and diverse area of research, as confirmed by the development of new products and their integration on building envelopes (Frontini et al, 2012). Despite this technological progress, only a small part of the available local PV potential is exploited in urban areas. Different types of obstacles limit a large-scale PV integration into urban renewal

processes, namely, 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 these challenges, architectural design towards increased integration – and therefore increased acceptance – must be supported. 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" (Aiulfi and Rey, 2010). Prioritizing architectural quality and dialogue with the built environment, it aims at identifying which construction elements can be substituted by PV components, fulfilling the building envelope requirements while producing on-site from a renewable energy source.

This paper is an integral part of an ongoing research project entitled ACTIVE INTERFACES, which aims at studying the technological, spatial, legal and socio-economic parameters related to the development of new adapted BIPV solutions (Rey et al, 2015).

Based on the architectural design strategies already developed in the first step of the project and published in Aguacil et al (2016, 2017), we here present the impact on the final performance of an optimization process based on the annual irradiation threshold to choose the active surfaces for two case studies in Neuchâtel (Switzerland).

Research methodology

The methodology involves four main phases: 1) selection of archetypal residential buildings; 2) detailed analysis of each building; 3) development, for each archetype, of four architectural renewal scenarios embodying different levels of intervention; 4) multi-criteria assessment of the scenarios. While further details on the methodology and the detailed façade designs to obtain aesthetically convincing examples can be found in Aguacil et al (2016, 2017), each phase is briefly described below in reference to the two case studies.

Phase 1: Selection of an archetypal building

Considering Neuchâtel as a representative city of the Swiss Plateau (OFS, 2015) and based on its building stock analysis, five residential archetypes were identified, using selection criteria such as the construction period and heritage protection level. A representative building for each archetype was chosen to carry out a series of real case studies.

Phase 2: Detailed analysis of the buildings

The case studies presented in this paper are two multi-family residential buildings that correspond to archetypes 1 and 4. In their current status, to which we will refer as situation **E0**, both buildings, shown in Figure 1, present a low level of energy performance.

Archetype 1
Built in 1909
4 stories
8 apartments
788 m^2 floor area

Archetype 4
Built in 1972
11 stories
52 apartments
5'263 m^2 floor area

Figure 1. Images of the current status of each building along with their main characteristics.

Archetype 1 has an uninsulated envelope; its facades consist of 40 cm thick rubble masonry walls and exterior plaster, windows are simple glazing, and the sloped roof is finished with ceramic tile (Aguacil et al, 2017). **Archetype 4** has a poorly insulated envelope, with facades made of prefabricated concrete elements with 4 cm of expanded polystyrene (EPS) insulation,

double-glazed windows, and a flat roof with 6 cm of EPS insulation and 5 cm of gravel (Aguacil et al, 2016). In terms of active systems, both buildings have a central oil boiler covering heating and domestic hot water (DHW) needs.

Phase 3: Design of architectural renewal scenarios

Starting from **E0-Current status**, we define four renewal scenarios from an architectural and energy point of view. The **S0-Baseline** scenario aims at achieving at least the current legal requirements defined by SIA 380/1 (SIA, 2016), in accordance with current practices and only through passive strategies to reduce the energy demand (by improving the performance of the envelope using low-cost materials).

The other three design scenarios, defined as follows, incorporate BIPV in addition to passive strategies using more ecological materials such as recycled EPS insulation or wooden frames for windows. **S1-Conservation**: maintain the expression of the building while improving its energy performance (at least up to current legal requirements) and respecting the targets to obtain a subsidy of 60 CHF/m^2 from the "programme bâtiment" which promotes energy renovation of existing buildings (EnDK, 2015). **S2-Renovation**: maintain the general expressive lines of the building while reaching high-energy performance (taking as reference the Swiss Minergie® label (Minergie, 2016)). **S3-Transformation**: attain the best energy performance and maximum electricity production possible with aesthetic and formal coherence over the whole building (at least "2000WattSociety" (SIA, 2011)).

In combination with the integration of BIPV in S1 to S3, an active strategy, consisting in changing the original HVAC system, is considered to reduce GHG emissions linked to the type of energy source used. In both cases, we propose to replace the existing oil boiler by an electricity-based system to increase the self-consumption of the electricity produced on-site and reduce the consumption thanks to high-efficiency air-water heat pumps.

Phase 4: Multi-criteria assessment

The implementation of the renovation scenarios allows identifying the potential active surfaces of the building façades and roof. Following the design phase where we defined all potential PV surfaces designing the facade using standard- or custom-size panels (MB, 2017) with coloured films (CSEM, 2017), an optimization process is conducted to define which of these surfaces will finally be covered by BIPV elements versus non-active elements with the same aspect. The goal is to identify the annual irradiation threshold, which leads to maximizing both the self-sufficiency (energy independence) and self-consumption (level of use of the PV system), two concepts further described in Luthander et al (2015). Surfaces that achieve the optimal irradiation threshold are then considered to be active.

In parallel to the design process, and through an iterative cycle, we conduct a multi-criteria evaluation based on Life-Cycle Analysis (LCA) and Cost (LCC), taking into account energy consumption, GHG emissions, on-site PV generation, environmental impact of materials including BIPV elements, and cost-effectiveness for a 60-year lifespan. The LCA and LCC results, used to compare the scenarios and evaluate the impact of the optimization, are obtained through simulation and using reference values, as detailed below.

Energy modelling and simulation

The energy simulation is carried out in DesignBuilder v.5 (DB, 2017), based on the EnergyPlus® simulation engine. In an iterative simulation process, we verify the fulfilment of the objectives set for each scenario, adjusting the constructive details of each proposal. From the final design (Fig. 2) we obtain the hourly consumption of the building during the entire year for

each renewal scenario. In a second step, the estimation of the hourly on-site electricity production is done on a detailed 3D model created in the Rhinoceros 3D modelling tool, and using the visual programming software Grasshopper with the DIVA plugin (DIVA, 2017). This allows us to conduct a detailed analysis of the PV production as a function of the irradiation threshold for each envelope element and to perform a selection of the active surfaces.

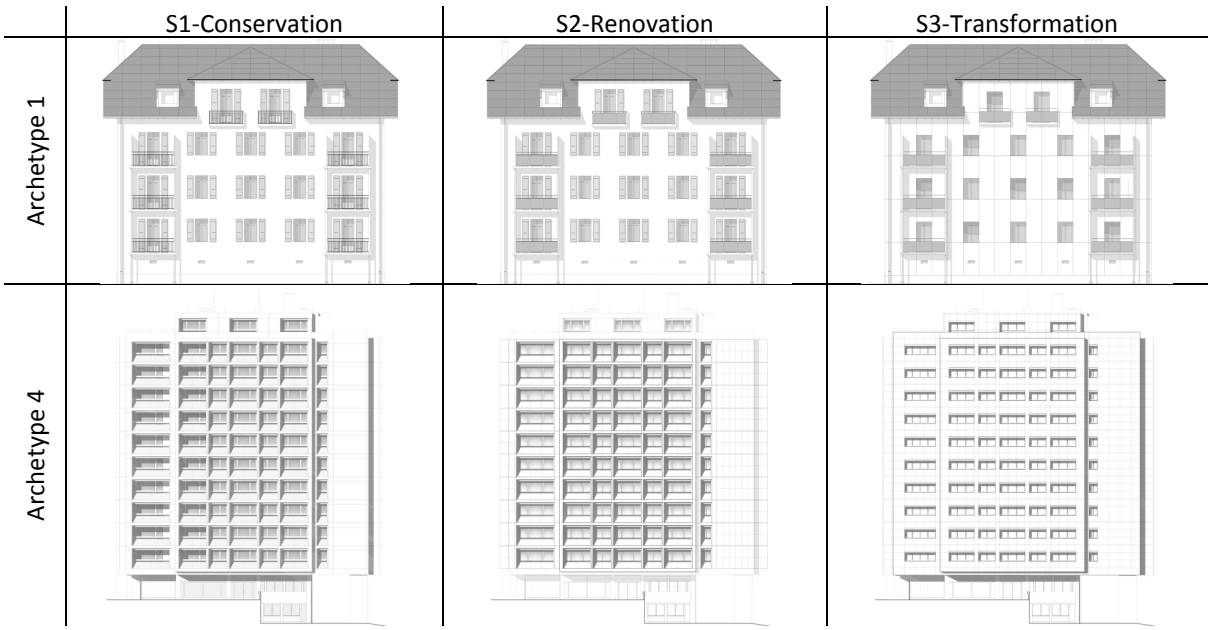

Figure 2. Main façade definition for each BIPV scenario, detailed in Aguacil et al (2016, 2017).

Reference values used in LCA and LCC

The environmental impact values for construction materials, PV elements, and HVAC systems are obtained with the ECO-BAT software (ECO-BAT, 2015), taking into account his different lifespans of 50, 30, and 20 years respectively. For the LCC analysis, the renovation cost is obtained using the EPIQR tool (Flourentzou et al, 2000), developed to perform the diagnosis of existing buildings and test different renewal scenarios. Subsidies for both the BIPV installation (Swissgrid, 2017) and energy renovation (EnDK, 2015) are taken into account. We used the existing PV technology based on the single-crystal silicon (sc-Si) cell, with 17% efficiency (Cerón et al, 2013). The expected cost is between 245 and 445 CHF/m^2 for standard-size modules and 780 CHF/m^2 for customized ones, including inverters, wiring and accessories.

To estimate the global cost-effectiveness, we considered a 50-year horizon with a 3% interest rate. The calculation considers energy savings and electricity production, including a 0.8% production decrease per year according to the guaranteed performance of PV elements (MB 2017), and a price of 0.1 CHF/kWh (for heating oil) and 0.2 CHF/kWh (for electricity), tax included. For electricity overproduction injected into the grid, we have taken into account a cost-covering remuneration (Swissgrid, 2017) between 0.064 and 0.106 CHF/kWh depending on the installation size, scenario, and case study. The payback time is calculated using the DCF (discounted cash flow) methodology by net present value (NPV), considering the real-time self-consumption with no battery systems and the injected electricity overproduction.

Results

Design scenarios implementation for each archetype

As described in Table 1, for **S0,** representing current practice, the insulation is increased for all opaque surfaces and windows are replaced to achieve the current legal requirements

(SIA, 2016). For scenarios **S1** to **S3**, in addition to the interventions of **S0** we propose to integrate BIPV elements on roof and facades taking into account the requirements of the design scenarios defined in phase 3 of the methodology and favour more ecological materials over low-cost materials. Regarding the façade definition (Fig. 2) of the different BIPV scenarios (S1 to S3), we propose for **archetype 1** an external insulation system with synthetic coating cladding for **S1** and **S2**, with PV elements on roof (S1) and balustrades (S2). In S3, a ventilated façade system is implemented using PV elements, prefabricated, modular and built with wooden structure for **S3**. For **archetype 4**, an internal insulation system covering the railing of windows with customized PV elements is proposed for **S1**, and a ventilated façade system incorporating PV panels on the biggest opaque surfaces for **S2**, in order to reproduce the geometry of the existing façade. For **S3**, a ventilated façade system using PV elements, prefabricated, modular and built with wooden structure is implemented.

Sc.	Arch.	Type (colour) of materials		Insulation	Target U-value [W/m2.K]		Infiltr.
		Roof	Façades	Thingness (type)	Opaque	Windows	[r/h]
E0	1	*Tiles (brown)*	*Synthetic coating*	-	1.33	5.7 (sg-w)	2
	4	*Gravel*	*Concrete*	4 cm (EPS - Int)	1.09	2.6 (dg-a)	
S0	1	*Tiles (brown)*	*Synthetic coating*	14 cm (EPS - Ext)	0.25	1.3 (dg-pvc)	1
	4	*Gravel*	*Concrete*	10 cm (EPS - Int)			
S1	1	SSz (*brown*)	*Synthetic coating*	17 cm (rEPS - Ext)	0.20	1 (tg-w)	0.7
	4	SSz-f (black)	CSz (concrete)	14 cm (rEPS - Int)			
S2	1	SSz (*brown*)	SSz (ochre)	18 cm (rEPS - Ext)	0.19	0.7 (tg-w)	0.5
	4	SSz-f (black)	CSz (concrete)	15 cm (rEPS - Ext)			
S3	1	SSz (*brown*)	SSz (ochre)	20 cm (rEPS - Ext)	0.17	0.7 (tg-w)	0.5
	4	SSz-f (black)	SSz (grey)	17 cm (rEPS - Ext)			

Abbreviations: Custom-size (CSz) or standard-size PV panels (SSz), with frame (-f), standard expanded polystyrene (EPS), 100% recycled expanded polystyrene (rEPS), internal (Int) or external insulation (Ext), single (sg), double (dg) or triple glazing (tg), aluminium (-a), polyvinyl chloride (-pvc) or wooden windows frame (-w).

Table 1. Summary of design scenarios implementation for each archetype.

Active surfaces optimization

The optimization process begins with a study based on the cumulated annual irradiation threshold (varying from 0 to 1'200 kWh/m^2.year). Figure 3 highlights the surfaces that do not receive enough solar energy to be considered as active (in scenario S3-Transformation). From these results and the derived self-consumption and self-sufficiency, we identify the optimum threshold and the corresponding annual PV production.

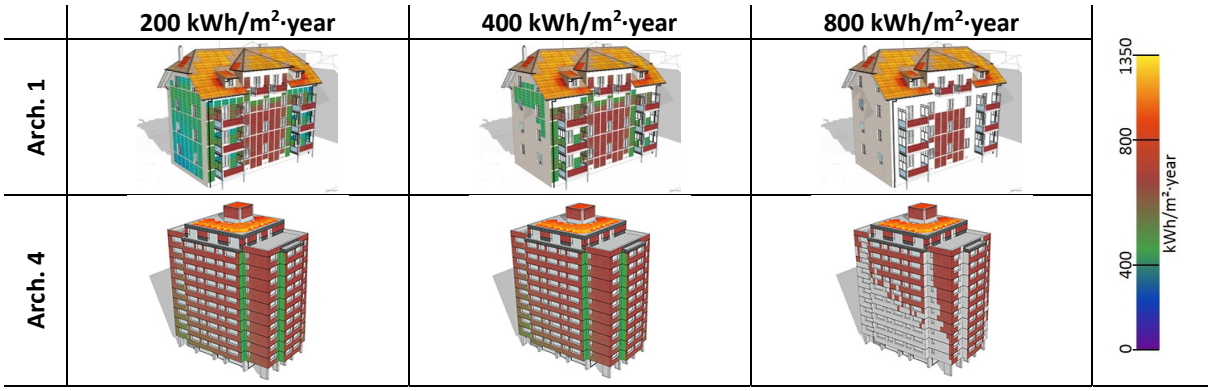

Figure 3. Annual irradiation threshold study for the scenario S3 (SE-SW façades) for archetype 1 (top) and 4 (bottom). Coloured surfaces (according to the scale on the right) reach the threshold values (top).

For each scenario, two different thresholds are obtained, depending on whether the existing boiler is maintained or replaced. Figure 4 shows an example of optimization results for scenario S3. For **archetype 1**, the threshold is 1'175 kWh/m^2 (oil-boiler) and 800 kWh/m^2 (heat pump), leading to 14 and 28 MWh/year of on-site production respectively, and to 29% of self-consumption and 24.5% of self-sufficiency. For **archetype 4**, the threshold is 800 kWh/m^2 (oil-boiler) and 600 kWh/m^2 (heat pump), for 87 and 139 MWh/year of on-site production respectively, and 32% of self-consumption and 29% of self-sufficiency.

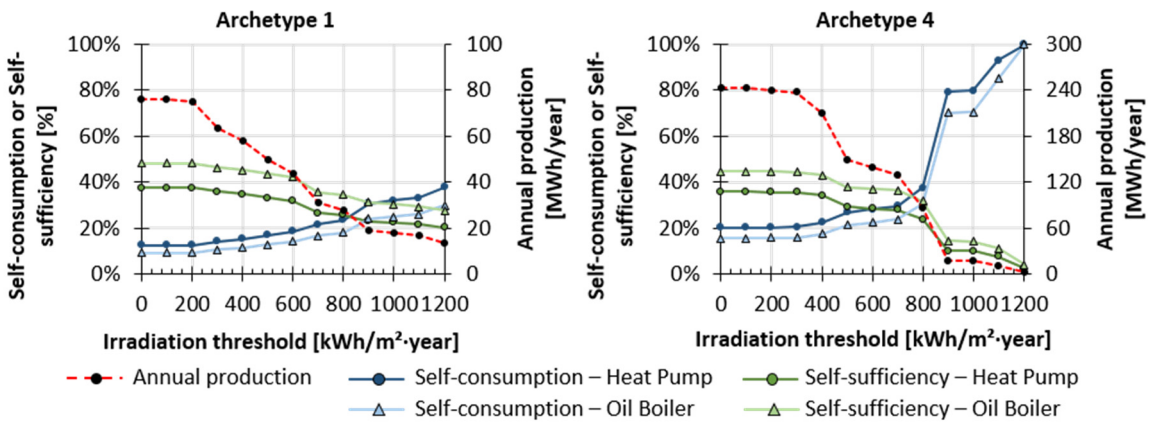

Figure 4. Example of irradiation threshold study based on self-consumption and self-sufficiency for scenario S3.

Life Cycle Analysis (LCA)

From **E0** (current status) to **S0** (current practice), we obtain a 60% improvement in energy consumption and 30% in GHG emissions. Results for the renovation scenarios (**S0** to **S3**) are illustrated in Fig. 5. As the performance of the buildings increases, the weight of the embodied energy related to the construction materials also becomes more important. Results shows that scenarios S1, S2 and S3 respect the Swiss targets. It is important to highlight the fact that it was only possible to achieve the "2000WattSociety" targets by changing the type of energy source, which increases the self-consumption of the electricity production, and by using low-carbon materials. These points represent key elements toward real carbon neutrality. In addition, the optimization process of the active surfaces allows achieving the performance objectives in a more rational way, avoiding the excessive injection of electricity into the grid.

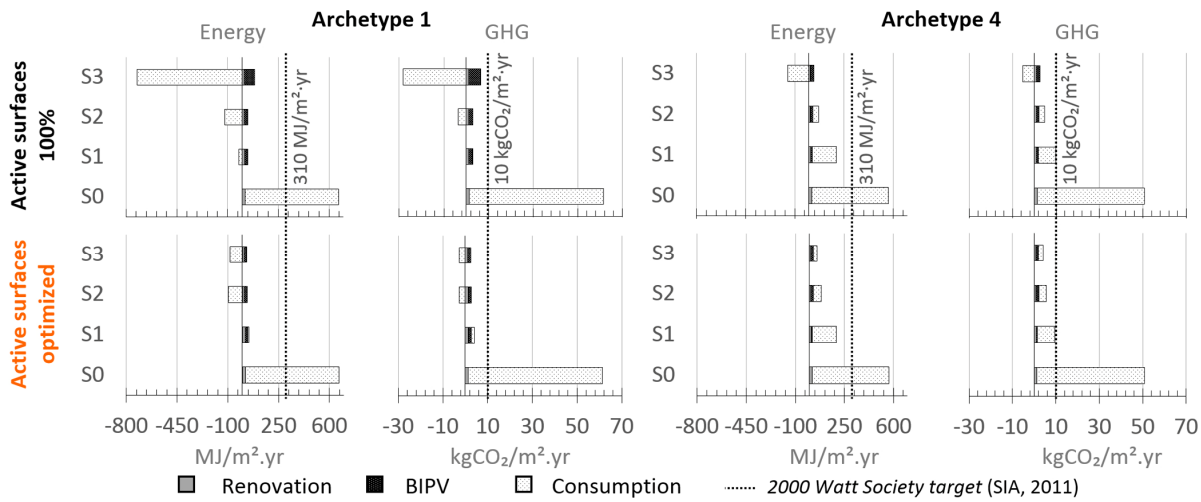

Figure 5. LCA results in terms of embodied energy, GHG emissions and end-use consumption. Taking into account 100% of potentially active surfaces (top) and optimizing the active surfaces (bottom).

Life Cycle Cost (LCC)

The investment-cost of each renewal scenario is represented in Figure 6 by the value corresponding to year 0. The difference between these values depends on the type of passive strategy, the amount of active surfaces installed, and the level of subsidies obtained. Results show that scenarios S1, S2 and S3, which include BIPV strategies, present a shorter payback time compared to scenario S0 (without BIPV), due to the energy savings and the extra revenue generated by the injected electricity into the grid.

The result of the optimization of the surfaces has a more pronounced effect (payback time) for archetype 4 due to the larger active surface on facades compared to the active surface on the roof. Above all, in scenario S3 where more PV surfaces are proposed, we observe that the optimization increases payback but avoids excessive electricity injection into the grid. However, S3 continues to be more cost-effective than scenario S0.

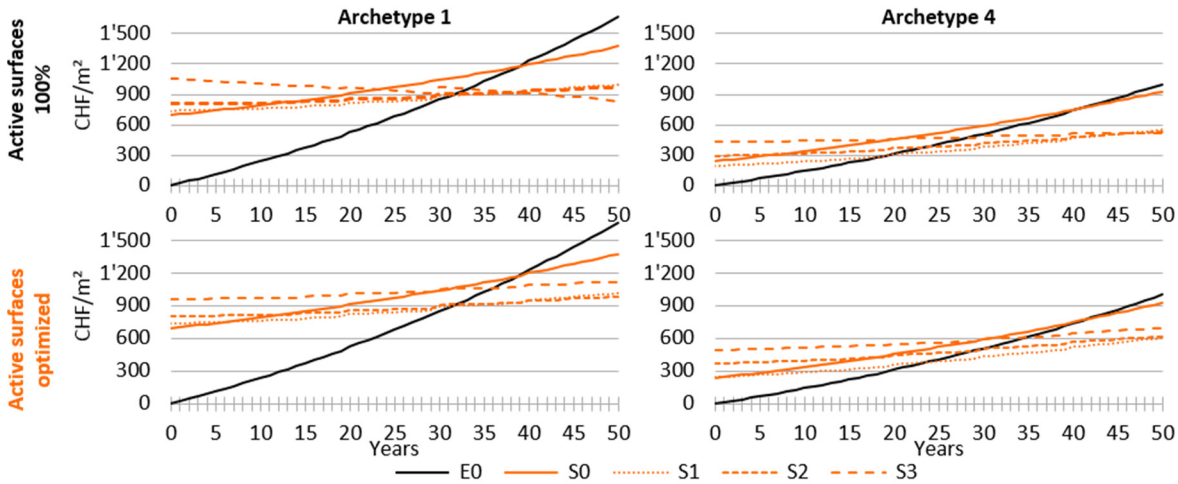

Figure 6. LCC results in terms of accumulated energy consumption cost with a heat pump system and payback time (vertical dotted lines), including maintenance and repair-replacements costs for the BIPV installation. Taking into account 100% of potentially active surfaces (top) and optimizing the active surfaces (bottom).

Conclusion

Based on this paper's results, it seems clear that energy renovation projects without integration of PV are no longer an option if we want to achieve long-term carbon targets. 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 a number one priority. By proposing new adapted BIPV solutions for urban renewal processes, this research contributes to advancing architectural design practices in this direction.

The results of the two case studies highlight the best cost-effectiveness of the BIPV scenarios and the importance of optimizing the location of the active surfaces to maximize the self-consumption with respect to the building's consumption profile. These are key elements toward real carbon neutrality, allowing us to achieve the performance objectives in a more rational way by optimising the installation to minimise the grid-injected energy. This in turn allows avoiding the intrinsic problem linked to decreasing prices of injected electricity.

The next step in our research is to integrate a battery system to further increase self-consumption and self-sufficiency. Ultimately, our case studies shall 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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