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ACTIVE RENOVATION STRATEGIES WITH BUILDING-INTEGRATED PHOTOVOLTAICS (BIPV). APPLICATION ON AN EARLY 20TH CENTURY MULTI-FAMILY BUILDING

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ABSTRACT

Tomorrow's cities are already largely built, as much of the existing building stock – with a low level of energy performance – will still be standing in 2050. Urban renewal processes therefore play an essential role towards the sustainable transition of European cities. In this context, building-integrated photovoltaic (BIPV) systems can potentially provide a crucial response to achieve current energy and mid- to long-term carbon targets. Functioning both as envelope material and electricity generator, BIPV systems can simultaneously reduce the use of fossil fuels and greenhouse gas (GHG) emissions, while providing savings in materials and electricity costs. These are precisely the objectives of most European energy directives, from zero- to positive-energy buildings. However, despite continuous technological progress and increasingly favourable economic conditions, the significant assets of BIPV remain broadly undervalued in the current practice.

Focusing on the architectural design, this paper presents the results of a multi-criteria evaluation in terms of Life-Cycle Assessment (LCA) and Cost (LCC) of different renovation and energy-use scenarios, showing which strategies can allow to achieve the ambitious targets for the 2050 horizon by integrating into the design process: (1) Passive strategies, to improve the envelope through low-embodied energy materials and construction systems; (2) BIPV strategies, using innovative photovoltaic products as a new construction material for façades and roofs, and by selecting the BIPV surfaces in order to synchronize on-site generation with the building consumption profile; (3) Active strategies, adapting the HVAC system to improve its efficiency and maximize PV self-consumption, thus reducing the dependence on feed-in-tariffs to ensure the profitability of investments.

The research methodology, presented in this paper through the comparison of different renovation scenarios applied on a 1900's archetype building in Neuchâtel (Switzerland), proposes a new way to address rehabilitation projects of existing buildings in urban environments towards Low Carbon Buildings. The main outcome provides - to architects and engineers - advanced BIPV renovation strategies depending on the building typology, the architectural design goals, and the level of intervention.

KEYWORDS: renovation; multi-criteria assessment; life-cycle assessment; low-carbon buildings; building-integrated photovoltaics

1. INTRODUCTION

One of the main issues to address in order to mitigate the consequences of climate change is to reduce energy consumption and greenhouse gas (GHG) emissions. Many strategies stress the importance of renovation projects in the built areas towards a greater reduction of the environmental impact. Without a doubt, there are still enormous potential energy savings to be made on the European continent. As in Switzerland, most of the residential buildings in EU cities were built before 1985 and need large amounts of energy to ensure inhabitability in terms of thermal comfort [1]. In reaction to this fact, ongoing research has begun considering the entire existing building stock, showing the importance of urban renovation for the sustainability of the built environment in the next decades [2]. Apart from the reduction of the energy consumption, the majority of energy strategies for 2050 in EU countries includes the necessity to increase the amount of energy produced by renewables sources. As indicated by the International Energy Agency (IEA), it is conceivable to cover 1/3 of the yearly Swiss demand for electricity using building-integrated photovoltaic (BIPV) systems [3], providing a real solution helping to achieve the ambitious objectives of the energy turnaround [4]. The application of the photovoltaic elements, including new better-adapted products [5], to design building envelopes, particularly for existing buildings, is a growing research area.

2. RESEARCH OBJECTIVES

Despite the technological progress already done, only a small section of the available potential for BIPV is exploited in the existing built environment (considering the whole building envelope, façades and roof). Diverse sorts of barriers limit a large-scale deployment of PV integration into renovation processes. Most obstacles are associated to the restricted motivation of architectural designers, a limited knowledge of the BIPV possibilities and an insufficiency of aesthetically-convincing exemplary projects [6]. Architectural design towards increased integration could help overcome these barriers. Indeed, although the architecture realm remains mostly disconnected from solar renewable energy issues [7], it represents a key factor in the direction of establishing a systematic link between BIPV and the renovation of the existing residential building stock.

Therefore, instead of perceiving BIPV as a technical constraint for designers, we propose a design-based approach, understanding and using BIPV elements as a “raw material” for building envelope renovation [8–10]. By prioritizing architectural quality and dialogue with the neighbouring buildings, we aim at figuring out which inert building-envelope components can be substituted by active photovoltaic elements giving the most suitable response to the necessities of the overall design concept of the renovation. These PV elements will not only provide technical answers to the same requirements as different components of the building envelope (water and air protection, mechanical resistance, etc.), but additionally produce electricity on-site from solar energy. Crossing over the limits of present day practices, this research aims to design and assess BIPV-adapted scenarios embodying different building-envelope renovation strategies in the Swiss context through a multi-criteria evaluation methodology considering the whole life cycle of the renovation project. The present paper is an integral part of an ambitious and interdisciplinary project entitled Active Interfaces [11]. Focusing on the architectural scale, this paper provides specific architectural design strategies with BIPV elements for a case study in Neuchâtel from the 1900’s. A multi-criteria evaluation of the proposed design allows comparing the results of different BIPV strategies. It highlights the influence of the architectural design decisions on the final overall performance of the building, supporting us to move in the direction of a more precise definition of how BIPV elements could be used on building-envelope renovation processes.

3. METHODOLOGY

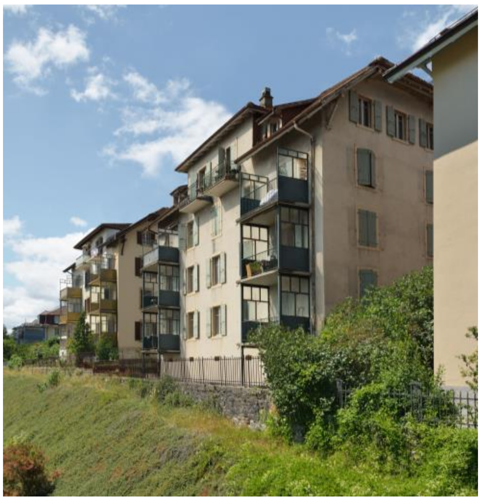
The methodology presents four phases: **Phase 1)** residential building archetype identification; **Phase 2)** selection and analysis of case studies; **Phase 3)** implementation of three design scenarios embodying different levels of intervention; **Phase 4)** multi-criteria assessment of each scenarios. While the in-depth description of the methodology is detailed in [8], we briefly introduce each phase below.

3.1. Phase 1 - Residential building archetype identification

Considering Neuchâtel as a case study sufficiently representative of the typical middle-size city of the Swiss Plateau, an in-depth analysis of its building stock using Geographical Information System (GIS) and statistical data from building and population census [12] was conducted. During this process, five residential archetypes were identified with the purpose to select a representative building per archetype, to be used as case studies. The different archetypal situations were defined based on four selection criteria - which are related to the opportunity to implement BIPV elements - a) Construction period (main indicator), b) Context (connection to neighbour buildings), c) Solar access (façades and roofs), d) heritage protection level.

3.2. Phase 2 - Selection and analysis of case studies

To illustrate the approach, the building presented in this paper is a multifamily residential building (Figure 1), typical of the 1900's. This building is not specially protected; it is classified by the heritage department of Neuchâtel as Category II [13], i.e. typical or picturesque building. The quasi total absence of decorative elements is to emphasise. It is located on ancient vineyard terraces, and is part of a set of three identical standalone buildings (non-adjacent to other buildings). There is a ground floor, three upper floors and an attic, for a total of five floors. The main façade is south facing. The sloped roof presents two sides facing north and south. There are two apartments per floor, except for the ground floor, which is dedicated to cellar spaces, laundry room and the facility spaces with an oil-boiler for heating and domestic hot water (DHW). The north façade (access and street side) has a sober appearance with small vertical openings, symmetrical composition, median axis marked by the entrance with windows illuminating the stairwell space. The south façade (lakeside) presents eminently vertical openings that punctuate the symmetrical composition of the façade with two rows of balconies supported by columns. All openings are composed of natural stone framing to emphasise the outline of the windows, the rest of the façade is finished with plaster.



Main characteristics of the building

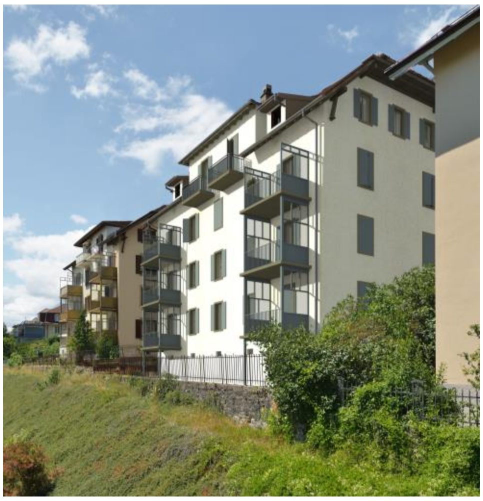
- Total floor area: 788.5 m^2.
- Sloped roof (uninsulated), wood structure and terracotta colour ceramic tiles.
- Monolithic walls in rubble masonry walls and exterior plaster without insulation.
- Wooden frame windows with single glazing and exterior wooden shutters.
- Balconies with reinforced concrete slab with metal profiles and supported by metal columns. Metal railings.
- The slab of the first floor is built in hollow slabs, the remaining four floors are built with wooden beams embedded in the façades and resting on walls in the centre of the building.
- Oil-boiler for heating and DHW supply.

Figure 1: Current status of the building. Image and main characteristics.

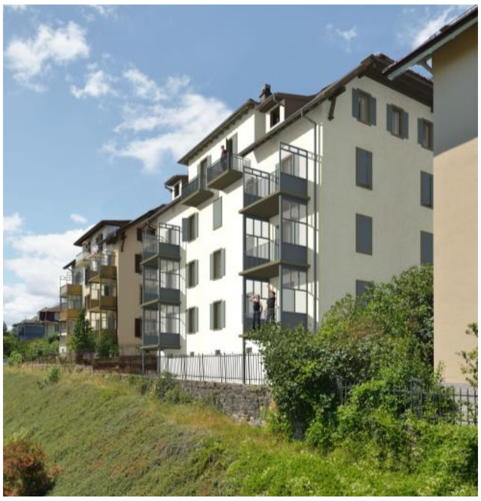
3.3. Phase 3 - Implementation of design scenarios

The implementation of the different scenarios starts with the study of the current status of the building, analysing its constructive characteristics to highlight BIPV implementation opportunities and to define renovation strategies. Four general design scenarios are defined as follows:
S0-Baseline scenario, without BIPV strategies, represents current practices, a reference scenario that aims to achieves compliance with the minimum legal requirements in terms of energy performance defined in SIA 380/1:2016 [14].

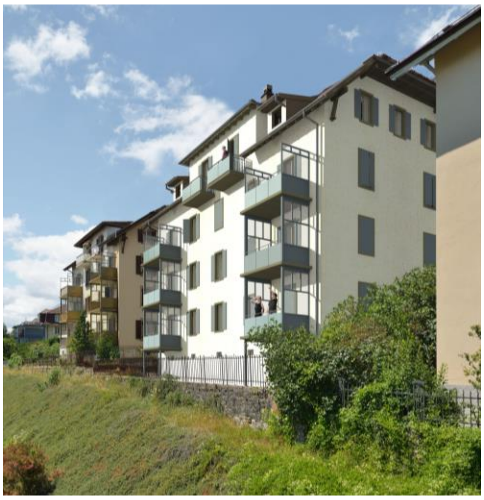
S1-Conservation scenario aims to maintain the original aspect of the building while improving its energy performance, at least achieving the minimum legal requirements [14] as S0.
S2-Renovation scenario searches to maintain the general architectural expression of the building while reaching high-energy performance, at least the requirements defined by Minergie® standard [15].
S3-Transformation scenario aims to achieve the best energy performance possible with aesthetic and formal coherence over the whole building, taking as target reference the 2000-Watts society concept in line with the 2050 objectives in Switzerland [16,17].



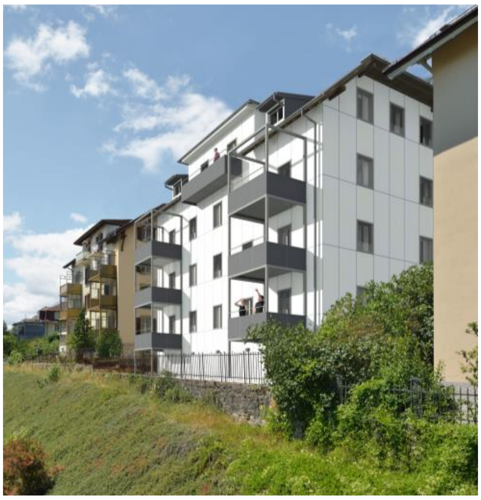
S0-Baseline



S1-Conservation



S2-Renovation



S3-Transformation

Figure 2: Rendering images showing the results of the four renovation scenarios (S0, S1, S2 and S3).

Following these general design guidelines, the specific strategies for our case study are presented as follows and illustrated in Figure 2 (rendering images showing the resulting aspect of each scenario) and Figure 3 (building envelope improvements at constructive detail level). For **S0-Baseline**, only passive strategies are implemented -to reduce energy demand- improving the performance of the building envelope by an external insulation and substitution of the existing windows to achieve the minimum legal requirements in terms of U-value of the different building envelop elements. For **S1-Conservation**, in addition to the interventions of S0, the idea is to use the entire roof of the building to integrate BIPV elements, without perturbing the original aspect of the building. For **S2-Renovation**, in addition to the interventions of S1, the balcony railings are used to implement customized BIPV elements, maintaining the main architectural characteristics of the building. Finally, for **S3-Transformation**, a new aspect of the building is proposed using a prefabricated façade element to plug-in directly on the existing façade. This industrialised element includes insulation (ventilated façade), new high-performance fenestration and three different types of BIPV elements covering all opaque surfaces (roof, façade and balcony railings).

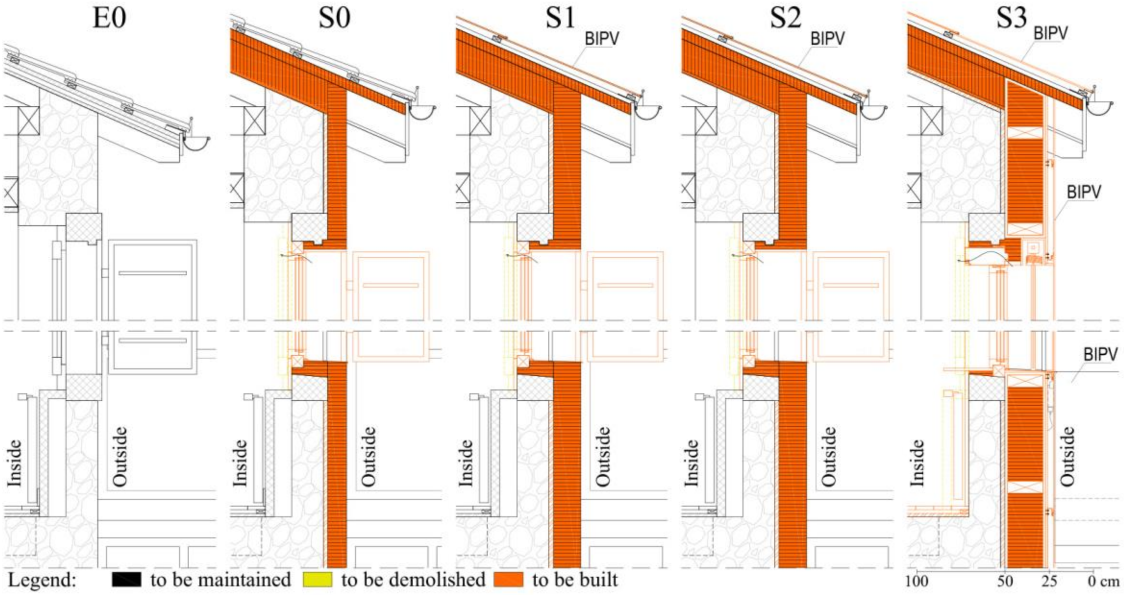


Figure 3: Detailed section of the main façade for each renovation scenario.

3.4. Phase 4 - Multi-criteria assessment

This phase aims to carry out a multi-criteria evaluation of the different design scenarios (E0, S0, S1, S2 and S3); four groups of indicators are defined in order to assess and compare the global performance of the different renovation scenarios in terms of photovoltaics, energy balance, environmental impact and economic/financial aspects. The whole set of indicators assessed are listed in Table 1.

Table 1. Overview of the assessment indicators.

Group	Indicator	Units
Photovoltaic performance	Levelized Cost of Energy ($LCOE_{PV}$)	CHF/kWh_{e-pv}
	NR Primary Energy Factor ($NRPEF_{PV}$)	kWh_{NRE}/kWh_{e-pv}
	Carbon Content Factor (CCF_{PV})	$kgCO_{2-eq}/kWh_{e-pv}$
	Energy Payback Time ($EPBT_{PV}$)	years
	GHG Emissions Payback Time ($GPBT_{PV}$)	years
	Energy yield	kWh_{e-pv}/kWh_{p}
Final energy balance (Operational phase)	Power needed for heating and DHW	kW
	Final energy consumption (FE)	$kWh/m^2 \cdot year$
	PV electricity self-consumed by building (PVSC)	$kWh_{e-pv}/m^2 \cdot year$
	PV electricity injected into grid (PVI)	$kWh_{e-pv}/m^2 \cdot year$
	Self-consumption rate (SC)	%
	Self-sufficiency rate (SS)	%
	NR Cumulative Energy Demand (CEDnr-op)	$kWh_{NRE}/m^2 \cdot year$
	Global Warming Potential (GWP-op)	$kgCO_{2-eq}/m^2 \cdot year$
Life-Cycle Analysis (LCA) (Operational and construction phase)	NR Cumulative Energy Demand (CEDnr)	$MJ_{NRE}/m^2 \cdot year$
	Global Warming Potential (GWP)	$kgCO_{2-eq}/m^2 \cdot year$
	Energy Payback Time (EPBT)	years
	GHG Emissions Payback Time (GPBT)	years
Life-Cycle Cost (LCC)	Investment cost (I)	CHF/m^2 or CHF
	Net present value (NPV) – 30 years investment horizon	CHF/m^2 or CHF
	Internal rate of return (IRR) – 30 years investment horizon	%
	Payback time (PBT)	years

4. RESULTS

4.1. Photovoltaic performance

Table 2 presents the results of the different indicators regarding the photovoltaic performance for each scenario. Overall, results are much better than those obtained using the Swiss grid electricity, which presents 2.52 $kWh_{NRE}/kWh_{e\text{-}grid}$ and 0.102 $kgCO_2/kWh_{e\text{-}grid}$ [18]. Indeed, even though the cost of a BIPV installation remains high, the LCOE, between 0.042 and 0.089 CHF/kWh, is much more beneficial than the 0.25 CHF/kWh from the grid. The same trend is obtained for the non-renewable primary energy factor and the carbon content of the PV electricity produced. In this case, values are between 0.156 and 0.200 kWh_{NRE}/ $kWh_{e\text{-}pv}$ (for NRE_{PV}) and 0.041 and 0.052 $kgCO_2$/ $kWh_{e\text{-}pv}$ (for CCF_{PV}), again better than the values from the grid which are of 2.52 and 0.102 respectively. In terms of energy (EPBT) and GHG emission (GPBT) payback time, all values are lower than 25 years (performance warranty period of the PV modules). These values highlight that the preconceived idea that BIPV installations are not effective in terms of environmental impact is questionable, even in the case where the active surfaces do not present an optimal orientation/inclination. In this case, the values of the energy yield, which give an idea of the production performance of the BIPV installation, are between 748 - 957 $kWh_{e\text{-}pv}/kWh_p$. Logically, when the active surfaces are selected to reach a good balance between SS and SC, instead of using all available surfaces, a higher value could be obtained as shown in [8,19].

Table 2: Photovoltaic performance indicators (regarding only the BIPV installation)

Indicator [units]	E0	S0	S1	S2	S3
$LCOE_{PV}$ [CHF/$kWh_{e\text{-}pv}$]	-	-	0.042	0.056	0.089
NRE_{PV} [kWh_{NRE}/ $kWh_{e\text{-}pv}$]	-	-	0.156	0.157	0.200
CCF_{PV} [$kgCO_2$/ $kWh_{e\text{-}pv}$]	-	-	0.041	0.041	0.052
$EPBT_{PV}$ [years]	-	-	3.2	3.3	4.1
$GPBT_{PV}$ [years]	-	-	11.9	12	15.2
Energy yield	-	-	957	950	748

4.2. Final energy balance (operational phase)

In order to conduct the hourly-step energy performance simulations using DesignBuilder [20], the thermal envelope features are defined and presented in Table 3. The U-values for the E0 are defined through a detailed analysis of the existing building envelope. For scenarios S0 and S1, the target corresponds to SIA 380/1:2016 [14] requirements. For scenarios S2 and S3, it corresponds to the values obtained for the constructive detail proposition showed in Figure 3.

Table 3: Final U-value of the different parts of the building envelope and the infiltration rate for each design scenario. Layers composition and materials according to data from: * Swiss catalogue [21]; ** Database WINDOW [22] and DesignBuilder [20].

<table>
<tr><th></th><th>Roof*</th><th>Façade*</th><th>Internal floor*</th><th>External floor*</th><th>Openings**</th><th>Infiltration rate</th></tr>
<tr><td></td><td colspan="5">U-value [W/m².K]</td><td>ACH</td></tr>
<tr><td>E0</td><td>1.69</td><td>1.07</td><td>0.94</td><td rowspan="5">1.74</td><td>5.70</td><td>2.00</td></tr>
<tr><td>S0</td><td colspan="2">0.25</td><td rowspan="4">0.30</td><td>1.30</td><td>1.00</td></tr>
<tr><td>S1</td><td colspan="2">0.20</td><td rowspan="3">0.77</td><td rowspan="2">0.70</td></tr>
<tr><td>S2</td><td colspan="2">0.19</td></tr>
<tr><td>S3</td><td colspan="2">0.17</td><td>0.50</td></tr>
</table>

Observing the final energy balance presented in Table 4, the considerable energy consumption of the current status (E0) highlights the importance of an energy renovation for this type of building. In scenario S0, implementing a current practice renovation without BIPV elements reduces the total energy consumption from 262 to 95 $kWh/m^2\cdot year$ (representing a 64% of reduction). When, in combination with the passive strategies, the HVAC system is replaced by a high-efficiency heat pump, the final energy savings achieve 83% (S1), 85% (S2) and 87% (S3). In addition, S1-S3 produce a considerable amount of electricity on-site, in some cases making the building a positive energy building that produces more energy than it needs over an annual balance (negative values in Table 4). In terms of environmental impact of the energy consumption (operational phase) considering the different energy sources (oil and electricity), results for the current status (E0) are far from the 2’000-Watt Society targets for both CEDnr (target of 69.4 kWh/m^2·year) and GWP (target of 5 kgCO$_2$/m^2·year). For this building, S2 and S3 scenarios comply with the 2050 targets.

Table 4: Energy balance indicators (operational phase)

Indicator [units]	E0	S0	S1	S2	S3
FE Consumption (Oil) [kWh/m^2·year]	243	76	-	-	-
FE Consumption (Elec.) [kWh/m^2·year]	19	19	43	37	31
PVSC [kWh$_{e-pv}$/m^2·year]	-	-	10	10	13
PVI [kWh$_{e-pv}$/m^2·year]	-	-	29	33	84
SS | SC [%]	-	-	24 | 26	27 | 24	38 | 13
CED$_{nr}$ [kWh$_{NRE}$/m^2·year]	346	141	14	-15	-184
GWP [kgCO$_2$/m^2·year]	75	25	1	-1	-13

4.3. Life-cycle analysis (operational and construction phase)

This section shows the global Life-cycle analysis results, considering both the operational phase and the environmental impact of the construction materials. Table 5 shows the results for all scenarios (E0, S0, S1, S2 and S3). Results are expressed in CEDnr and GWP to compare with the 2’000-Watt Society targets respectively of 310 MJ$_{NRE}$/m^2·year and 10 kgCO$_{2-eq}$/m^2·year. Considering the injection into the grid of the electricity overproduced, the three BIPV scenarios comply with the requirements of the 2’000-Watt Society. In terms of payback times (Table 5), values obtained are between 2.7-2.6 years (for EPBT) and 2.9-4.6 years (for GPBT).

Table 5: Life-cycle analysis indicators (operational and construction phase)

Indicator [units]	E0	S0	S1	S2	S3
CEDnr [MJ$_{NRE}$/m^2·year]	1246	539	95	10	-502
GWP [kgCO$_{2-eq}$/m^2·year]	75	27	5	4	0
EPBT [years]	-	2.7	2.6	2.6	2.4
GPBT [years]	-	2.9	3.4	3.6	4.6

4.4. Life-cycle cost

This section shows the results of the life-cycle cost assessment to give an overview of the cost-effectiveness of the different renovation scenarios. Results for all economic indicators are presented in Table 6, including the global investment cost, the net-present value (NPV) and the internal rate of return (IRR) for 30 years investment horizon, and the payback time (PBT) corresponding to the year when the NPV becomes positive or the IRR is equal to the discounted rate (3%). It can be observed how, despite the fact that the scenarios with BIPV present a greater investment, the profitability values (IRR and PBT) are equivalent or better than the values obtained in the S0 scenario (without BIPV), highlighting the self-financing effect of the on-site energy production by the BIPV installation.

Table 6: Life-cycle cost indicators

Indicator [units]	E0	S0	S1	S2	S3
Investment [CHF/m2]	-	715	777	814	1098
NPV* [CHF/m2] – 30 years invest. horizon	-	222	461	481	272
IRR* [%] – 30 years invest. horizon	-	4.7	6.2	6.2	4.5
PBT [years]	-	18	16	16	19

5. CONCLUSIONS

This article has focused on the potential for improvement that can be achieved using photovoltaic energy and showing, through photorealistic images and construction details, that a quality architecture can be obtained using existing products on the market. Based on the results of the multi-criteria evaluation, there is no doubt that energy renovation projects without renewal energy integration (in this case BIPV) are no longer an option if we want to achieve the 2050 objectives. The improvement of the building envelope using passive strategies is a crucial first step, but is not enough. Compensating buildings' energy consumption by producing and consuming electricity on-site has become a priority. In this sense, by proposing new BIPV applications for renovation projects in the built environment, the research contributes to advancing architectural design practices in this direction. The results of this case study highlight several interesting elements, such as that the self-financing effect offered by the renewal design scenarios with BIPV solutions. Our example shows that it is possible to achieve up to 83% of total energy savings by implementing a mix of strategies composed by passive, active and BIPV strategies. Therefore, in order integrate PV on existing buildings from a holistic point of view, an iteration process between constructive design and building performance simulation appears as a key factor to achieve high-level of self-consumption with a reasonable PV installation. This iterative process allows us to optimise the installation by minimising the energy injected into the grid. The outputs of this case study could contribute to provide architects, installers and public authorities with examples of how PV elements could be integrated to achieve both design and energy-performance objectives.

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