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Influence of Design-Decisions on The Energy Performance of Renovation Projects with Building-Integrated Photovoltaics:
Results for a 1968 residential archetype in Neuchâtel (Switzerland)

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ABSTRACT: The renovation of existing buildings is one of the priorities of western countries and needs to be promoted to increase the current low renovation rate, estimated to be of 0.6% per year in the European and Swiss contexts. In parallel, the implementation of building-integrated photovoltaic (BIPV) elements during the renovation process can provide a crucial response to achieve the 2050 targets in terms of greenhouse gas (GHG) emissions and energy savings. In this context, architects, designers and engineers have a key role in achieving these objectives, mainly because they are responsible for the design decisions during the development of the projects, especially during the early-design phase when the most influential decisions are taken. Through a real-case study built in 1968, this research shows how certain design-decisions in renovation processes can affect or compromise the final performance of the building from a global life-cycle and multi-criteria approach. Life-Cycle Analysis (LCA) and Cost (LCC) results show the importance of not losing the opportunity to go beyond current practices when a building needs to be renovated and highlight the necessity to take into consideration BIPV strategies to guarantee both economic and environmental targets.
KEYWORDS: Integrated design, Building renovation, Building-Integrated Photovoltaics, Life-Cycle Analysis, Life-Cycle Cost

1. INTRODUCTION
The renovation of buildings is one of the priorities of western countries, where regulatory frameworks are becoming increasingly demanding in terms of energy performances. For instance, Switzerland has an ambitious target for 2050, year at which primary energy consumption and greenhouse gas (GHG) emissions must be reduced by 45% and 76% respectively compared to 2005 [1]. However, with the current renovation rate of 0.6% per year [2], it is impossible to achieve the 2050 targets. The implementation of building-integrated photovoltaic (BIPV) systems during the renovation process can provide a crucial response to the Swiss energy turnaround challenges [3]. Functioning both as envelope material and on-site electricity generator, they can simultaneously reduce the use of fossil fuels and GHG emissions, and promote energy efficiency renovation projects [4]. In this context, architects have a key role in achieving these objectives, mainly because they are responsible for the design decisions that are made in the energy renovation projects of existing buildings [5]. They have the opportunity to convince owners to implement more energy-efficient solutions. This article shows how certain design decisions during renovation projects' processes can affect the final energy performance of a building while simultaneously showcasing new BIPV products available, therefore promoting high quality architecture with active elements. Through a real-case study built in 1968, results show the Life-Cycle Analysis (LCA) and Life-Cycle Cost (LCC) performance of different renovation design scenarios, and different energy use scenarios studied in an iterative process between the design and simulation phases.

2. LITERATURE REVIEW
This section presents a concise literature review to contextualise this research. There are recent publications about how to help designers in decision-making during the design process for new buildings [6–8], using multi-criteria assessment [7]. However, there is lack of studies convening renovation, residential buildings and BIPV in the same study. The originality of this study lies in this combination, focusing on helping decision-makers to better deal with the renovation projects of existing residential buildings integrating photovoltaic energy from the early design stages.

3. METHODOLOGY
The research involves four main phases: **1**) identification of five residential archetypes taking Neuchâtel as a representative city in Switzerland; **2**) detailed analysis of a real case study per archetype; **3**) implementation of

design scenarios embodying BIPV solutions and different levels of intervention; **4**) multi-criteria assessment of the scenarios. While further details on the methodology can be found in [4,9], emphasis here is placed on the results obtained after the implementation of each design scenario, to analyse how the design decisions condition the LCA and LCC performances. Our calculation takes into account the whole renovation process, including operational energy as well as the embodied energy from construction materials, BIPV elements, and heating, ventilation and air-conditioning (HVAC) system improvement. After the selection of a real case study, five renovation scenarios are defined from an architectural point of view. The **E0-Current status** scenario reflects the actual situation of the building. The **S0-Baseline** scenario – without BIPV – aims at achieving at least the current legal requirements SIA 380/1:2016 [10], in accordance with current practice. The last three scenarios incorporate BIPV strategies. **S1-Conservation** aims to maintain the expression of the building while improving its energy performance (at least up to current legal requirements). **S2-Renovation** has as purpose to maintain the general expressive lines of the building while reaching high energy performance (at least *Minergie*® standard). For **S3-Transformation,** the goal is to achieve the best energy performance (at least the Swiss targets for 2050 [1]) with aesthetic and formal coherence over the whole building.

These general design concepts are implemented taking into account the specific characteristics of each building. Consequently, the strategies are adapted to each case study to provide the most adequate means for achieving the design objectives. The results of the design scenarios implementation, described in the following section, allow to define constructive details and identify all possible active surfaces on roof and façades, which will be considered to substitute traditional inert construction elements by BIPV elements permitting to produce electricity. During this phase, an iterative process between design and energy simulation is conducted using DesignBuilder v.5 [11] and DIVA v.4 [12] via the Grasshopper graphical algorithm editor integrated with the Rhino 3-D modelling tool [13].

All data are saved in an Excel database, allowing to create an in-house assessment tool allowing to easily compare between scenarios and extract results.

This paper shows two kinds of results. First, the range of results obtained according to the design parameters (Table 1), using an online application to generate parallel coordinate plots (PCP) [14]. The use of PCP allows users to detect which are the key parameters to be able to reach one or several pre-set objectives. Second, we present the detailed results of the LCA and LCC for the scenarios that allow reaching a higher level of performance compared with the Swiss objectives for 2050 (Fig. 6 and 7).

Table 1 presents the different design parameters used in this study. In terms of inputs we propose five options: 1) design concept (or renovation design scenarios), 2) active strategy (maintaining the existing gas-boiler or replacing it by an electric heat-pump), 3) using active elements or not (to compare with a non-active renovation option and highlight the benefits of including BIPV elements), 4) three possible energy-use scenarios: (*A-100%*) using all possible active surfaces detected in the design process, (*B-Selection*) making a selection according to the energy demand of the building or (*C-Batteries*) including batteries [9], 5) with or without the possibility to inject the overproduction into the grid, and 6) taking into account or not the public subsidies (for BIPV, HVAC and improvement of the thermal envelope).

The selection of the façade elements that would be active – versus “dummies” or “inert” modules – depends on an optimisation process between on-site production and building consumption to maximise self-consumption and self-sufficiency ratios (corresponding to the energy-use scenario named *B-Selection*).

In addition, our holistic approach also considers the integration of batteries (*C-Batteries*) with an adapted sizing method based on the cost-effectiveness of this additional investment, to guarantee the optimum size of the storage system according to the lifespan of the existing products on the market, specifically lithium-ion batteries technology [15–17].

Table 1: Input-Output design parameters.

Input parameters	**Values**
Design Concept	E0, S0, S1, S2 or S3
HVAC	Gas-Boiler or Heat-Pump
Active elements	Active or Non active
Energy-use scenario	A, B or C
Injection	Yes or No
Subvention	Yes or No
Output parameters	**Units**
Total PV production	MWh/year
Self-consumption (SC) ratio	%
Self-sufficiency (SS) ratio	%
Electricity consumption	kWh/m^2.year
Gas consumption	kWh/m^2.year
Cumulative energy demand	kWh/m^2.year
Global warming potential	kgCO_2/m^2.year
Net investment cost	CHF
Energy bill	CHF/year
Payback period	Years
Internal Rate of Return	%

For example, implementing the scenario S3-transformation including the replacement of the exiting HVAC system and an optimization of the actives surfaces, the storage system (sized for a mean daily electricity demand of capacity) presents about 1100 discharge cycles per year. Thus, if batteries could support about 7500 cycles at 80% depth of discharge (DOD)[16], that means about 7 years of life span.

The output parameters correspond to the multi-criteria evaluation process based on the LCA and LCC approach.

These parameters and the methodology used in this research are fully described in [4,9].

4. RESULTS

The case study presented in this paper corresponds to a residential archetype built in 1968 (Fig. 1) of 7 stories, 48 apartments and 4'415 m^2 of total floor area. It has a poorly insulated envelope, its façades are made of perforated brick with a 4 cm air gap and double-glazed windows, and it has a flat roof with 6 cm of expanded polystyrene (EPS) insulation and 5 cm of gravel. In terms of active systems, this building has a central gas boiler covering heating and domestic hot water (DHW) needs.

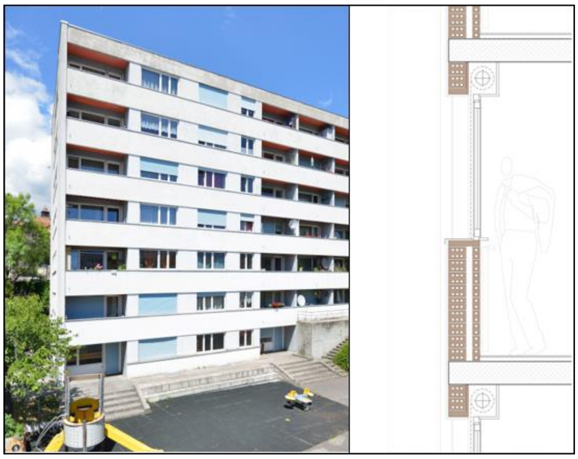

Figure 1: Scenario E0 - Current Status. Image and construction detail of the existing façade.

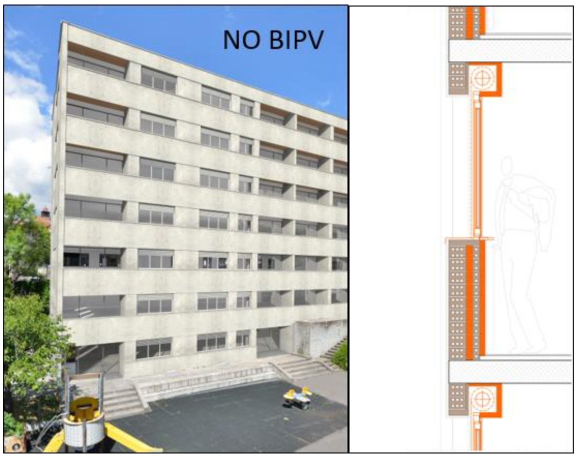

Figure 2: Scenario S0 - Baseline.

The results presented here correspond to the implementation of the renovation design scenarios into concrete strategies for the present case study. For **S0** (Fig. 2), only passive strategies are applied to reduce the energy demand. The performance of the envelope is improved by adding internal insulation (filling the air gap of the existing façade) and by substituting the windows to achieve the current legal requirements.

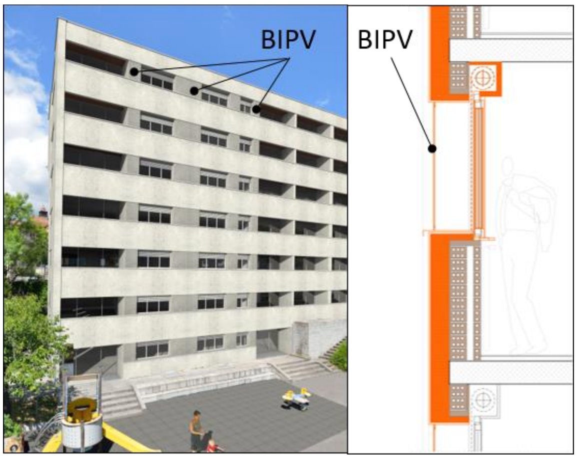

Figure 3: Scenario S1 - Conservation.

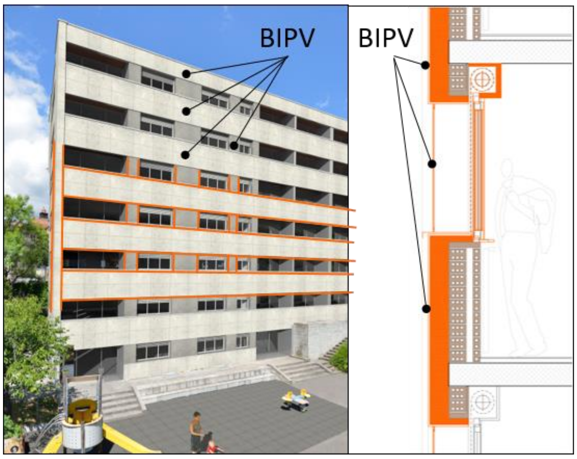

Figure 4: Scenario S2 - Renovation.

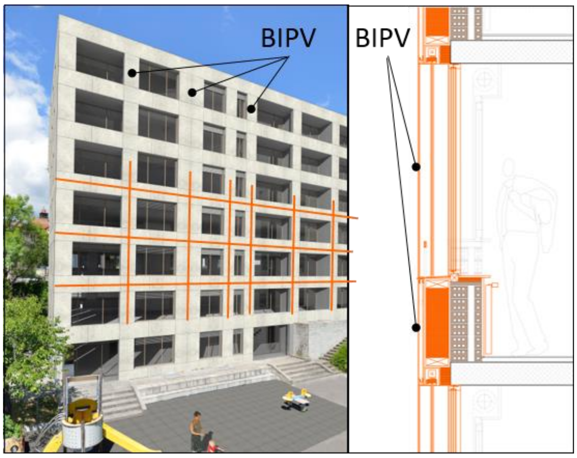

Figure 5: Scenario S3 - Transformation.

For **S1** (Fig. 3), we propose an external insulation façade system and the replacement of existing windows (frame and glazing). Moreover, the space between the windows is covered with custom sized coloured BIPV elements, maintaining the original aspect of the building.

For **S2** (Fig. 4), in addition to S1 strategies, active elements are installed over the long horizontal bands between floors with standard-size coloured BIPV panels, respecting the main expressive lines of the building's architecture while accepting visible joints between panels and completing the rest of the surfaces with non-active panels with the same appearance.

Finally, for **S3** (Fig. 5), we propose a prefabricated low-carbon façade system to plug directly onto the existing façade, including insulation (ventilated facade), new windows, and BIPV elements covering all opaque surfaces. Standard-sized panels are used to modulate the entire façade, accepting visible joints and a new aspect of the building.

An optional active strategy for the S1, S2 and S3 scenarios regarding the HVAC system (for heating and DHW) is proposed: substituting the existing gas-boiler by an electricity-based system using an air-water heat-pump (AWHP) to increase the energy efficiency of the HVAC system and the self-consumption (SC) ratio (by using more intensively the BIPV installation).

As defined in Table 1, three energy-use scenarios are tested (*A-100%*, *B-Selection* and *C-Batteries*). These are defined in three sequential design phases using parametric simulations, as further detailed in [9].

By conducting hourly simulations with a 3D model generated according to the above mentioned design scenario implementation, taking into account the urban context, we obtain the global warming potential (GWP) expressed in GHG emissions and non-renewable cumulative energy demand (CEDnr) results shown in Fig. 6.

We observe that for **S0** (Fig. 2), the design concept remains too conservative with only passive strategies implemented, thus limiting (for the operational phase) the energy savings to 47% and the GHG to 51%.

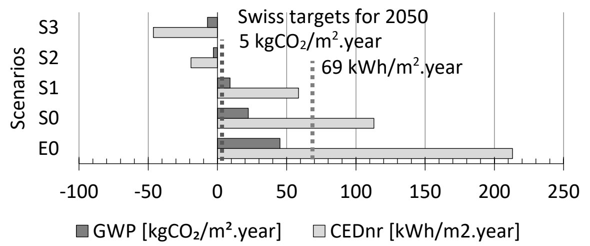

Figure 6: Results for the operational phase (use of building).

The **S1** design concept allows to achieve 72% of savings. This scenario requires fully customized BIPV elements, but it does not take advantage of the improvement potential of the building. For **S2** and **S3** the building produces more energy than it consumes, thus meeting the Swiss targets for 2050.

The implementation of the **S2** design concept, which allows visible joints without disturbing the horizontal expression of the building, enables the building to achieve 109% of energy savings. **S3** reaches 122% of energy savings, while ensuring an aesthetic and formal coherence of the completely active façade using standard-size BIPV element. Moreover, the change in the proportion of windows allows increasing the daylighting potential (results not shown here).

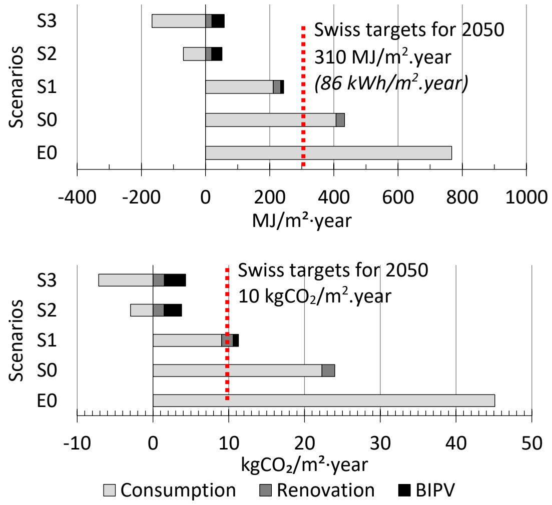

Figure 7: Life-Cycle Analysis (LCA) results in terms of CEDnr (top) and GWP (bottom).

In order to highlight the improvement potential of this real case study from 1968, Fig. 7 shows the most energy performing cases, which correspond to BIPV scenarios with the replacement of the existing gas-boiler by an AWHP, with the possibility of injecting the overproduction into the grid.

The results are for the whole LCA, considering CEDnr and GWP for both the operational phase (use of building) and construction materials (including BIPV elements). The savings needed to achieve the 2050 targets are of 59% (for CEDnr) and 77% (for GWP). It is important to highlight that all scenarios including BIPV elements achieve the CEDnr target, but only **S2** and **S3** achieve both the CEDnr and GWP targets.

In terms of LCC, Fig. 8 shows the payback time (PBT) resulting of the application of the different design scenarios, using three distinct energy-use options and with the possibility of injecting the electricity overproduction into the grid.

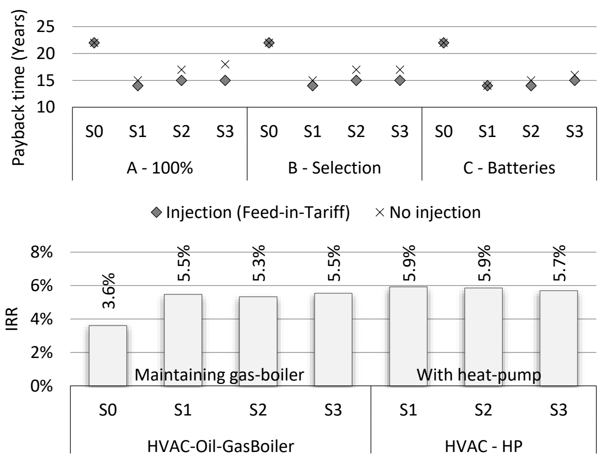

Figure 8: Life-Cycle Cost analysis (LCC) results in terms of payback time (top) and internal rate of return (IRR) (bottom).

We observe that BIPV scenarios have a lower PBT, thus are significantly more cost-effective than the **S0** (current renovation practice). As mentioned in [2], current practices in renovation projects like the S0 scenario make it difficult to achieve cost-effectiveness objectives such as an internal rate of return (IRR) of 4% or more, where 4% corresponds to a typical value used in economic analysis for private construction investors.

These results indicate that renovation with BIPV scenarios could help to overcome this economic barrier. Fig. 8 also shows the results in terms of the annual financial viability of the investment, using economic savings due to both energy consumption reduction and energy efficiency increase. It is important to highlight that the best results correspond to BIPV scenarios, achieving between 5.3% and 5.9% of annual profitability. Considering the amount of data generated in this study, as mentioned in the methodology section, the objective is to help architects, engineers and stakeholders involved in renovation processes to explore the whole range of solutions and highlight the influence of the different design decisions according to the parameters of Table 1. Fig. 9 shows, through a PCP, the range of solutions and highlights the design parameter combinations that allow to achieve CEDnr and GWP targets. It is possible to explore the results of this case study by following this link: https://goo.gl/JspwGL.

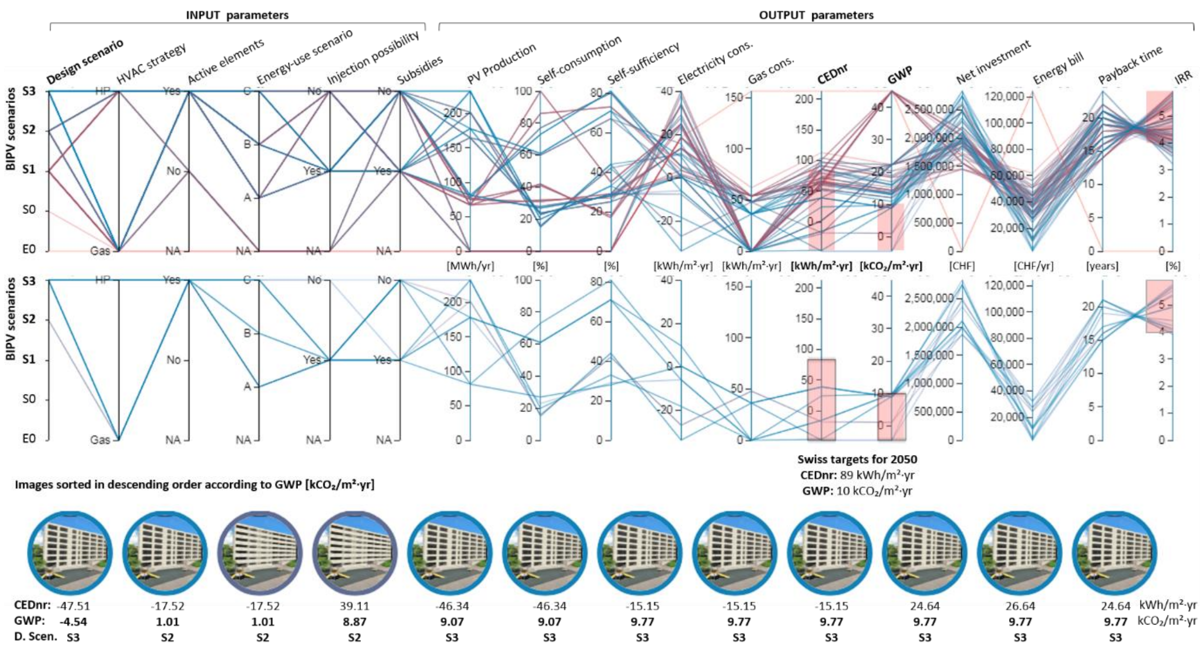

Figure 9: Parallel coordinate plot (PCP) with all design variants (top) and filtering results according to the Swiss targets for 2050 (bottom). Visualisation data using the Design Explorer online application [14].

5. CONCLUSION

In light of our results, it is important not to miss the opportunity and to carry out a detailed analysis considering BIPV strategies when planning the renovation of a building, instead of settling for a superficial renovation. Likewise, this study highlights the necessity to take into consideration BIPV strategies to guarantee both economic and environmental targets.

It is important to conduct these variations in terms of energy-use scenarios (*A-100%, B-Selection and C-Batteries*) to ensure a better integration of BIPV elements not only from a construction point of view, considering BIPV as a new construction material, but also from an operational and exploitation approach.

By exploring results using PCP, it is possible to highlight the range of strategies that helps to achieve certain objectives and to check the compatibility between other strategies.

For example, filtering results with the 2050 targets (CEDnr = 86 kWh/m^2.year; GWP = 10 CO_2/m^2.year) and a typical profitability objective (IRR = 4%), only two BIPV scenarios (S2 and S3) remain possible. The range of valid scenarios includes variants without necessity of subsidies, which means that the results of this study can be used to more effectively manage the economic resources allocated to subsidies, prioritizing for instance projects with more difficulties to obtain an acceptable profitability.

These results should motivate the use of BIPV elements in renovation projects, accelerating the renovation rhythm of the building stock. They also provide valuable information to make new guidelines to be included for example in masterplan developments to ensure the realisation of high quality active renovation projects.

Through a design-driven approach, the use of BIPV elements can be promoted as a new construction material for facades and roof, as it allows great variety of formal solutions.

Finally, results show that if a greater degree of intervention is permitted, without compromising the architectural quality, the necessary levels of energy performance can be achieved, significantly reducing the environment impact, increasing indoor comfort and the value of the existing building stock.

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