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Exploring the Robustness of Building-Integrated Photovoltaics Renovation Scenarios to Climate Change Perspectives:

Results for a multi-family building in the Swiss context

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ABSTRACT: Building renovation is one of the main strategies put forth in western countries, where energy regulations are becoming increasingly demanding. Switzerland for example has set the ambitious target aiming at carbon neutrality for 2050. Building-integrated photovoltaic systems, functioning both as envelope material and on-site electricity generator, have the potential to strongly contribute towards these objectives. When designers consider the fulfilment of the 2050 objectives, the question of the robustness of the design decisions to the different climate change (CC) scenarios appears. Designing today, but taking into account climate evolution pathways, is a new challenge that architects must face. Based on publications from the IPCC, we know that CC effects, characterized by global warming, are already visible. In this context, we must learn to design by integrating uncertainty related to CC. One way to take these changes into account is the use of artificial weather files representing different possible scenarios. Focusing on the energy performance of a multi-family building, this article compares the results obtained for a series of BIPV renovation variants based on three IPCC scenarios. Despite the impact on the energy performance, results show no contradiction with respect to the strategies designed using the typical meteorological year scenario.

KEYWORDS: building-integrated photovoltaic, renovation, robustness, climate change, synthetic weather files

1. INTRODUCTION

Energy regulations in western countries are becoming increasingly demanding. Switzerland for example has set the ambitious target for 2050 of reducing its greenhouse gas (GHG) emissions by 76% compared to 2005 [1]. More recently, the government has even announced aiming at carbon neutrality for 2050 [2].

In this context, within the building sector, the renovation of the building stock – which contains a significant proportion of buildings of over 40 years old [3] – is put forth as one of the main energy efficiency strategies. Within the design decisions made for the renovation of a building, the relevance of the concept of building-integrated photovoltaic (BIPV) systems, functioning both as envelope material and on-site electricity generator, is only starting to emerge [4,5]. Together, renovation integrating BIPV strategies have the potential to strongly contribute towards the carbon emission reduction objectives.

However, at the moment when the design team considers the fulfilment of the objectives for a future horizon such as 2050 or even 2100, the question of the robustness of the design decisions to the different climate change (CC) scenarios arises. Designing today, but taking into account various climate evolution pathways, is a new challenge that architects and building engineers must face. Based on publications from the Intergovernmental Panel on Climate Change (IPCC) [6], we know that CC, characterized by global warming, is a reality and its effects are already visible. In this context, actors from the construction sector must learn to design by integrating uncertainty related to CC. One of the tools available to take these changes into account is the use of artificial weather files representing different possible scenarios.

There are recent publications about research projects [7,8] that are concerned with this issue from the point of view of resilience – generally defined as the ability of humans to adapt positively to adverse situations – measured in terms of the structural resistance to catastrophic events such as earthquakes, etc. Some articles apply this concept to the energy performance of buildings, using building performance simulation (BPS) to study various design scenarios and evaluate the changes in the energy efficiency as a function of climate evolution (increase in average temperature, increase in cloudiness, decrease in effective solar radiation, ...) [9,10,19–23,11–18].

However, there is lack of studies convening the renovation of residential buildings and BIPV.

This article proposes a new approach focusing on the evaluation of the robustness of decision making in renovation projects that integrate photovoltaic strategies (using facades and roofs). The notion of robustness is here understood as the stability of a building energy performance over time in the face of changing climate conditions. In the sense it can be seen as a part of the resilience concept.

Focusing on the energy performance of an existing multi-family building, this article compares the results obtained for a series of BIPV renovation variants based on three different IPCC scenarios (A1B, B1 and B2) for time horizons from 2020 to 2100.

The question to be answered by this research is related to the sizing method of photovoltaic installations based on a trade-off between self-consumption and self-sufficiency (the full calculation method is exposed in [24,25]). To calculate these two parameters, hourly simulations are carried out, taking into account the urban context and using a TMY climate file (with historical data from the last 30 years).

Due to the global warming that is already evident, we can state beforehand that, if the average temperature increases, the demand for heating would tend to decrease and the opposite for the demand for cooling. However, the electricity production by a photovoltaic installation, and the match between demand and production, are more difficult to anticipate or predict.

For this reason, this article explores the variations in terms of energy consumption and production, as well as the match between the two, to assess whether the use of artificial climate files – reflecting future scenarios according to the IPCC – could substantially change the decisions made using a TMY climate file.

2. METHODOLOGY

The research involves four main phases: **1**) detailed analysis of the building and implementation of design scenarios embodying BIPV solutions and different levels of intervention; **2)** iterative process between design and building-performance simulation (BPS) to define the construction strategies and to obtain the final energy needs and the photovoltaic performance using a TMY (typical meteorological year) weather file with historical data from 1991 to 2010; **3)** BPS process for all renovation variants and CC scenarios using the different artificial weather files according to the IPCC; **4)** comparison of the results in terms of energy consumption and production. While further details on the implementation of each renovation scenario (phase 1) and the simulation conditions (phase 2) can be found in [25], the emphasis is here placed on the comparison of the different IPCC synthetic weather files and comparison of the energy performance results, to analyse the level of robustness of the different renovation scenarios originally designed using a traditional TMY weather file.

The case study presented in this paper corresponds to a multi-family building built in 1968, with 7 stories, 48 apartments and 4,415 m^2 of floor area. This building is highly representative of the Swiss building stock from the late 60's – early 70's [25].

It has a low-performance building envelope: non-insulated façade composed by ceramic brick with a 4 cm air gap and double-glazed windows. The flat roof holds 6 cm of EPS insulation protected with 5 cm of gravel. Five renovation strategies, including both passive (e.g. insulation addition) and active (i.e. related to the systems) strategies are implemented. The **E0** scenarios corresponds to the current status of the building and the **S0** scenario represents the achievement of minimum legal requirements in terms of energy performance [26], both are without BIPV. The **S1**, **S2** and **S3** scenarios include BIPV strategies and respectively correspond to three levels of interventions regarding both architectural expression modification and energy performance targets (from current practice to Swiss targets for 2050 [1]). Passive strategies (**Fig. 1**) mainly involve, the increase of the global thermal insulation of the roof and façades (adding insulation on the opaque parts of the building envelope and replacing the existing windows).

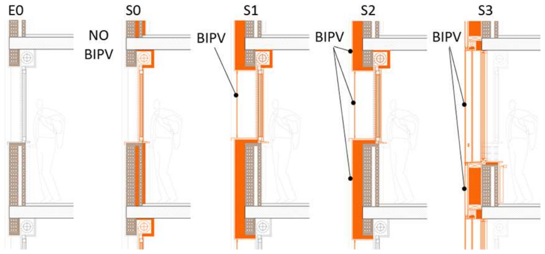

Figure 1: South façade section for each renovation scenario. In orange: added or modified construction elements.

For scenarios **S1**, **S2** and **S3**, the strategies include BIPV elements on the façade (as cladding material) and a standard PV installation on the flat roof (with south-oriented panels inclined at 45°). In terms of active strategies, for this study, a typical central HVAC system based on an electric heat-pump is proposed to cover heating, cooling and domestic hot water (DHW) needs.

To conduct the BPS process (to obtain hourly-step energy consumption and PV production), four different weather files were used for the analysis: the TMY based on historical data from 1991 to 2010, and three synthetic files generated with Meteonorm [27] corresponding to the three main IPCC scenarios (B1, A1B and A2). These files have been extracted for 5 time-horizons: 2020, 2030, 2040, 2050 and 2100. Apart from the BPS using

DesignBuilder [28] to obtain the energy needs, a detailed calculation of the PV performance (on-site production, self-consumption (SC) and self-sufficiency (SS) rates) is conducted considering the BIPV surfaces proposed for each scenario (the full calculation method is exposed in [24,25]). **Figure 2** shows the results of the irradiation study for each BIPV scenario using the TMY weather file.

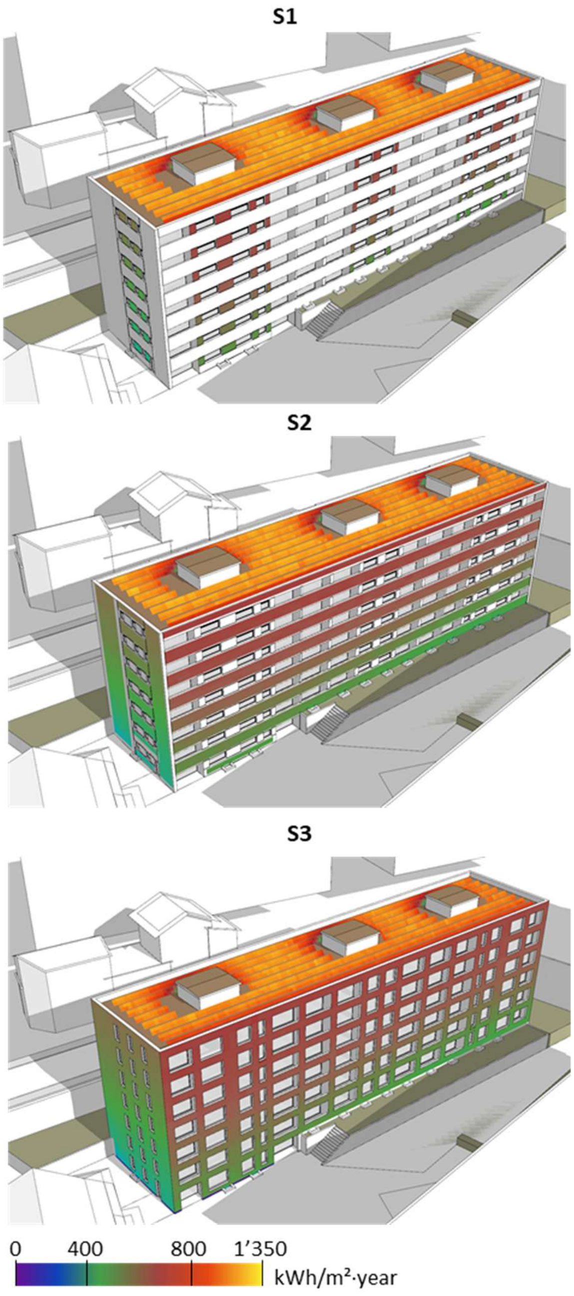

Figure 2: Example of annual irradiation study results for each BIPV scenario (façade and roof) using the TMY weather file (1991-2010).

In its Fourth Assessment Report (AR4) [6], the IPCC has developed 40 emission's scenarios that are grouped into four families, each based on some assumptions related to, for instance, human activity and projected global average surface warming until 2100. Each scenario follows different hypotheses for future greenhouse gas emissions, land-use, technological development as well as future economic development. It is important to know that all these scenarios are defined as "neutral" by the IPCC, meaning that they don't take into account future catastrophes (e.g. geopolitical conflicts, war, pandemics, and/or environmental collapse).

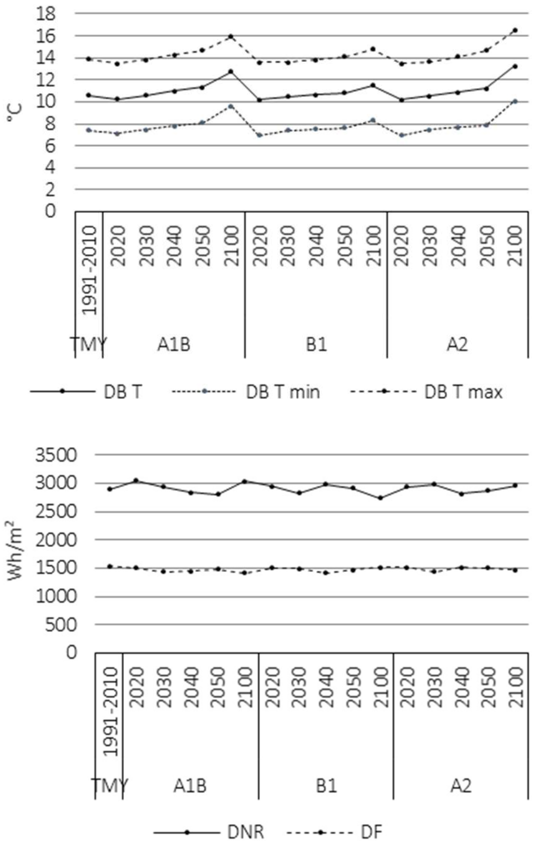

Figure 3: Dry-bulb temperature (DBT), direct normal radiation (DNR) and diffuse radiation (DF) of the different weather files and horizons.

For this publication, three scenarios that follow distinct paths and that are part of three different families are considered: **A1B**, **B1** and **A2**.

A1B is characterized by a) rapid economic growth, b) population increase to 9 million by 2050 followed by a gradual decline, c) quick application of cutting-edge efficient technologies emphasising a balance on all energy sources, d) globalisation approach with extensive social and cultural interactions worldwide. The projected global average surface warming (PGASW) until 2100 is between 1.4-6.4°C.

B1 is characterized by a) an integrated and more ecologically friendly world, b) rapid economic growth with rapid changes towards a service and information economy, c) population increase to 9 million by 2050 followed by a gradual decline, d) introduction of clean and efficient technologies. The PGASW range until 2100 is of 1.1-2.9°C, lower and narrower than A1B.

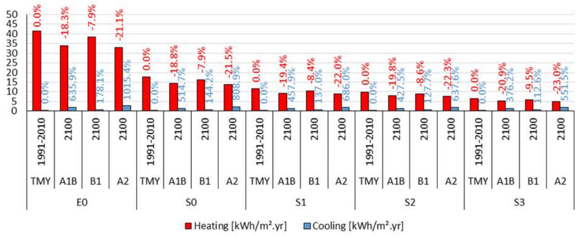

Figure 4: Heating and cooling consumption for each renovation and CC scenario for 2100. The percentages indicate the change with respect to the corresponding TMY case.

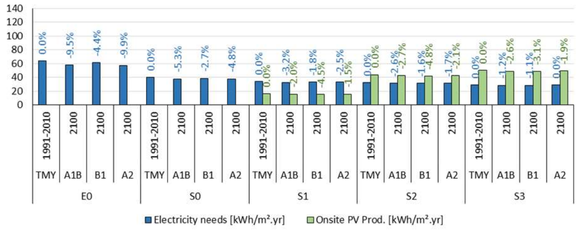

Figure 5: Total energy needs (heating, cooling, domestic hot water, lighting and appliances) and onsite PV production for each renovation and CC scenario for 2100. The percentages indicate the change with respect to the corresponding TMY case.

Finally, **A2** is characterized by a) continuously increasing population, b) low emissions, c) regional oriented economic development with self-reliant nations. The PGASW until 2100 is between 2.0-5.4°C.

Before applying the IPCC weather files to the BPS, we conduct an analysis of the different files using the climate consultant application [29]. Key information such as dry-bulb temperature (DBT), direct normal radiation (DNR) and diffuse radiation (DF) is visualised to understand the differences and their correlation with the IPCC emission's scenarios [6]. **Figure 3** shows that, compared with the TMY, the IPCC scenarios present lower solar radiation, specially A1B-2050 and B1-2100. For all IPPC scenarios, the yearly average dry-bulb temperature increases up to 2.7°C.

3. RESULTS

The results presented here correspond to the application of the method for the horizons from 2020 to 2100 using A1B, B1 and A2 scenarios compared to TMY.

Figure 4 shows the results of the heating and cooling needs for the different renovation and CC scenarios for 2100. Compared to the results obtained with the TMY of each scenario (also shown on the graph), the demand for heating decreases between 7.9-23% and cooling increases between 112-1,015%, reflecting the effect of global warming from the CC scenarios.

Comparing, this time, the total final energy consumption (heating, cooling, domestic hot water (DHW), lighting and appliances) and the onsite PV production, **Figure 5** shows – for the 2100 horizon – that the deepest renovation scenarios (S1, S2 and S3) present less difference (between 1.1 and 3.8%) compared to the results obtained with the TMY than E0 and S0 (between 2.7-9.5%). In terms of on-site PV production, the reduction is between 1.9-4.8%.

In order to explore the robustness of the different BIPV scenarios to CC perspectives, we propose to analyse the results using standardized boxplot charts showing the distribution of the data. In general, the wider the interquartile box, the greater the spread of the results, which could thus be interpreted as a lower robustness.

Figure 6 shows, as already observed in **Figure 5** for the 2100 horizon, that the deepest renovation scenarios (S1, S2 and S3) present more concentrated results, meaning that the electricity needs show less variation across the CC scenarios. The shallow renovation (S0) also shows less variation than the non-renovated scenario (E0), whose energy efficiency depends heavily of the CC conditions. In that sense, it can be seen as less resilient.

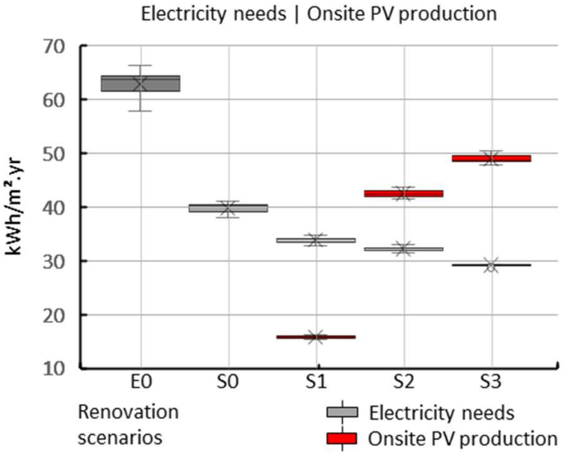

Figure 6: Total energy needs and onsite PV production for each renovation scenario (all CC scenarios and horizons combined). No BIPV installation for E0 and S0 scenarios.

On the other hand, among the BIPV scenarios, those with installations covering more surface (particularly façade surfaces) – S2 and S3 – show greater sensitivity to weather scenarios across time horizons.

The self-sufficiency (SS) and self-consumption (SC) ratios are shown in **Figure 7**. The most stable result is the SC of the S1 scenario, which varies within a 0.5% range across all weather files (TMY and CC scenarios for all horizons). Less stable is the SS of S2, showing a (still low) 2% variation.

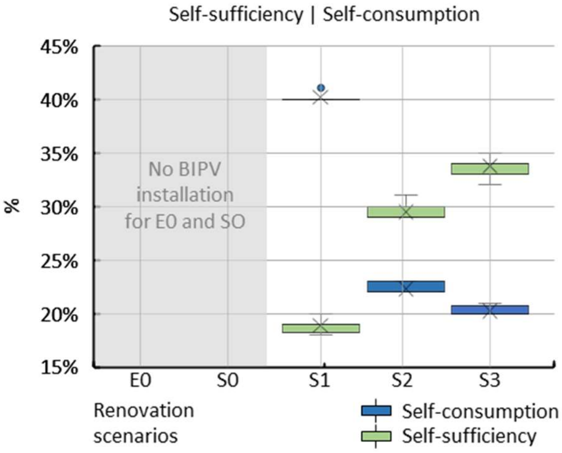

Figure 7: Self-consumption and self-sufficiency ratios for each renovation scenario (all CC scenarios and horizons combined). No BIPV installation for E0 and S0 scenarios.

Comparing the energy balance calculated by subtracting the energy needs to the onsite PV production (**Figure 8**), we observe that the uncertainty within the renovated scenarios, with or without BIPV strategies, is less important than for scenario E0. For S2 and S3, the building remains energy-positive.

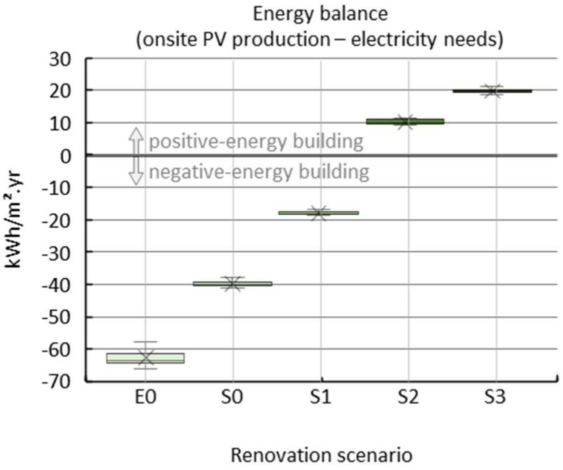

Figure 8: Energy balance (onsite PV production – electricity needs) for each renovation scenario (all CC scenarios and horizons combined).

From all these graphs, we observe that the distribution of the results is not distinct enough to say that the decisions made using a TMY weather file would be different if a CC scenario was considered. Indeed, design choices and BIPV sizing made based on the TMY appear as valid for the future, although uncertain. This is supported by the relatively narrow variations between the CC scenarios and horizons – as illustrated by the box charts – as well as the stability in the pattern among renovation scenarios (with S2 and S3 always performing better).

4. CONCLUSION

This paper presents a comparison of the simulated energy consumption and production (through BIPV) of different renovation strategies using distinct weather files: the commonly used typical meteorological year and three climate change scenarios for 2020 to 2100.

Despite the fact that the overall energy performance of the building varies between scenarios, results show that, if the renovation strategies were devised based on future climate scenarios, the influence would be minimal. Indeed, tendencies show no contradiction with respect to the TMY results, on which the strategies were based.

Results also serve to reiterate the importance of renovating the building stock, by highlighting the important energy efficiency gains that can be achieved through various renovation strategies, some involving BIPV systems.

Future work foresees the analysis from the point of view of the increase in hours of discomfort, especially in summer since in the Swiss context, it is very probable that no cooling system will be installed. In addition, an analysis of the insulation thickness dimensioning using the different climate change scenarios and their impact on the whole life cycle analysis, including the embodied energy of the BIPV installation, is being integrated into the study.

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