Influence of future climate scenarios on the sizing of Building-Integrated Photovoltaics (BIPV) installations. Case study of a new research-center building in Switzerland

Sergi Aguacil[1]
[1]Building2050 group, Ecole Polytechnique Fédérale de Lausanne (EPFL), Fribourg, Switzerland.

Abstract

This paper analyzes the findings obtained when applying a multi-criteria performance-based method for sizing a BIPV installation considering different weather files, representing historical data (TMY; typical meteorological year) and prospective data (three alternative future climate change (CC) scenarios; RCP2.6, 4.5 and 8.5) with time horizons from 2030 to 2100. Through a solar and energy simulation process over a case-study building, electricity consumption and production values are computed along with various performance parameters such as self-sufficiency and carbon content of the electricity produced, for each simulated weather scenario. Results show that characteristics (i.e., size, etc.) of the BIPV installation that represents the best trade-off solution are slightly different according to the weather file considered. Given the warming climate, the global performance of a given BIPV installation can be expected to increase over time.

Highlights

- Novel design-driven and building-coherent photovoltaic sizing method based on the self-consumption and self-sufficiency ratios requirements.
- Methodology to help architects conduct a project-specific analysis (rather than using rules-of-thumb), given that they are key decision-makers and influencers.
- Demonstrates the importance of considering future climate scenarios in design decisions and proposes a methodology for integration.
- Emphasizes the role of architects in decision-making and the potential for research-based technology transfer.
- Shows that BIPV installation sizing varies slightly based on weather files used and predicts increased performance due to climate change.

Practical implications

This article – at the interface between research and professional practice – examines the implications of using historical weather data versus future climate scenarios when designing buildings, including identifying active surfaces, assessing energy and environmental performance, and evaluating cost-effectiveness. The findings highlight the need to update building performance standards and develop new simulation methods to achieve carbon neutrality by 2050.

Introduction

Designing buildings with both low energy demand and on-site energy production is one of the main strategies put forth in Switzerland and many other western countries in order to achieve carbon neutrality by 2050 (OFEV, 2019; SIA, 2017). Building-Integrated Photovoltaics (BIPV) systems functioning both as envelope material and electricity generator have the potential to strongly contribute towards this objective (Aguacil Moreno, 2019). Nowadays, when design teams – architects and engineers – consider the fulfilment of the objectives for a future horizon, the question of the influence of the different climate change (CC) scenarios on the design decisions arises. Designing today, but taking into account various climate evolution pathways, is a new challenge that the design teams must face (Aguacil Moreno, Nault, & Rey, 2020; Heinstein, Ballif, & Perret-Aebi, 2013). Indeed, global warming is a reality and its effects are already visible (IPCC, 2000). In this context, building designers must learn to work by integrating uncertainty related to CC. In a context where the use of energy simulations to aid decision making is commonplace, one of the tools available to take CC into account is the use of artificial weather files representing different possible scenarios. This exercise of simulating with future climates to size installations or make decisions on the thermal envelope of buildings is however not yet part of common practice (Aguacil Moreno et al., 2020; Heinstein et al., 2013). The literature (Pelle, Causone, Maturi, & Moser, 2023; Zanelli & Freitas, 2019; Zhang, Wang, & Yang, 2018) also points to a lack of global approaches such as the one proposes here, i.e., that integrates a multi-criteria evaluation to support early-stage building design by setting clear objectives for the efficiency of the PV-building pair. Focusing on the energy performance of a soon-to-be built research-center building in Fribourg (Switzerland) (Aguacil Moreno, 2022), this article compares the results obtained when simulating a series of BIPV installation sizes based on a TMY (typical meteorological year) and three different future climate scenarios (RCP 2.6, 4.5 and 8.5) for time horizons from 2030 to 2100 (IPCC, 2000; Meteotest, 2018). More specifically, we are interested in (i) seeing how the BIPV system, designed and sized based on the TMY weather data, could perform in the future, and (ii) if a similar installation would be conceived when considering weather data representing a future climate scenario in the design and sizing process.

Methodology

The scientific methodology involves four main phases: 1) Developing solar and energy models, 2) Generating artificial weather files for TMY and CC scenarios (Meteotest, 2018), 3) Conducting an iterative simulation process based on the self-sufficiency (SS) and self-consumption (SC) rates achieved (Aguacil Moreno, 2019; Ballif, Perret-Aebi, Lufkin, & Rey, 2018) and 4) Analyzing and comparing the results to identify the most optimal installation. To better illustrate the methodology, the outputs from phases 1-3 are included below, while the Results section presents the base case design and the results from phase 4.

Phase 1 – Solar and energy models

The first phase consists in the identification of potentially active surfaces – i.e., envelope surfaces that could be made of BIPV – based on the proposed architectural design. These surfaces have a defined (by the architectural design proposition) dimension and orientation distributed between the roof, the pergola and the south, east and west facades. **Figure 1** shows in blue the identified surfaces that can be activated. These surfaces are used in the calculation process taking into account the different climate scenarios (introduced further).

Figure 1: Building Solar Model (BSM) of the building. Blue surfaces represent the potential active surfaces.

Figure 2: Building Energy Model (BEM) of the building.

The simulation workflow is created in Grasshopper for Rhino (Davidson, 2018) and uses DIVA (Solemma LCC, 2018) to obtain irradiation and electricity production values. The existing neighboring buildings, as well as the more distant context are taken into account. This phase includes the use of a detailed Building Energy Model (BEM) (**Figure 2**) generated in the DesignBuilder software (DesignBuilder, 2021) based on the EnergyPlus (US Department of Energy (DOE), 2020) engine to obtain hourly time-step electricity needs for each climate scenario. The BEM is configured using standardized data from the Swiss norm SIA 2024 (SIA, 2015).

Phase 2 – Artificial weather files generation

This phase consists in the generation of different artificial weather files in EnegyPlus Weather (EPW) file format using the Meteonorm software (Meteotest, 2018).

In total, 11 different weather scenarios are obtained, divided in two categories: **a**) Two EPW files with historical data based on TMY (typical meteorological year) which we call HIS and CON. The HIS (historical) file contains the average data between 1961 and 1990, and the CON (contemporary) file is based on average data between 2000 and 2019. It is important to point out that the HIS file data is what is generally used today in practice for energy simulations, sizing of solar installations and decision making. **b**) For the analysis of the influence of CC scenarios, we have generated three different EPW files corresponding to the future climate scenarios following three Representative Concentration Pathways (RCP 2.6, 4.5 and 8.5) for time horizons 2030, 2050 and 2100. These RCP scenarios, from the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2000, 2018), range from a strict greenhouse gas (GHG) emission reduction trajectory (RCP 2.6) to a continuous rise in GHG concentrations (RCP 8.5).

It is to note that in the IPCC's Sixth Assessment Report on climate change (published on August 9, 2021), the RCP made way to the Shared Socioeconomic Pathways (SSP) scenarios, which integrate the global socioeconomic changes expected up to 2100. These pathways are summarized as: SSP1: Sustainability, SSP2: Middle of the Road, SSP3: Regional Rivalry, SSP4: Inequality and SSP5: Fossil Fuel-based Development. However, the available artificial weather files, needed to conduct energy simulations for the research presented in this article, in the Meteonorm software (Meteotest, 2018) are based on the RCPs and not yet on the SSPs. The four main RCPs (2.6, 4.5 and 8.5) are labeled according to a range of possible radiative forcing values in the year 2100 (2.6, 4.5 and 8.5 W/m^2, respectively). The literature shows that an equivalence in terms of global emissions and global mean change in radiative forcing exists (Kebede et al., 2018; Meinshausen et al., 2020; O'Neill et al., 2016; Riahi et al., 2017; Rogelj et al., 2018; Schleussner et al., 2021). In this case, according to (Riahi et al., 2017), SSP1 corresponds to RCP 4.5 (and is slightly higher than RCP 2.6), and SSP5 matches quite well with RCP 8.5. With this, we can be sure that we have been able to study the two extremes for the different time horizons. However, as soon as the new SPP scenarios will be integrated in the Meteonorm software, it would be interesting to evaluate whether there are differences in the results.

Figure 3 compares these different weather data in terms of two key parameters, the Annual Dry Bulb temperature

(DBT), average, minimum and maximum values, and the Direct Normal Radiation daily average (DNR).

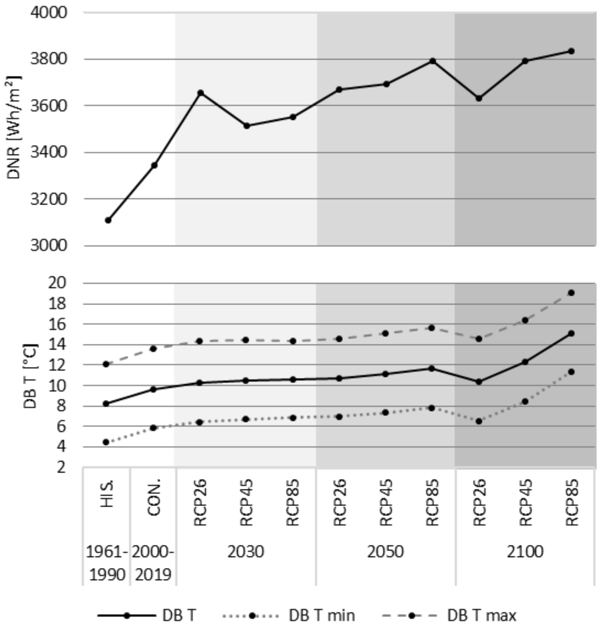

Figure 3: Comparison of Annual DBT [°C] (average, min and max values) and DNR average daily [Wh/m²] between different climate scenarios and time horizons.

Phase 3 – Iterative simulation process

Using the 11 weather scenarios to run the simulations of the building energy and solar models, we obtain the electricity demand (appliances, artificial lighting, ventilation, circulation pumps, heating, cooling and domestic hot water) and the PV electricity production, both with an hourly time-step resolution. For the PV analysis, the PV electricity production is computed using an active surface selection method that consists of filtering the potentially-active surfaces using the annual amount of cumulative irradiation received by each surface, with a threshold varying from 0 to 1,200 kWh/m^2.year (Aguacil Moreno, Lufkin, & Rey, 2019). This allows us to see, for each irradiation threshold value applied and CC scenario, the electricity production values. With the 0 kWh/m^2.year threshold, all surfaces (**Figure 1**) are considered as active, thus leading to the maximum production (biggest installation).

Applying the 1,200 kWh/m^2.year threshold, only surfaces receiving more than 1,200 kWh/m^2.year of cumulative irradiation are considered as active, thus leading to the minimum production (smallest installation). To illustrate this filtering method, **Figure 4** shows the remaining active surfaces when applying a threshold of 700 kWh/m^2.year for all climate scenarios. Differences can notably be seen between the HIS and RCP scenarios; in the HIS figure, less irradiation is received over the year, leading to less surfaces achieving the irradiation threshold.

The electricity demand also varies according to the weather data taken into consideration. **Figure 5** summarizes the annual electricity demand of the building in these different conditions, and the minimum and maximum (depending on the threshold applied) PV electricity production. This comparison allows us to see the percentage of annual coverage of the electricity needs that we could reach for each scenario, in this case between 19 and 78%.

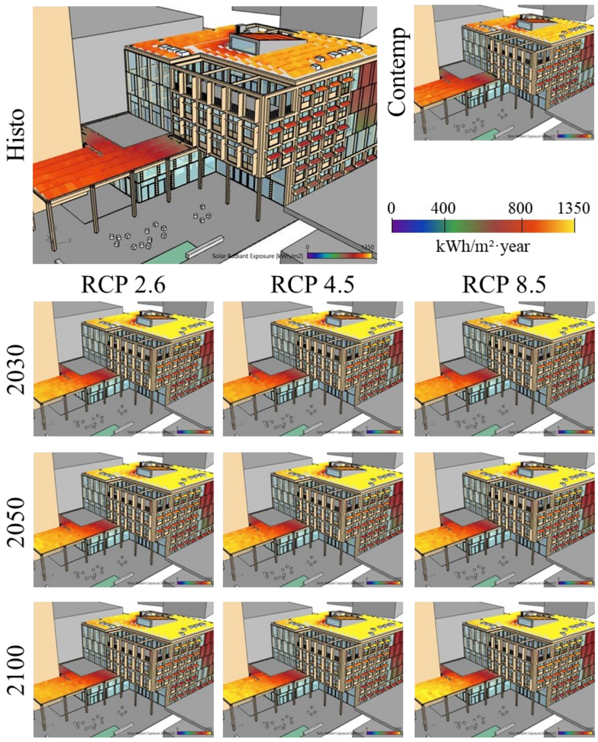

Figure 4: Remaining active surfaces with a 700 kWh/m^2.year threshold for all climate scenarios.

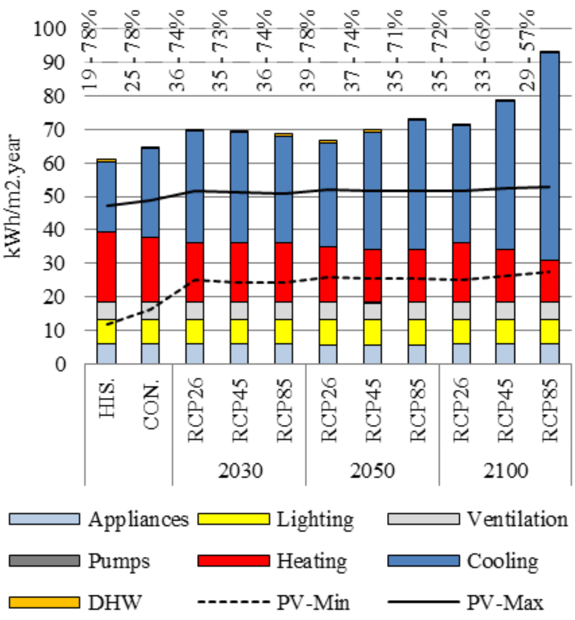

Figure 5: Annual comparison of electricity demand, min/max PV electricity production, and corresponding annual global coverage ratio for the different scenarios.

Phase 4 – Optimization analysis

In this phase, using the data obtained in phase 3 with an hourly time-step, we conduct an optimization analysis in order to define the most suitable threshold considering a trade-off among the following parameters:

(SS) Self-sufficiency rate [%] – Energy autonomy of the building.

(SC) Self-consumption rate [%] – Amount of energy consumed at the same time as it is produced by the PV installation.

(P) Total annual production [kWh_{pv}/yr] – Over one year, the total electricity produced by the PV installation.

(EF) Global PV efficiency [kWh_{pv}/kWp] – Efficiency of the installation, represented by the total electricity production per kWp installed according to the standard test conditions (STC).

(CF) Cashflow balance [CHF/m^2] – Economic balance comparing the investment cost of the installation with the incomes (price of the avoided electricity import from the grid (due to self-consumption) and feed-in tariff) that the installation generates during the 25-year guarantee cycle.

(CI) Carbon intensity of PV electricity [gCO_2/kWh_{pv}] – Carbon content of each kWh output of the PV installation evaluated with the CO_2 emissions due to the manufacturing of the plant components and 25-year of energy production.

The optimization process consists in finding the irradiation threshold that **maximizes** the SS, SC, P, EF, CF and **minimizes** the CI.

Results and discussion

This section of the article is divided into three parts and shows 1) the description of the BIPV installation, 2) the results of phase 4 (optimization analysis) and 3) the answer to the two questions posed in the introduction.

Description of base case BIPV installation

During the design phase of the building – used as a case study for this research – an advanced study was conducted to identify the best-oriented and most productive photovoltaic surfaces on the building envelope considering the energy demand of the building (Aguacil Moreno, 2022), to match the electricity production as closely as possible to the electricity demand. An electricity storage system with 100 kWh of capacity was integrated in the system.

The HIS weather file was used, resulting in the BIPV installation described in **Table 1**. Results presented below obtained with the other weather files are compared to this base case scenario.

Table 1: Performance of the base case PV installation (sized using HIS and 700 kWh/m².year).

Irr. Thr. filter [kWh/m².yr]	**700**
PV Surface [m²]	696
(P) PV Production [MWh/yr]	134
(SS) Self-sufficiency rate [%]	**73**
(SC) Self-consumption rate [%]	42
(CI) Carbon intensity [gCO_2/kWh_{pv}]	**40**

Results from Phase 4 (optimization)

Figure 6 shows the results obtained for the base case for each performance parameter. The trade-off threshold value varies between 400 and 900 kWh/m^2.year, according to the parameters. For example, the 900 kWh/m^2.year cut-off should not be exceeded to fulfill the SC minimum requirements, whereas the other parameters such as the carbon intensity or cashflow balance become more interesting above the 400 kWh/m^2.year limit. As shown in **Table 1**, a 700 kWh/m^2.year threshold was set during the design phase to define the most suitable surfaces, as this cut-off value allowed achieving a good compromise in terms of economical, energy and environmental efficiency.

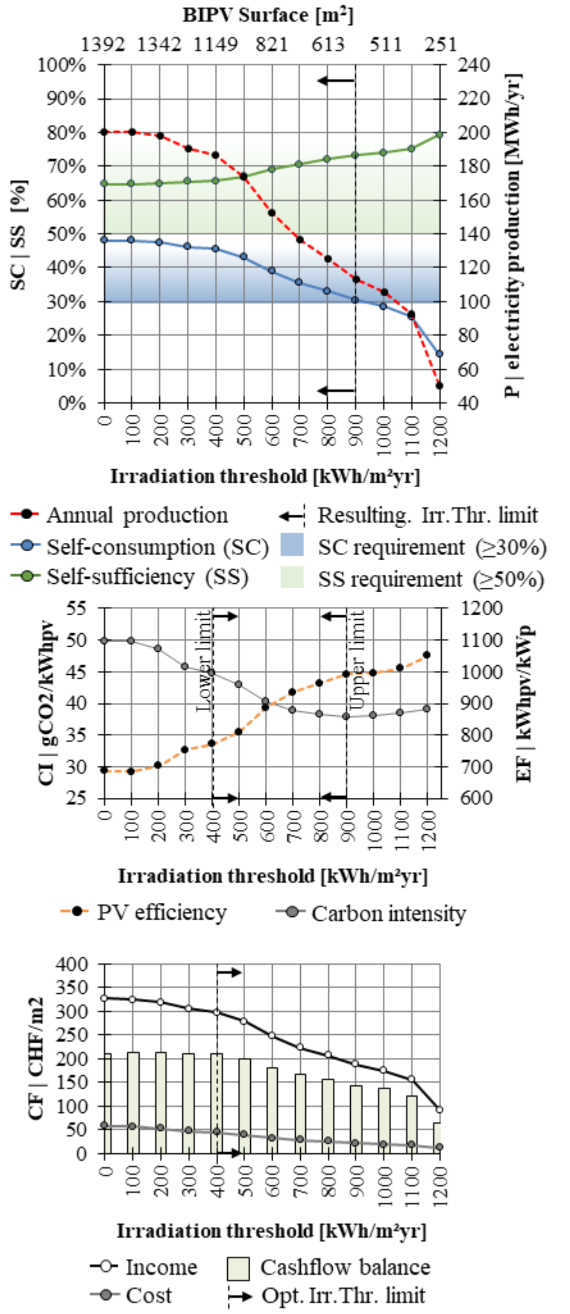

Figure 6: Results of the optimization for historical 1961-1990 weather file (HIS) considering a battery of 100 kWh.

Concerning the carbon intensity of the electricity coming out of the PV installation, the objective is not to exceed the values offered by the grid. In this way we ensure that the PV installation makes sense in terms of its environmental impact. In the case of Switzerland (Electricity Maps ApS, 2023), the carbon intensity of electricity from the grid can vary in a year between 118 and 195 gCO_2/kWh (monthly average), daily this variation is between 65 and 198 gCO_2/kWh (daily average), and if we look at a 24 hour period, the variation can be between 62 and 144 gCO_2/kWh (for a day in March).

This content depends on the energy produced by the country, as well as on the energy imported from and exported to neighboring countries. For our specific case, the limit of acceptance of the carbon intensity of our PV installation would be the reference value of 62 gCO_2/kWh.This limit value corresponds to the data of the current energy ecosystem, but as all countries are taking measures to reduce CO_2 emissions drastically, among others, by promoting renewable energy production, this limit value will be reduced, making the sizing of new PV installations more demanding.

As shown in **Figure 6** and **Figure 7**, the carbon intensity values are between 38 and 50 gCO_2/kWh (simulating with TMY) and between 34 and 46 gCO_2/kWh (simulating with RCP8.5 2050). With this data we can see that we still have some margin. However, if our PV installation was in a country with cleaner grid electricity, such as Iceland or Sweden (to cite extreme examples), the carbon intensity limit would be around 40 gCO_2/kWh.

Translated to the PV installation of our case study, this data would lead to limiting the irradiation threshold to between 500 and 600 kWh/m^2.year, making the compromise range smaller. This directs decisions towards installations that are better adapted to the demand of the building, avoiding oversized installations.

Figure 7 shows the same graphs as Figure 6, but for the RCP 8.5 scenario at the 2050 horizon. To achieve the same efficiency (SS≥50%, SC≥30%, highest possible cashflow balance with the lowest carbon content), the optimal range of irradiation values for filtering potentially active surfaces would be between 500 and 900 kWh/m^2.year. Although the absolute values for energy efficiency are not the same because production and demand vary due to climate conditions, this result is consistent with what has been obtained using the historical TMY weather file for the base case design

However, considering that the amount of irradiation received and the energy demand depend on the CC scenario, the final number of active surfaces varies between climate scenarios.

Table 2 shows the values for the smallest installations, that meet the SS and SC requirements, filtering with 500, 700 and 900 kWh/m^2.year taking into account all CC scenarios and historical/contemporary weather files.

Table 2: Result of the smallest possible PV installation that meets the SS and SC requirements with a threshold between 500 and 900 kWh/m^2.year and a battery of 100 kWh.

Irr. Thr. filter [kWh/m^2.yr]	**500**	**700**	**900**
PV Surface [m^2]	1017	697	543
(P) PV Production [MWh/yr]	174	136	113
(SS) Self-sufficiency rate [%]	**77**	**73**	**70**
(SC) Self-consumption rate [%]	34	41	47
(CI) Carbon intensity [gCO_2/kWh_{pv}]	**43**	**39**	**37**

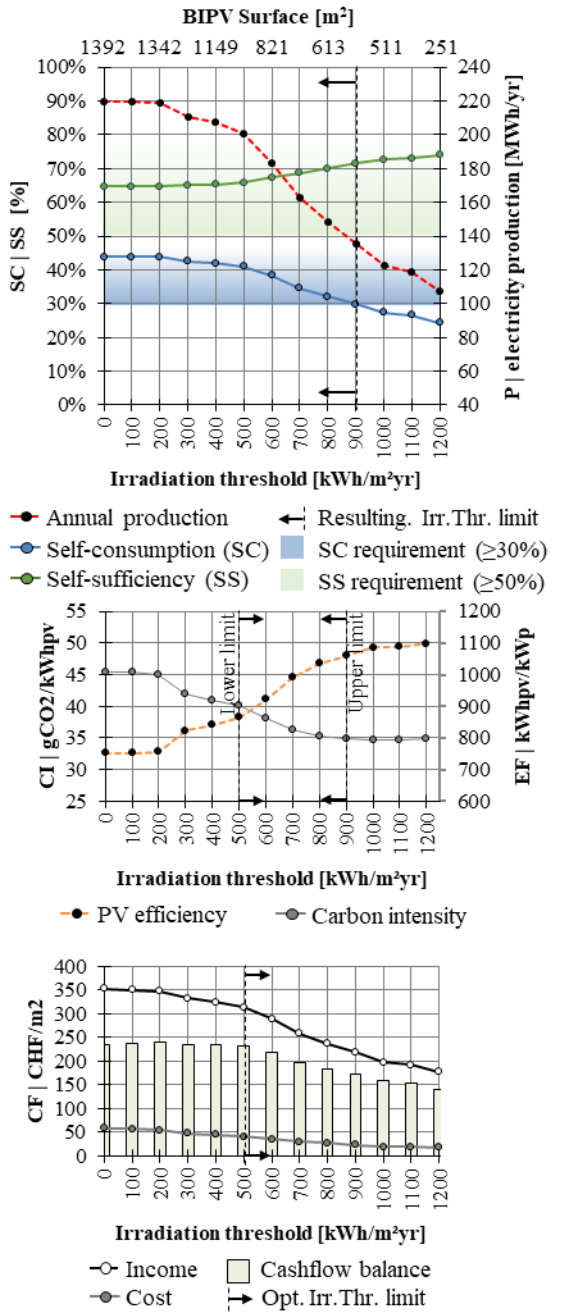

Figure 7: Results of the optimization for horizon 2050 and scenario RCP 8.5 weather file with a battery of 100 kWh.

Coming back to the two questions stated in the Introduction, results from this study lead to the following answers.

(i) How would the base case BIPV system, designed and sized based on the TMY weather data, perform in the future?

The results in **Table 4** show that the efficiency requirements (SS≥50% and SC≥30%) for the BIPV installation – set by the design made with the TMY and using the threshold of 700 kWh/m^2.year – are met by all scenarios. However, although the total annual production is higher with the CC scenarios, the self-consumption value is slightly lower due to a higher electricity demand which causes a slight mismatch between demand and production, and the loss of a small amount of electricity (injected into the grid). This makes it clear that if we want the same efficiency as we obtained with the designed installation but in the horizon 2030 - 2100, the installation must be dimensioned taking into account the future climate.

Table 4: Performance of the base case PV installation (sized using HIS and 700 kWh/m^2.year) compared to the range of performance obtained using CC scenarios.

	HIS	CC scen.
PV Surface [m^2]	696	
PV Efficiency [kWh/kWp]	915	987 - 993
(P) PV Production [MWh/yr]	134	144 - 145
(SS) Self-sufficiency rate [%]	**73**	**75 – 76**
(SC) Self-consumption rate [%]	42	39 - 40
(CI) Carbon intensity [gCO$_2$/kWh$_{pv}$]	**40**	**36 - 37**

Furthermore, by designing with future scenarios for the same requirements, we generally obtain a 20-30% smaller installation. This information can be very useful to optimize the embodied energy used for the manufacturing of the components of the BIPV installation.

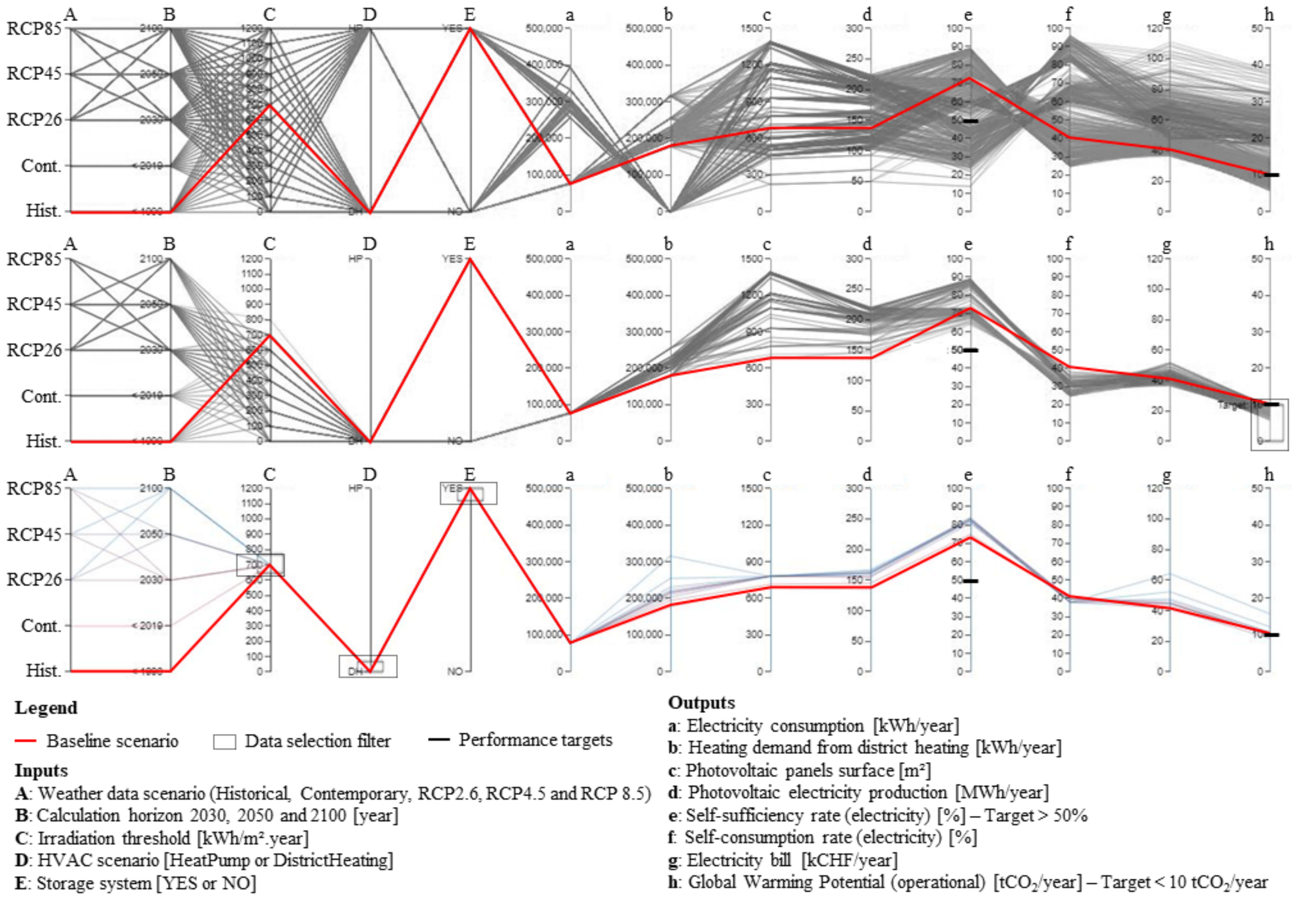

Figure 8: Parallel coordinate plots. 1) First graph shows all conducted simulations, 2) Second graph shows the combination of parameters that allows to respect the GWP target, and 3) Third graph shows the results filtering by an irradiation threshold of 700 kWh/m^2.year.

Also, as in our case study, the projects usually take some time to be realized. When this happens, from the time the preliminary design is made until the project is realized, between 2 and 8 years may have passed (EPFL Fribourg, 2022).

During this period of time, photovoltaic technology has advanced, efficiency requirements have increased, among other things by placing limits on carbon emissions from construction (materials). Summarizing, it is not problematic to design with TMY files, but it is strongly recommended to make the sizing taking into account the CC scenarios.

(ii) Does considering, in the design and sizing process, weather data representing a future climate scenario lead to a similar installation?

The irradiation threshold for the selection of active surfaces is consistent for all CC scenarios. That is, for a minimum efficiency equal to that defined for the base case (SS≥50% and SC≥30%) but using weather files associated to the CC scenarios, the design threshold is 800-900 kWh/m^2.year (this can also be seen in Figures 6 and 7 above). This threshold is slightly higher than for the base case due to the higher irradiation received. The resulting installation size for the different CC scenarios is between 650 - 680 m^2, slightly smaller than the installation obtained using the TMY (696 m^2). With the design using the CC scenarios, the energy demand of the building is between 12 and 30% higher, the resulting PV production is about 8-9% higher and the self-sufficiency rate is improved by 9-11%.

By exploring the set of results using parallel coordinate plots of the inputs and outputs (**Figure 8**), we can analyze the variability of the results and their sensitivity to the input data. The first graph in **Figure 8** gives an overview of the variability in the results obtained by varying the different input data (A/B, C, D and E). Focusing on the respect of the efficiency targets, i.e., 50% SS (parameter e) and 10 tCO_2/year (parameter h), these are only reached by 145 of the 572 simulated scenarios. The scenarios that do not meet the targets are those with heat pumps without connection to district heating, those using irradiation thresholds for PV sizing of more than 800 kWh/m^2.year and in no case the target will be met if a climate scenario represented by RCP8.5 - 2100 were to become reality.

Returning to the main objective of the article - the analysis of the robustness of the decision making on a PV installation by comparing the sizing performed using TMY files or using CC scenarios for the horizons 2030 to 2100 - considering the combination of parameters defining the Baseline scenario (red line in Figure 8) and configuring the data filters with the decision taken in the early stages of the project (C: 700 kWh/m^2.an, D: District Heating and E: Battery of 100 kWh), we see that for the same irradiation threshold of 700 kWh/m^2.an the variability due to climate scenarios is not negligible, and all variations are above the target values in terms of GWP (parameter h).

Considering what is observed in graph 2 (**Figure 8**), this confirms that the maximum threshold that allows to reach the objectives for any CC scenario with highest SS rate is between 600 and 700 kWh/m^2.an. This irradiation filter to choose the surfaces to be activated (PV panels) would give a variation of the size of the installation between 782 and 930 m^2. The PV size in the TMY scenario corresponds to 821 m^2, with this surface the objectives are reached for all CC scenarios (except for RCP 8.5 - 2100).

Conclusion

Designing photovoltaic installations for buildings based on historical weather data may no longer be sufficient in light of the changing climate. This study highlights the importance of considering future climate scenarios in the design process, as it can result in a more efficient and cost-effective installation. By optimizing the embodied energy used for the manufacturing of the components and taking into account the future climate, the building industry can work towards achieving carbon neutrality by 2050. The results of this study can assist architects in conducting project-specific analyses and contribute to the development of new simulation methods for building design. All the results of this study are available at https://design-explorer.epfl.ch/ (projects section 2023), where they can be explored using the open source tool DesignExplorer (CORE studio & Thornton, 2017).

In future studies we will integrate a sensitivity and uncertainty analysis with respect to the input data for the building energy simulations. For this purpose, we plan to launch a series of parameterized simulations by varying the parameters that may represent a different user behavior than that simulated with the standardized data. Without wishing to be exhaustive, examples of parameters that we will integrate in this further study are: different temperature setpoints, different activation parameters for solar shading and window opening, different occupancy levels in relation to the various layouts that are planned to be tested in the building, etc.

In addition, we will include the uncertainty levels that Meteonorm indicates (Meteonorm et al., 2020) in the process of generating the artificial climate files.

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