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Mahdavi, Ardeshir; Wolosiuk, Dawid; Berger, Christiane

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Can photovoltaic systems' energy harvesting potential inform building design and retrofit decisions?

Ardeshir Mahdavi[1], Dawid Wolosiuk[2], Christiane Berger[3]
[1]Institute of Building Physics, Services, and Construction, Faculty of Civil Engineering Sciences, TU Graz, Austria
[2]VRVis Zentrum für Virtual Reality und Visualisierung Forschungs-GmbH, Vienna, Austria
[3]Department of Architecture, Design and Media Technology, Aalborg University, Denmark

Abstract

Simulation methods can support both building design and building-integrated photovoltaic (PV) systems configuration. Related processes in this area typically start with a given building design, which is then considered in view of a fitting PV system configuration (i.e., type, size, orientation, local storage and/or grid export options). Simulation methods can specifically help with matching the temporal profiles of available solar energy and buildings' energy demand, which is especially relevant if a high level of energy self-sufficiency is targeted. However, the computational procedures in this area are rather one-way: Whereas relevant aspects of building designs (e.g., geometry and demand profile) inform the PV systems design, information on electricity generation potential via PV does not usually find its way back to building design decision making (e.g., building shape and orientation, transparent area fraction of the envelope, thermal mass). In this paper, we explore the potential of a bi-directional information flow between building design/retrofit decisions and PV system options. To this end, we illustrate how building design variables (e.g., orientation, glazing fraction) can be fine-tuned based on available PV system installation options. Thus, the proposed approach facilitates the exploration of the implications of PV-based energy generation options for building design decisions.

Highlights

- Concurrent exploration of building and PV system design options
- Bi-directional inferences between building design variables and PV system configurations
- Option comparison via payback time of PV-related investments

Introduction

Computational methods can support the configuration of building-integrated photovoltaic (PV) systems. Especially when a high energy self-sufficiency degree is desired, such methods can match the temporal profiles of available solar energy and building's energy demand. Typically, such matching has a mono-directional character, that is the building's demand profile is assumed as given, and used to inform PV system's configuration. It would be thus useful to develop bi-directional computational methods (Mahdavi et al., 2021), such that relevant building design variables such as orientation, transparent envelope elements, and thermal mass could be optimized based on information regarding the intensity and temporal profile of PV-based energy generation potential. In this paper, we further explore the potential of a bi-directional information flow between building design/retrofit decisions and PV system options. To this end, we illustrate how building design variables (e.g., orientation, glazing fraction) can be fine-tuned based on available PV system installation options. Thus, the proposed approach has the potential to support the exploration of the implications of PV-based energy generation options for building design decisions.

Computational elements

To facilitate the aforementioned bi-directional building and PV system design, it is necessary to *i)* compute, parametrically, building's energy demand profile, *ii)* compute, again parametrically, PV system's electricity generation potential, *iii)* process generated data toward obtaining relevant whole-system performance indicators.

Energy demand calculation

In the present effort, the steps to compute building's energy demand (magnitude and temporal profile) are as follows: First, the geometry of the building is modelled in Rhino (Rhinoceros 3D, 2023). Second, the geometry model is enriched with required input assumptions using the visual scripting platform Grasshopper (Rhinoceros 3D, 2023) and the plug-ins Honeybee and Ladybug (Ladybug Tools, 2023), whereby relevant building information (i.e., location, construction, occupancy, equipment, lighting, control systems) is specified. Subsequently, energy simulation is conducted using EnergyPlus (EnergyPlus, 2023).

PV-based energy computation

PV-based electricity generation is computed using the Python programming language and the pvlib-python library, which includes a PV-related package of functions and classes (Holmgren et al., 2018; Stein, 2012). The computational process needs input data regarding sun position, solar radiation and further microclimatic information, PV panel orientation, and requisite equipment specifications. EPW (EnergyPlus Weather) data files provide the source of Metadata regarding location (latitude, longitude, altitude), solar radiation (direct normal, global and diffuse horizontal), air temperature, and wind speed (Crawley et al., 1999). This is used to compute solar position (Reda and Andreas,

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2004), optimal panel tilts, incident irradiance, and generated electricity (King et al., 2004).

Data processing

To calculate the payback time of the investment in a PV system, estimations are needed regarding *a)* the projected system's total lifecycle cost and *b)* the monetary benefit due to the energy produced by the system. The former includes the system's initial purchase and installation cost as well as the lifetime maintenance expenses. The purchase cost is dependent on the size of the solar array and can be estimated based on the market price kW peak (kWp) power (for instance, in Austria currently approximately 1550 euros per kW peak power) (Biermayr et al., 2022). Annual maintenance costs can be estimated in terms of a fraction (e.g., 1%) of the PV system's initial PV cost (Fu et al., 2018). Estimates of the maintenance costs of the lifetime of the system (say 25 years) need also to take inverter replacements and panel servicing into consideration.

The annual monetary benefit depends on the building's energy demand profile, PV system's energy generation potential, and the market electricity prices. The latter can of course highly fluctuate. In the present treatment, the electricity price scheme is parametrized according to recent and current prices in Austria (PVAustria, 2023; Eurostat, 2023; RIS, 2023) (i.e., 0.21, 0.31, 0.41 €.kWh^{-1} for import and 0.07, 0.15, 0.30 €.kWh^{-1} for export). The annual gain is derived as the sum of *a)* the monetary value of the energy saved through the coverage level of the building's energy demand via local production and *b)* the sale of the surplus energy. For the illustrative purposes of the present contribution, a simple payback analysis is performed, resulting in the payback duration (total lifetime of the PV system cost divided by the annual monetary gain generated by the PV system).

Note that, given the price difference in buying and selling electricity, the performance indicator value (in this case, the payback time) depends on the matching degree between the temporal profiles of the PV installation's energy supply and the building's electricity demand. As such, scenarios that maximize the coverage of electricity demand via PV-generated electricity are advantageous. Building design solution options with high electricity demand during low-supply periods necessitate import of high-price electricity from the grid and are thus less advantageous.

A case study

The building

The application potential of the proposed approach can be illustrated through a case study involving a building design scenario of eight identical row houses (see Figure 1) located in the city of Vienna, Austria. The flat roof of these complex with an area of 480 m^2 offers the opportunity for installation of PV panels in different configurations. To keep matters simple, we assume that some attributes of these houses are fixed, namely the overall geometry, the thermal transmittance of external walls and windows (0.26 and 1.21 W.m^{-2}.K^{-1} respectively), the occupancy density, the ventilation rate (0.4 h^{-1}) and the (electricity-powered) heating, cooling, and ventilation system. However, some attributes were subjected to parametric analysis together with the PV installation options. These included three façade glazing fractions (20, 30, and 40%) and four building orientations, namely East_West (E-W), South-East_North-West (SE-NW), South_North (S-N), and South-West_North-East (SW-NE).

PV installation

The PV panel system options considered for the above residential building complex are considered to have a nominal power of 300 W and an efficiency of about 18%. Three attributes of the PV array were subject for parameterization. The first attribute pertains to the system size, whereby three levels were considered, namely 18, 36, and 54 kWp, corresponding to 60, 120, and 180 PV panels respectively. The second attribute is the panel inclination, which was assumed to have also three options (15°, 30°, 45°). Finally, the panel orientation (or azimuth) was assumed to have three options as well, namely South-East (SE), South (S), and South-West (SW). The case study involves no local storage option for the generated electricity. Rather, the assumption is that energy deficit is covered by import from grid and energy surplus is exported to the grid, whereby the aforementioned pricing scheme options apply.

Simulations

The 12 building design options, 9 PV panel configurations, 3 PV system sizes, and 9 price schemes result in 2916 distinct scenarios. For these scenarios, hourly profiles were generated for both building energy demand and PV-based electricity generation. It was assumed that the locally generated electricity is used to cover the building's energy demand. In case of deficit, energy is imported from the grid and in case of surplus it is exported to the grid, whereby the aforementioned 9 import-export price combinations apply. To compare the performance of the different scenarios (combinations of building design options, PV system configurations, price schemes), payback times were computed. As mentioned before, this was by dividing the investment costs of the PV installation by the annual PV-driven savings due to *a)* reduced need for electricity purchase and *b)* exporting the surplus energy.

Illustrative results

To provide a broad impression of the range of computed results, Figure 2 shows the payback times for the three system size options. Note that the order of the scenarios along the x-axis in this Figure is not identical for the three system sizes. Rather, for each size category the results are separately arranged in ascending order. The broad overview in Figure 2 warrants already certain inferences. First, the range of payback times is considerable, reaching from about 6 years to 19 (18 kWp), 23 (36 kWp), 26 (52 kWp). Second, it appears plausible that the higher investment costs associated with larger system sizes result, in many scenarios, in longer payback times.

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The results can be explored in further detail to address a number of relevant questions. For instance, to which extent can we explain the differences in performance (payback times) based on the energy price (import versus export) schemes? Another essential question is as follows: Are there design scenarios that perform better relative to other design scenarios, independent of the price scheme? This is an important point, because such scenarios, if they existed, point to the possibility of identifying robust designs.

To further pursue these questions, consider the visualized data in Figure 3, which illustrates the estimated payback time for PV system's installation and maintenance cost for different combinations of building design and PV system configurations. To make inferences from data more manageable, this Figure focuses on data from one of the three previously mentioned system sizes (8 kWp). Payback times are plotted against the scenarios 1 to 108 on the x-axis of the Figure. The key to the numbering system of the scenarios is provided in Table 1. The 9 distinct functions in Figure 3 correspond to the 9 energy price scenarios considered (purchase_selling price in €). Note that the order of the scenarios on the x-axis (from 1 to 108) corresponds to the descending order of the performances as relevant to the price scheme 0.31_0.15 (electricity purchase versus selling prices in euros). Table 1 entails the state description of all scenarios. As such, it specifies, for each scenario, the value of the design variables regarding the building orientations (E-W, SE-NW, S-N, SW-NE), glazing fraction of the façade (20, 30, and 40 %), the PV panels' tilt (15, 30, 45 degrees), and the PV panels' azimuth (SE, S, SW). As mentioned before, the numbering of scenarios in this Table corresponds to the numbering in the x-axis of Figure 3.

Information provided in Figure 3 and Table 1 facilitates the treatment of the aforementioned two questions. Regarding the role of the price schemes for electricity import and export, Figure 3 shows a significant influence. Shorter payback times correspond to scenarios where both import and export prices are high. Obviously locally generated electricity has an effectively high value when it can replace the need for importing high-price energy. And of course, high energy export prices are always conducive to reaching shorter payback times. A similar reasoning can explain why the combination of lowest energy import and export prices result in the longest payback times.

Information in Figure 3 is also helpful in addressing the question regarding the robustness of building and PV design scenarios. It appears that, independent of the price schemes, certain scenarios (in the top rows of Table 1 and on the left side of Figure 3) perform tendentially better than other scenarios (in the bottom rows of Table 1 and on the right side of Figure 3). To put numbers on this observation, consider a comparison of the mean payback times of top twenty and bottom twenty of the 108 scenarios of Table 1 and Figure 3. This comparison reveals that the mean payback time of the bottom 20 scenarios is 15±3 % longer than the top performing 20 scenarios.

These results clearly demonstrate that electricity pricing developments, which may be affected by economic constraints or policy considerations, introduce major uncertainties in the estimation of monetary aspects of investments in PV installations. In our case study of the 18 kWp case (see Figure 3), the mean payback time of all 106 scenarios varied about 10 years (from ca. 6.5 to ca. 16.5 years). However, the results also suggest that it is possible to identify specific combinations of building and PV system design variables that would yield better performing solutions independent of future price developments.

In this context, it is instructive to consider the logic of reshuffling in the values of the different variables in Table 1. In our specific case study, certain values of certain variables appear to be associated with higher or lower levels of performance. For instance, when considering building design variables, E-W orientation or glazing ratio of 40% (as opposed to 20%) appear frequently in the top performing scenarios. Likewise, when considering PV system variables, a PV panel tilt of 30 degrees is prominently present in performant scenarios, whereas the SW azimuth option for the panels is associated with rather low-performing scenarios. We can reflect on specific circumstances (e.g., building location, daylight utility and solar gains) to explain these tendencies in this specific case. But the more interesting lesson from this case study may line in the following observation.

In contrast to the assumption of one single optimum solution, the concurrent consideration of multiple building and PV system design variables reveals a rich and flexible option space. One can start with certain preferred building design options and look for PV system options that would complement those toward performant solutions. One can also, specifically in case of new building projects, where designs are not yet fixed, start from PV system options that appear preferable (for instance, because they would maximize the lifecycle energy production) and decide then what building design features would best complement those. The former approach can be perhaps recognized as the more conventional one, whereas the latter has the potential to open new doors toward creative and efficient solutions. This would of course make more sense, if a PV system is not merely viewed as an ad hoc add-on to the building, but rather as a lasting integrated component of a building project. Note that the concurrent consideration of multiple building and PV system design options does not imply that strict constraints are imposed on the selection of building design solutions. In fact, as Table 1 and Figure 3 demonstrate, a targeted performance level can be achieved via multiple and diverse configurations of building and PV system design variables.

Conclusion

We presented and discussed an approach to the concurrent computational performance analysis of building and PV system designs. The approach is meant to support not only the assessment of the implications of buildings' energy demand profile for the configuration of building-

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integrated PV installations, but also the reverse path: In projects involving new buildings or in case of major building retrofit projects, certain design decisions may be flexible and hence open for parametric explorations. In such cases, the proposed approach allows to start with PV installation options and explore them in view of complementary building design features that would maximize the overall system performance. As such, the proposed approach has the potential to support the parametric and iterative analysis of multiple variables pertaining to both building design and PV configuration.

The working of the approach was demonstrated via a computational procedure applied to an illustrative case study. To this end, a virtual building complex comprising eight identical row houses with a roof-top PV installation was selected, whereby certain variables of both building and PV system designs were assumed to be flexible within certain ranges and hence amenable to parametric analysis.

The assessment of the option space was performed via computation of the payback time of the PV system as the designated system performance indicator, whereby multiple electricity price options (import and export) were considered. This exercise could demonstrate that high performance levels can be achieved with very different constellations of building and PV system design options.

It is important to emphasize that the point of the study was not to identify universally applicable features of either building designs or PV system characteristics. The far too limited scope of the presented study could by no means aspire to such a grand outcome. Only a simple building scheme for only one location was considered, and multiple highly simplified assumptions were made regarding building features and its operation modus. For instance, issues such as occupancy dynamics, shading and natural ventilation, as well as alternative heating and cooling systems were not addressed. The assumed electricity price options were rather speculative, and only one performance indicator was considered (payback time), which was calculated in a highly simplistic manner.

Future implementations of the proposed approach must thus address these limitations, via inclusion of much more detailed building and PV system representations (including dynamic processes of occupancy), consideration of local storage options, justification of assumptions regarding the electricity price parametric, and multiple and more detailed performance indicators. Last but not least, future demonstrations of the idea need also to address multiple layers of uncertainty associated with assumptions regarding building properties, PV system attributes, microclimatic conditions, as well as economic and policy-related boundary conditions.

Nonetheless, while acknowledging all these limitations, it is important to emphasize that the main point of the presented limited exercise was to introduce a methodologically relevant idea pertaining to navigation strategies of building-integrated PV systems. As such, the study can be suggested to affirmatively answer the question posed in terms of the paper's title: Exploration of the photovoltaic systems' energy harvesting potential does indeed offer the potential to inform building design and retrofit decisions.

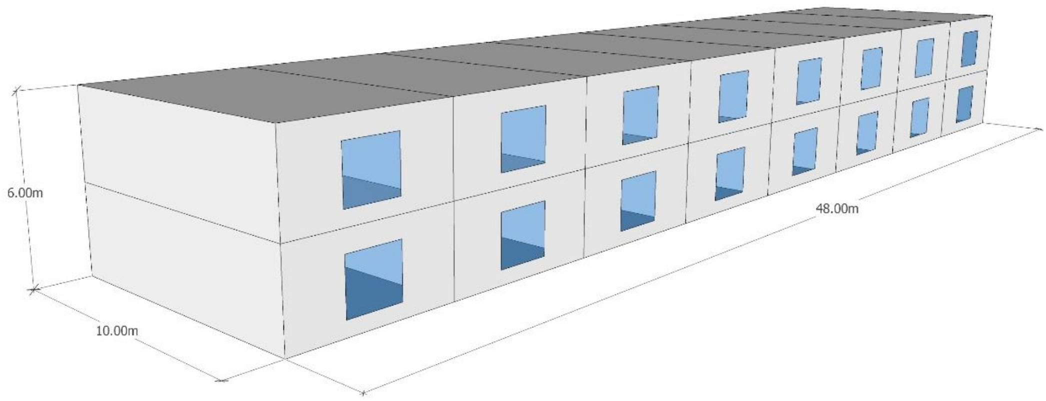

Figure 1: Schematic depiction of the eight-unit row house complex design (Mahdavi et al., 2021).

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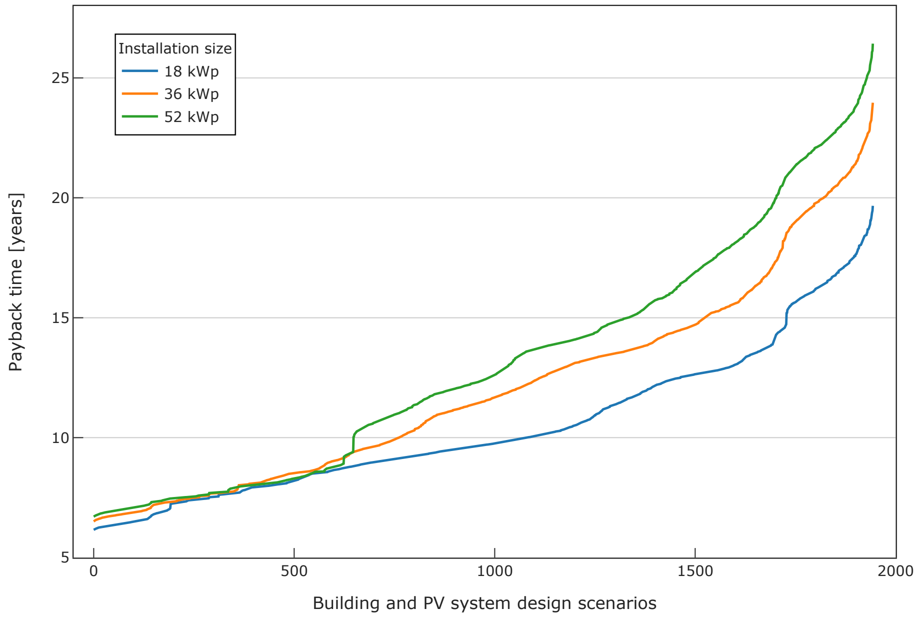

Figure 2: Estimated payback time for PV system's installation and maintenance cost for different combinations of building design and PV system configurations, shown for three distinct classes of PV installation sizes.

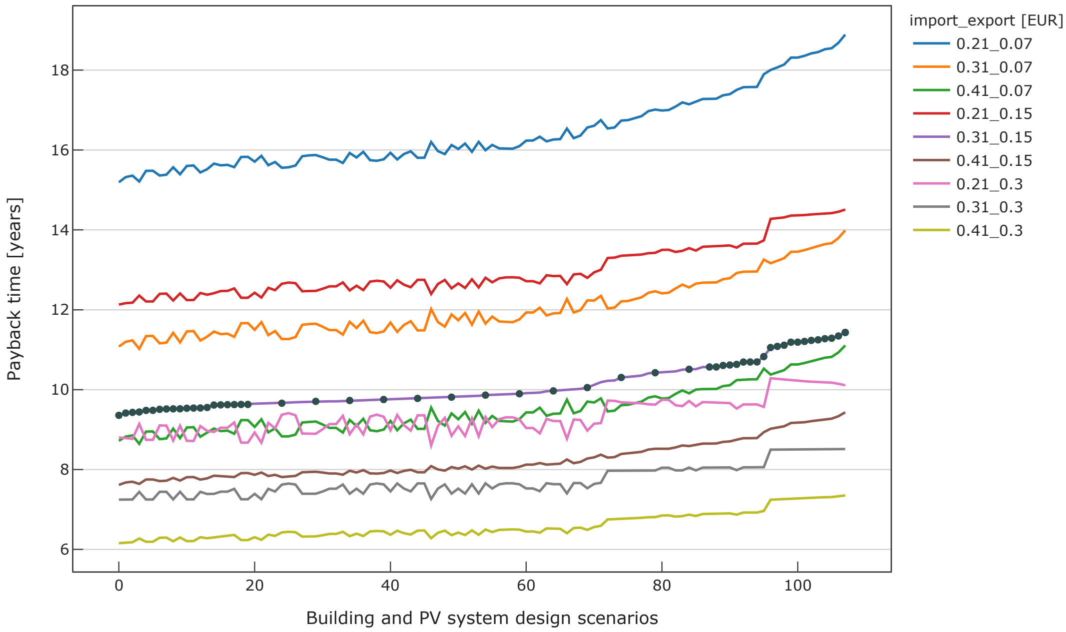

Figure 3: Estimated payback time for PV system's installation and maintenance cost for different combinations of building design and PV system configurations, shown for the system size option 18 kWp and 9 energy price scenarios (purchase_selling price in €). See Table 1 for the key to the numbering system of the scenarios (x-axis). Note that the order of the scenarios on the x-axis (from 1 to 108) corresponds to the descending order of the performances as relevant to the price scheme 0.31_0.15 (electricity purchase versus selling prices in euros).

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Table 1: State descriptions of the design variables regarding the building (orientations E-W, SE-NW, S-N, SW-NE; glazing fraction of the façade 20, 30, and 40 %) and the PV system (PV panel tilts 15, 30, 45 degrees; PV panel azimuth values SE, S, SW). The numbering of scenarios in this Table corresponds to the numbering in the x-axis of Figure 3.

	Building Orientation				Glazing			PV Tilt			PV Azimuth		
	E-W	SE-NW	S-N	SW-NE	20%	30%	40%	15°	30°	45°	SE	S	SW
1	√						√		√			√	
2		√					√		√			√	
3	√					√			√			√	
4	√						√		√		√		
5			√				√		√			√	
6				√			√		√			√	
7		√					√		√		√		
8			√				√		√		√		
9		√				√			√			√	
10	√					√			√		√		
11	√				√				√			√	
12				√		√			√			√	
13				√			√		√		√		
14	√						√			√		√	
15	√					√				√		√	
16		√				√			√		√		
17				√		√			√		√		
18	√						√	√				√	
25	√						√	√			√		
30			√				√			√		√	
35		√				√				√		√	
40				√			√	√			√		
45				√			√			√	√		
50				√	√					√		√	
55				√		√				√	√		
60			√			√		√			√		
65				√	√			√			√		
70			√		√			√				√	
75			√				√	√					√
80	√				√			√					√
85	√					√			√				√
91				√		√			√				√
92			√		√			√					√
93		√			√				√				√
94				√	√				√				√
95			√			√			√				√
96			√		√				√				√
97	√						√			√			√
98		√					√			√			√
99	√					√				√			√
100	√				√					√			√
101		√				√				√			√
102				√			√			√			√
103				√		√				√			√
104			√				√			√			√
105				√	√					√			√
106		√			√					√			√
107			√			√				√			√
108			√		√					√			√

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