Optimisation de l'Intégration Photovoltaïque (PV) dans les Bâtiments Résidentiels

Optimization of Photovoltaic (PV) Integration in Residential Buildings

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Résumé
Avec la hausse des prix de l'énergie, le photovoltaïque devient une option attractive pour les bâtiments résidentiels. Cependant, son intégration peut poser des défis à cause des déséquilibres entre l'offre et la demande et donc impacter les réseaux. Cette étude analyse le placement optimal des panneaux PV, en tenant compte des profils de charge afin d'atteindre une meilleure adéquation. Les objectifs énergétiques (par exemple, l'adaptation de la charge) et économiques (par exemple, la valeur actuelle nette du kWh) sont optimisés. Les résultats montrent que les profils de charge influencent les solutions optimales, les façades étant meilleures pour l'objectif énergétique et les toits pour les objectifs économiques.

Abstract
As energy prices rise, solar photovoltaic (PV) has become an attractive option for residential buildings. However, their integration can pose challenges due to mismatches between energy supply and demand. This study investigates the optimal placement of PV panels on building envelope, considering various load profiles. Energy objective (e.g., load-matching (kWh)) and economic objectives (e.g., net present value (€)) are optimized. Results show that load profiles influence optimal solutions, with façades enhancing energy objective, while roofs are more favorable for economic objectives. Further findings are discussed.

Nomenclature

d	Discount rate
T	Lifetime of the system (y)
t	Actual time period (s)
$L(t)$	Load (kWh)
$P(t)$	PV production (kWh)
S_0	Subsidies (€)
P_r	Retail price (€)
P_w	Wholesale price (€)
I_0	Initial investment (€)
X_i	Fraction (between 0 and 1)
P_i	PV Power of surface i (kWh)
A_i	Area of surface i (m^2)
τ_{SC}	Self-Consumption rate
τ_{SS}	Self-Sufficiency rate
OM	Operation and Maintenance costs (€)
LM	Load Match (kWh)
NPV	Net Present Value (€)
PP	Payback Period (y)
$LCOE$	Levelized Cost of Electricity (€/kWh)

1. Introduction

Buildings are significant contributors to global energy demand, accounting for approximately 33% in 2022. To meet sustainable development goals, the International Energy Agency has projected that global energy use from buildings must be reduced by 13% between 2018 and 2040 [1]. Currently, renewable energy accounts for only 6% of the global final energy consumption

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in buildings. However, this share must increase to 18.1% by 2030 to align with the net-zero carbon targets set by the Paris Agreement [2]. Global renewable energy capacity grew by 36% in 2023, reaching a record 473 GW. Solar PV has emerged as the dominant force behind this growth, accounting for three-quarters of the annual increase. This growth has been facilitated by technological advancements and policy support, which have reduced economic factors making it more affordable than fossil fuel-based energy sources [3].

While solar PV systems offer substantial benefits in energy generation, their integration into buildings poses challenges due to the mismatch between energy supply and demand. Solar energy generation is intermittent, with peaks during sunny days and shortages at night or during winter months. This mismatch can lead to both overproduction and underproduction. In most cases, buildings with on-site electricity generation are connected to the grid; however, mismatches between PV generation and consumption can lead to issues such as power quality problems and over-consumption. To mitigate these challenges, indicators such as Load-Matching (LM) are used, which refer to the simultaneity of instantaneous electricity consumption and electricity generation in a PV system. Additionally, metrics such as τ_{SC} and τ_{SS} are applied to assess load matching performance. The former, the *self-consumption rate* (τ_{SC}), refers to the share of on-site produced electricity that is consumed directly within the building. This metric is important as it reflects the system's ability to reduce dependency on the grid and provide the energy for its own use. The latter, the *self-sufficiency rate* (τ_{SS}), represents the share of the building's electricity demand that is met by its own on-site generation. This indicator is essential for assessing the energy autonomy [4].

The effectiveness of load-matching is heavily influenced by consumption patterns and PV orientations [5]. Therefore, to improve LM, it is essential to identify the optimal integration and deployment of PV systems on the building envelope, including roofs and façades, to better align with the consumption profile. In other words, PV modules can be installed on non-optimal orientations of the building envelope (such as East and West) to better correspond to the load profile of residential buildings, which typically have higher consumption in the morning and evening.

Furthermore, the state-of-the-art shows that economic factors can influence PV implementation, both in terms of the expenses associated with using electricity from the grid and the financial returns from implementing PV installations. For instance, studies show that PV placement on non-optimal building envelopes can achieve high levels of self-consumption at lower costs, particularly in households without energy storage systems [7]. Studies show that Net Present Value (NPV), Payback Period (PP), and Levelized Cost of Electricity (LCOE) are the indicators commonly used to evaluate the financial aspects of PV implementation on buildings. The results indicate that, in most case studies, the cost of PV generation has already reached grid parity. However, these parameters also depend on factors such as the building's energy consumption, and other geometric properties that can influence the optimal distribution of PV installations [8].

This research, based on the literature [8], employs single-objective optimizations to determine the optimal area of PV panels integrated into building envelopes. For each objective, the optimal solution identifies the percentage of building envelope (façades and roof) that should be covered by PV panels. The primary objective focuses on LM, which aims to optimize the alignment between solar energy generation and building energy consumption. In addition, the study includes economic objectives as: NPV, PP, and LCOE. The study addresses two key aspects: Firstly, the optimal solutions for each objective are determined. And, secondly, the impact of varying consumption patterns on the objectives is analyzed.

2. Material and method

The following methodology was adopted for the current work: first, data collection on weather and household consumption data was conducted. Next, the building geometry and surface area were defined to establish the available surfaces for PV installation. Data analysis was then performed to simulate PV production based on the collected weather data. Finally, the optimization process was implemented to determine the optimal use of the building's envelope. Each of these steps is further explained in the following subsections.

2.1. Data collection

The location for simulation is Lyon, and the weather data for this location were sourced from the National Renewable Energy Laboratory (NREL) website [9]. Household consumption profiles were obtained from the EtudELEC dataset [10], which reflects various residential energy profiles in France. Both datasets provided a resolution of 30 minutes. Additional information regarding economic parameters was obtained from studies in France [11].

2.2. Building geometry and surface area

The analyzed building has a 10×10 m footprint, 3 m floor height, and a 30° pitched roof. Usable surface areas were determined based on building code constraints, including window-to-wall ratios. The optimization explored the best PV allocation across facades and the roof. Figure 1 shows a 3D view of the building (left) and a 2D unfolded plan of the façades and roof (right). The surfaces are labeled as follows: South (S), North (N), East (E), West (W), Roof-South (RS), and Roof-North (RN).Therefore, we have: $i \in \{S, E, W, N, RS, RN\}$

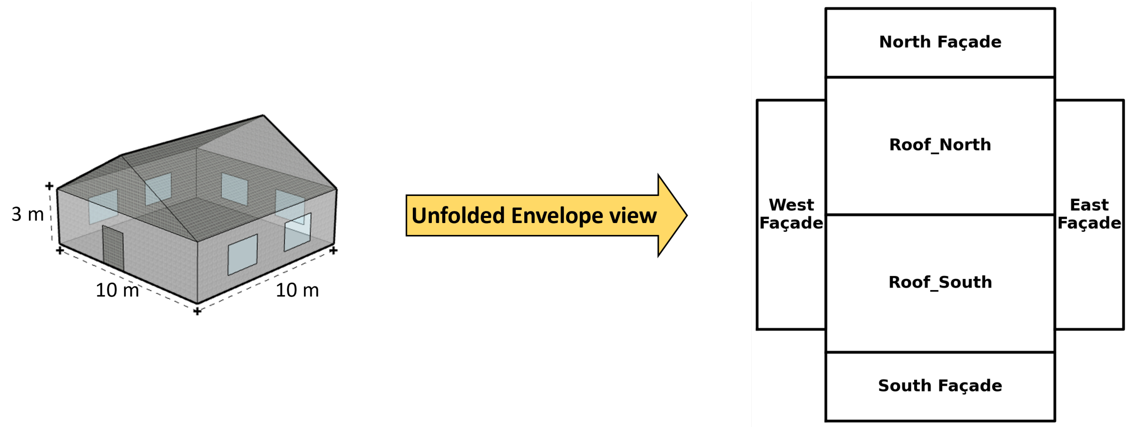

Figure 1: *Case study*

2.3. Data analysis

The PVLib library (in Python) was used to calculate the energy generation of the PV system using the collected weather data for Lyon. PVLib enables accurate modeling of PV output by considering solar irradiance, temperature, and other meteorological factors. For optimization, Genetic Algorithms (GA) was used due to their reliable global optimization results. The results were compared with those from other global optimization techniques, such as Particle Swarm Optimization, and were consistent with GA optimization outcomes.

2.4. Optimization process

The optimization process consists of single-objective optimizations, each determining the optimal distribution of PV panels on the building's façades and roof. For all objectives, the PV production can be expressed as: $P(t) = \int_{t=1}^{T} \sum_{i=1}^{6} X_i \cdot P_i \cdot A_i$

As discussed earlier, one objective related to energy is selected: Load Match (LM). As mentioned before, the LM function measures the degree of alignment between PV power generation and energy demand over time. The LM function is based on the absolute difference between the load and PV power at each time step. The goal is to minimize this difference across all time steps, which is why the LM function accounts for the absolute deviation at every time step, regardless of whether PV power exceeds or falls short of the load at specific moments. In addition, three economic objectives are chosen: Net Present Value (NPV), Payback Period (PP), and Levelized Cost of Electricity (LCOE). Each of these objectives is optimized individually. The optimization problem is formulated with the following objectives:

$$
\begin{aligned}
& f(x) = f(x) = [f_1(x) : \text{LM}, f_2(x) : \text{-NPV}, f_3(x) : \text{PP}, f_4(x) : \text{LCOE}] \\
& f_1(x) = \int_{t=1}^{T} |L(t) - P(t)| \; dt \\
& f_2(x) = \left(S_0 + \sum_{t=1}^{T} \frac{max(0, L(t) - P(t)) \cdot P_r + max(0, P(t) - L(t) \cdot P_w)}{(1+d)^t} \right) - \left(I_0 + \sum_{t=1}^{T} \frac{OM_t}{(1+d)^t} \right) \\
& f_3(x) = PP, \quad \text{with} \quad f_2(x, T = PP) = 0 \\
& f_4(x) = \left(I_0 + \sum_{t=1}^{T} \frac{OM_t}{(1+d)^t} \right) / \left(\sum_{t=1}^{T} \frac{P(t)}{(1+d)^t} \right)
\end{aligned}
$$

As mentioned before, self-consumption rate τ_{SC} and self-sufficiency rate τ_{SS} were applied to evaluate the objective results. The former, the (τ_{SC}), refers to the share of on-site produced electricity that is consumed directly within the building. This metric is important as it reflects the system's ability to reduce dependency on the grid and minimize energy exports. The latter, the (τ_{SS}), represents the share of the building's electricity demand that is met by its own on-site generation. This indicator is essential for assessing the energy autonomy [4]. Therefore, according to [8], the ratios can be expressed as:

$$\tau_{\text{SC}} = \int_{t=1}^{T} \frac{\min[P(t), L(t)]}{P(t)} \, dt \quad \tau_{\text{SS}} = \int_{t=1}^{T} \frac{\min[P(t), L(t)]}{L(t)} \, dt$$

3. Results

Firstly, the optimal solutions for the energy and economic objectives are presented, followed by an analysis of the impact of load profiles on the LM objective. Additionally, the variation in the final value of the objective functions *f(x)* is illustrated. Both energy objective (LM) and economic objectives (NPV, PP, LCOE) are optimized for *electricity_apartment* load profile and the optimal solution for each objective is as follows:

3.1. Optimal Solutions for Energy and Economic Objectives

The results of the LM objective indicate that implementing PV panels on façades provides a better match between the load and PV production compared to roof-mounted PV panels. For example, for the *electricity_apartment* load type (which relies solely on electricity from the grid), PV placement is suggested as 20% on the *S* façade, 7% on the *W* façade, and 2% on the *E* façade respectively. Additionally, 39% PV coverage is recommended for the *N* façade, which is attributed to reflected and diffuse radiation. In Figure 2, on the right, the placement of PV panels resulting from the LM optimal solution on the building envelope for *electricity_apartment* load profile is shown for better clarity.

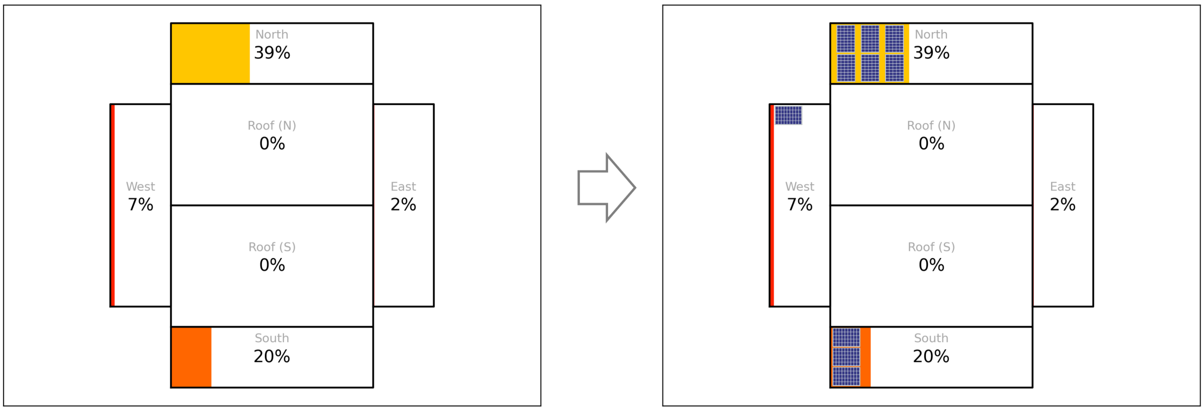

Figure 2: *Optimal solution for LM objective (electricity_apartment load profile)*

Moreover, the results of economic objectives show that roof is more favorable for PV implementation as it obviously produce more energy. The NPV objective shows that both *RS* and *RN* are fully utilized for optimal solution. The results align with previous studies [8]. For PP, it decreases to 60% of the *RS* since the time of payback period will offset it sooner than the optimal value for NPV. Finally, LCOE determines the full utilization of *RS* for having the lowest cost of energy. The reason for favoring roofs over façades in economic objectives is related to the costs considered in the optimization, as the cost of implementing PV on façades is assumed to be twice that of roof PV placement [11]. The optimal solution for economic objectives for *electricity_apartment* load profile is illustrated in Figure 3, 4, 5.

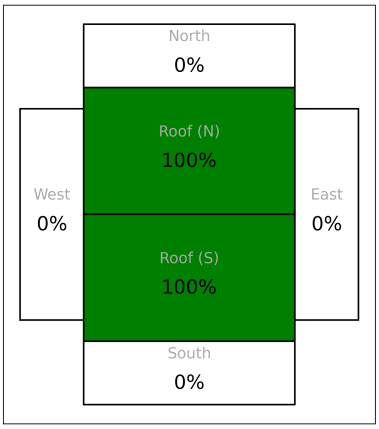

Figure 3: *Optimal NPV: electricity_apartment load profile*

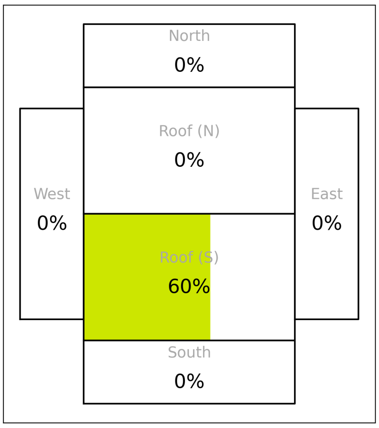

Figure 4: *Optimal PP: electricity_apartment load profile*

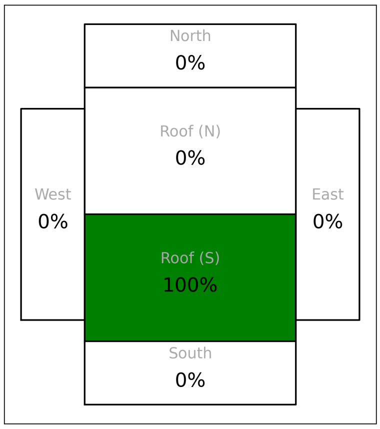

Figure 5: *Optimal LCOE: electricity_apartment load profile*

The findings show that the self-consumption rate (τ_{SC}) for the Load-Matching (LM) objective is approximately 0.20, whereas it decreases for the economic objectives: 0.16 for Payback Period (PP), 0.14 for Levelized Cost of Electricity (LCOE), and 0.12 for Net Present Value (NPV). Notably, prioritizing façades under the LM objective improves τ_{SC} by 0.10, though this results in a lower power output. In contrast, the self-sufficiency rate (τ_{SS}) exhibits opposite trends: it is 0.20 for NPV, 0.18 for LCOE, and 0.17 for PP, while the LM objective results in a lower value of 0.10. These findings indicate that prioritizing energy objectives increases the building's energy use by 10%, ensuring more locally consumed energy. However, when economic objectives are emphasized, the self-consumption rate decreases by 10%. Conversely, the economic optimal solution, focusing on roofs, enhances the self-sufficiency rate by 10%, meaning the building would rely on its own production for 10% more of its energy needs compared to energy objectives.

3.2. Impact of Load Profiles on Energy and Economic Indicators

Figure 6 shows the optimal solutions for the LM objective, represented by the X values (percentages of PV coverage) for each load type. Among the façades, the *N* façade shows the highest coverage. For the *S*, *W*, and *E* façades, the X-values range approximately from 5% to 20%, with the highest percentage observed for the *S* façade. This is likely due to the fact that south-facing surfaces generally receive more sunlight.

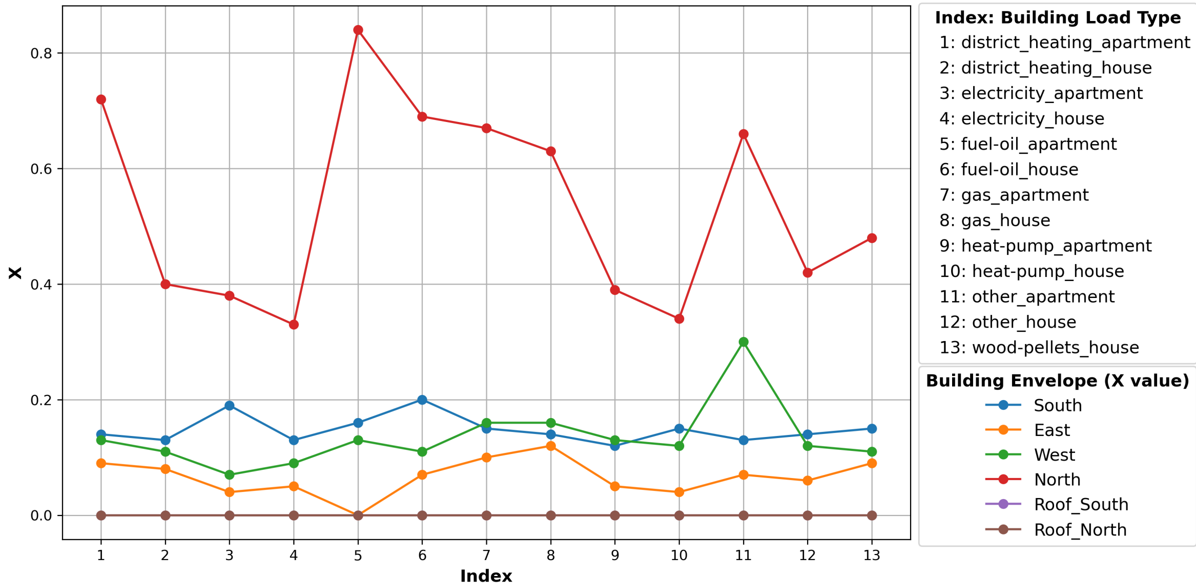

Figure 6: *PV panel coverage across building envelope for load types*

Figure 6 also illustrates the variation of X-values across façades, highlighting different fluctuation patterns. Notably, the *N* façade exhibits the highest fluctuation across all load types. For instance, in the case of *electricity* and *heat-pump*, the X-values range between 30% and 40% at the lowest level, whereas for *fuel-oil* and *gas*, they exceed 60%, reaching the highest values. It is interesting to note that load types relying on electricity allocate lower X-values to the *N* façade, whereas load types that incorporate other energy sources exhibit higher X-values. In contrast, the fluctuations for the other façades are significantly lower, with X-values confined to a narrower range and clustering more closely across load types. This suggests that changes in load type have a less significant impact on PV coverage. Notably, the *other_house* category follows a different pattern, indicating higher X-values for the *N* and *W* façades. However, since this category does not fall within a well-defined classification, its behavior is more difficult to interpret.
Regarding economic indicators, the results show that the percentage of PV coverage (X-values) remained consistent for the economic objectives of NPV and LCOE, as illustrated in Figures 3 and 5. However, the use of *RS* for PP varies between 50% and 90%, which indicates that the economic objectives are more stable when the load profile changes.

3.3. Impact of Load Profiles on Objective Function Outputs

In addition, the results show that the values related to the optimal solution of the objective function $f(x)$ differ for each load type. To facilitate comparison of the changes in the final output of each objective, $f(x)$ is normalized using the following equation: $\hat{f}_x = f_x / f_{\max}$ Where $\hat{f}_x$ is the normalized value of f_x, and $f_{\max}$ is the maximum value of f_x. This method of normalization is particularly useful, as it helps illustrate objectives that have a constant value across all load types. As Figure 7 shows, the range of changes in f_x across load types differs for each objective. The PP and LM objectives show a wider range of results, while NPV is less affected by variations in load types. It is worth noting that the LCOE objective remains constant regardless of changes in the load type. This information provides insight into the magnitude of the effect that changes in load profiles have on the final optimization solution.

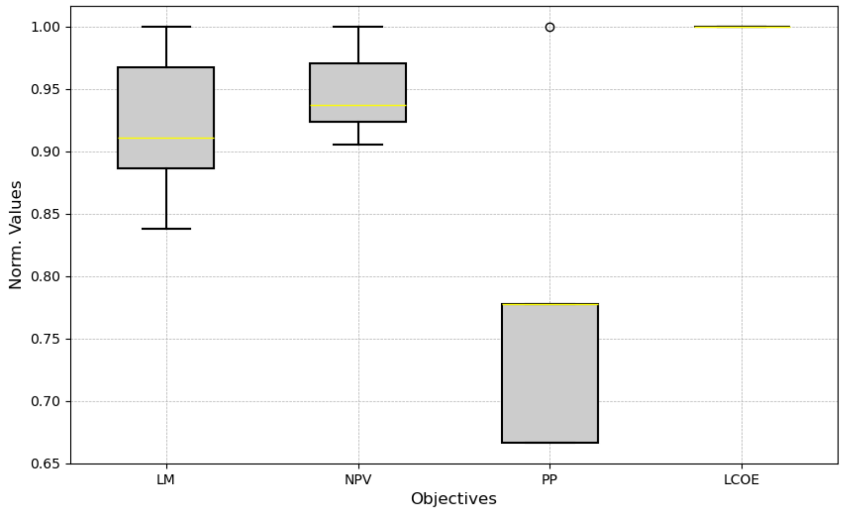

Figure 7: *Impact of load types on objective function results*

4. Discussion

The results of this analysis highlighted several important trends and outcomes: (i) The LM objective favored the valuation of building façades. This suggests that the façades align better with the load curve for energy generation for the studied load profiles. (ii) The economic objectives favored roof space for PV installation, as roofs generally offer higher economic returns due to lower installation costs. (iii) The results indicate that the *N* façade contributes to the LM objective. While previous studies often exclude the North façade [8], this study demonstrates that the optimal LM solution across load types generally requires PV coverage exceeding 30%. (iv) The load profile plays a crucial role in shaping optimization outcomes. The analysis demonstrated that different building types, with their unique consumption patterns, influence optimal PV coverage on the building envelope. However, a limitation of this study is the exclusion of grid interaction objectives, which limits the ability to assess the benefits of reducing grid dependence and optimizing grid interaction—an important aspect of PV system design. Further, the results revealed significant differences between energy and economic indicators, underscoring the need of multi-objective optimization for future work.

5. Conclusion

In conclusion, in this study, the type of load in a building can significantly influence the optimal PV implementation solution. It is demonstrated that different building consumption profiles lead to different outcomes in terms of PV allocation, with façades being more favorable for load matching and roofs providing better economic benefits. The results underscore the need for a balanced approach in PV system design that considers both energy and economic factors. This study, carried out on the scale of a single house, it could be extended to the scale of a neighborhood with different demand profiles (office, residential buildings), which could lead to the identification of integration strategies on larger scales. In addition, the results indicate the need for implementing a multi-objective optimization approach that simultaneously considers energy-related indicators and economic feasibility.

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