SOLAR PERFORMANCE INDICATORS FOR RESIDENTIAL BUILDINGS – INTERACTIONS BETWEEN BUILDING STRUCTURE, HVAC AND PV

Summary

In the assessment of Solar Performance in residential buildings, the transition from passive to active energy systems marks a significant evolution in building energy management. Active systems—including PV panels and HVAC units—introduce dynamic energy flows, enabling buildings to not only consume but also generate and exchange energy with the grid. This work underlines that the successful integration of active energy systems in buildings requires a holistic and adaptive approach. The 2.5 kWp roof-mounted PV system, combined with a radiative heating system and high thermal mass, represents an optimal configuration for most residential applications, balancing energy efficiency, renewable integration, and demand management. However, the study also reveals that oversized PV systems and advanced thermal storage strategies can offer additional benefits in specific contexts, provided that appropriate management strategies are in place.

Keywords: Solar systems, energy performance, indicators,

Field of application for the findings: The findings contribute to academic literature

Addressed audience: academicians, consulting offices

1. Introduction (SWC_Heading1)

In the assessment of Solar Performance in residential buildings, the transition from passive to active energy systems marks a significant evolution in building energy management. Passive strategies, such as insulation and solar shading, primarily aim to reduce energy demand by leveraging architectural design and material properties (Cillari et al. 2021). In contrast, active systems—including PV panels and HVAC units—introduce dynamic energy flows, enabling buildings to not only consume but also generate and exchange energy with the grid. This shift presents both opportunities and challenges: while active systems can enhance energy flexibility and enable net-zero or net-positive buildings, they also require sophisticated control strategies to manage the temporal mismatches between energy supply and demand (Clauss et al, 2024).

The methodology employs energy performance simulations of a detached house (six-minute time steps). The study aims to develop a good understanding of how active systems perform under different configurations and to identify optimal strategies for maximizing energy efficiency, renewable integration, and demand management. In this aim, different performance indicators are used (Chesné et al, 2012, Omar et al, 2020, Kylili et al, 2016).

2. Methodology: Simulation Framework and Case Studies

The INCAS house (individual residential house), with an externally insulated envelope, serves as the baseline model for all simulations.

Three PV configurations are evaluated to assess their performance under different conditions:

- 2.5 kWp façade-mounted system: Represents an architecturally integrated solution, though with suboptimal solar exposure.

- 2.5 kWp roof-mounted system: Offers better solar alignment and higher generation potential.

- 7 kWp roof-mounted system: Represents a maximum installation, covering the entire available roof area, to explore the effects of oversizing and surplus energy management.

All configurations utilize Dual Sun Flash 500 Half Cut-Black panels, which are representative of contemporary high-efficiency residential PV technology. These configurations allow for a comparative analysis of the trade-offs between architectural integration, generation capacity, and overall system performance.

Two heating systems are modeled to evaluate their interaction with the building's thermal mass:

- Convective system: Uses an air-source heat pump with a nominal COP of 2,
- Mixed radiative system: Combines 30% radiative and 70% convective heat transfer,

To further explore the role of thermal mass, an alternative heavy structure is introduced, increasing the thermal mass capacity from 21 to 104 $Wh/m^2 \cdot K$. This modification allows for an assessment of how enhanced thermal storage can smooth energy demand and improve the alignment between PV generation and heating needs.

3. Development of Performance Indicators for Active Systems

The integration of active systems necessitates the use of performance indicators that account for bidirectional energy flows, renewable energy integration, and temporal dynamics. Traditional metrics focused solely on energy consumption are insufficient for capturing the complexities of active systems.

The concept of "total exploited potential" is expanded to include both passive solar gains and active PV generation. This holistic metric provides a comprehensive view of how effectively solar energy is utilized within the building. Two complementary indicators—autoconsumption and autoproduction—are introduced:

- Autoconsumption rate: Measures the proportion of locally generated PV energy that is directly used on-site, reflecting the building's ability to align generation with consumption.
- Autoproduction rate: Indicates the percentage of total energy consumption met by on-site generation, highlighting the building's self-sufficiency.

The temporal mismatch indicator quantifies the instantaneous imbalance between energy generation and consumption, identifying periods of surplus or deficit. This metric is critical for designing storage solutions or demand response strategies. The load shift potential (LSP) assesses the effectiveness of demand-side management in redistributing energy consumption from peak to off-peak periods, particularly for preheating strategies.

4. Results and Analysis

The evaluation of the three PV configurations reveals distinct performance characteristics:

- The 2.5 kWp roof system achieves the best balance between generation and consumption, with an autoconsumption rate of 29.8% and an autoproduction rate of 12.7%. This configuration is optimal for most residential applications, offering a good compromise between performance and architectural integration.
- The 2.5 kWp façade system generates 12% less energy than the roof-mounted system due to suboptimal orientation. However, its architectural integration may justify its use in contexts where roof space is limited.
- The 7 kWp roof system demonstrates significant oversizing, with peak generation (2.3 kW) far exceeding instantaneous heating needs. While it achieves the highest autoproduction rate (17.5%), its autoconsumption rate is the lowest (14.8%), indicating that much of the generated energy is exported to the grid. This configuration highlights the need for advanced storage or demand management strategies to fully exploit its potential.

Three preheating windows (12:00-14:00, 14:00-16:00, and 16:00-18:00) are analyzed to assess their effectiveness in shifting energy consumption from peak to off-peak periods. The results show that all preheating strategies increase total energy consumption compared to the baseline, due to the additional energy required to raise the indoor temperature in advance. However, the increase is partially offset by the heavy structure, which reduces the additional demand by 9.0% to 18.4% depending on the configuration.

The 16:00-18:00 preheating window is the most effective at reducing evening peak demand, nearly eliminating it in some cases (4 kWh for the radiative system and 7 kWh for the convective system). This underscores the importance of temporal proximity between preheating and peak demand periods.

The autoconsumption rate improves significantly with preheating, reaching up to 55.7% for the radiative system in the 12:00-14:00 window, compared to 35.0% at baseline. This improvement reflects better alignment between PV generation and heating demand.

5. Conclusion

This work underlines that the successful integration of active energy systems in buildings requires a holistic and adaptive approach. The 2.5 kWp roof-mounted PV system, combined with a radiative heating system and high thermal mass, represents an optimal configuration for most residential applications, balancing energy efficiency, renewable integration, and demand management. However, the study also reveals that oversized PV systems and advanced thermal storage strategies can offer additional benefits in specific contexts, provided that appropriate management strategies are in place.

6. References

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