Assessing the Impact of Rooftop Area Constraints on the Techno-Economic Viability of Residential Photovoltaic Systems

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Abstract*– Residential photovoltaic (PV) systems offer the opportunity to reduce electricity costs and greenhouse gas emissions in the residential sector. However, townhouse developments and other types of urban housing often have roof space limitations that restrict the installation of PV capacity. This study evaluates the technical, economic, and environmental performance of a grid-connected rooftop PV system installed under space-constrained conditions in Wesley Chapel, Florida. Based on an annual electricity demand of 9,049 kWh, it was estimated that a 5.62 kWp system would be needed to fully offset consumption; however, the available roof area only allowed for the installation of a 3.0 kWp system. Simulations using PVsyst estimated an annual electricity production of 4,053.9 kWh, equivalent to 44.8% of the household's demand, with a performance coefficient of 83.04%. The proposed system requires an investment of approximately 4,500 U.S. dollars, resulting in an estimated return on investment of 11% and a payback period of less than 10 years. In addition, annual CO_2 emissions could be reduced by about 1.5 metric tons. The results indicate that rooftop photovoltaic systems can remain a viable option for the residential energy transition, even when physical limitations of the roof prevent it from being fully covered.

Keywords*-- Residential photovoltaics, rooftop constraints, techno-economic analysis, distributed generation, sustainability.

I. Introduction

Growing global energy demand and the need to mitigate the effects of climate change have driven the transition toward renewable energy sources, particularly solar photovoltaic energy. This resource has been studied in various countries due to its high energy potential [1]. In countries such as the United States, solar and wind energy are projected to account for about 17% of total electricity by 2025 [2].

Among U.S. states, Florida offers a particularly attractive environment for residential solar applications due to its high solar resource availability and growing photovoltaic market, taking advantage of the fact that the region has an average annual solar radiation of 1,610 [kWh/kWpf [3]. Residential energy consumption in Florida accounts for a significant portion of annual household expenses, especially in homes built before the widespread adoption of modern energy efficiency standards. High demand during the summer months is primarily associated with intensive use of air conditioning, which in Florida can account for more than 40% of total residential consumption [4].

Studies conducted in townhomes in warm climates have shown that combining monocrystalline solar panels with passive measures (insulation, solar shading) and active measures (LED lighting, energy-efficient appliances) can reduce grid consumption by up to 60% [5]. These improvements, both in energy efficiency and in the installation of new renewable technologies, contribute to the sustainable development of housing in the country. Additionally, they contribute to a clean and sustainable energy transition. These measures have the potential to generate economic benefits for households, which helps reduce long-term costs, thereby benefiting household finances and, in turn, addressing climate change.

In Florida, the Florida Solar Energy Center (FSEC) and the U.S. Department of Energy (DOE) promote the retrofitting of existing homes as part of the state's energy transition. Additionally, Florida law (Statute 163.04) protects the right to install solar systems in communities with homeowners' associations (HOAs), limiting their ability to prevent or significantly restrict such installations. Beyond the availability of rooftops, the challenge lies in sizing and implementing a photovoltaic system and efficiency improvements that maximize energy self-sufficiency, reduce costs, and minimize the carbon footprint.

Given the country's vast potential for solar photovoltaics, government support, and sustainability benefits, installing these types of systems is considered highly beneficial. However, at the residential level, roof space is a crucial factor in their installation, but it is a challenge that can be overcome to maximize the benefits.

Several articles have addressed this issue. Vecchi et al. analyzed the photovoltaic potential of various residential buildings in Toronto using real-world roof constraints [6]. Villa-Ávila et al. developed a methodology to determine the photovoltaic generation potential on urban rooftops, considering geometry, space, and physical constraints [7]. Zhang et al. evaluated the photovoltaic potential of residential, commercial, and industrial buildings and demonstrated that the function and configuration of buildings directly influence installed capacity and achievable generation [8]. These works contribute useful methods for photovoltaic capacity assessment; however, they fail to consider the impact of the mentioned extreme physical rooftop limitation on the

efficiency of a single house solar system. Hence, the research gap that is covered by this study is the absence of a comprehensive analysis of PV capacity at the residential scale, where first the achievable rooftop capacity is estimated based on the real dimensions of a roof, and then it is assessed in terms of technical, economic and environmental aspects. The innovation of this research is in the integration of the geometric restriction of the real roof and the production of solar power in terms of PVsyst, economic factors for 25 years, and CO_2 reduction. In the case of the residential building considered in Wesley Chapel, Florida, the available roof space restricts the installation of the PV system to 3.0 kWp in comparison to 5.62 kWp needed for covering the annual electricity consumption.

The rest of this article is organized as follows: Methodology, which explains the techniques and methods used during the research; Results and discussion which presents the main findings; and finally, Conclusions, which summarizes the research findings.

II. METHODOLOGY

In this section the methodology is explained. Figure 1 summarizes the main steps of the research.

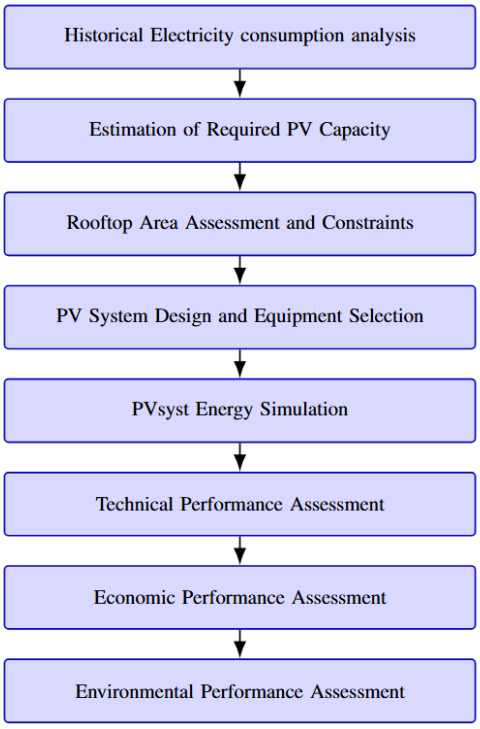


Fig. 1 Research Methodology Flowchart

A. Historical Electricity consumption analysis

At this stage, it is necessary to analyze the electricity consumption history of the residence in question. A baseline for the home's energy consumption over the past 12 months will be established. Based on this consumption, the home's energy capacity is determined.

This consumption data can be obtained from the electricity company's bills, or a power meter can be installed to create a load profile for the residence. Although the load profile is more accurate, due to equipment limitations, the energy consumption data from the utility bills will be used.

B. Estimation of Required PV capacity

To determine the photovoltaic capacity theoretically required to offset the annual electricity demand, the annual consumption was compared with the average specific photovoltaic yield for the study area.

The required PV capacity was calculated using Equation 1.

$$P_{req} = \frac{E_{load}}{Y_{spec}} \quad (1)$$

Where:

- P_{req} = required photovoltaic capacity [kWp]
- E_{load} = annual household electricity demand [kWh/year]
- Y_{spec} = specific PV yield [kWh/kWp year]

C. Rooftop area assessment and constraints

The roof area was evaluated by analyzing the space available for installing the solar system. First, it is necessary to calculate the space required for the photovoltaic system to meet the full capacity using Equation 2.

$$A_{pv} = N \times A_m \quad (2)$$

Where:

- A_{PV} = photovoltaic array area [m^2]
- N = number of modules
- A_m= area of single module [m^2]
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Next, the available space is analyzed and compared with the result obtained from Equation 2. The assessment of the available space considers:

- **Roof geometry:** The shape of the roof and its surface areas were analyzed.
- **Available installation surface:** The most suitable area for installing the system is determined based on its orientation and angle.
- **Module dimensions:** Using the physical characteristics of the solar module.
- **Spacing requirements between modules:** Minimum spacing requirements were incorporated to ensure proper installation practices, thermal dissipation, and maintenance accessibility.
- **Structural installation limitations:** Based on roof configurations and requirements from the manufacturer.

This step constitutes the main constraint analyzed in the study.

To evaluate the spatial impact of the installation, the total length of the photovoltaic array was determined according to the module arrangement using Equation 3.

$$L_{row} = (N \times W_m) + [(N-1) \times S] + 2M \quad (3)$$

Where:

- L_{row} = total row length [mm]
- N = number of modules
- W_m =module width [mm]
- S = spacing between modules [mm]
- M = edge safety margin [mm]

D. PV system design and equipment selection

The solar photovoltaic system was designed based on the required photovoltaic capacity. This step was taken to determine the number of solar modules needed to meet the residence's energy demand. Next, based on the determined usable area, the number of solar modules that can actually be installed is determined.

Based on the maximum number of modules that could be physically accommodated, the feasible installed capacity was determined using Equation 4.

$$P_{installed} = N \times P_{module} \quad (4)$$

Where:

- $P_{installed}$ = installed PV capacity [kWp]
- N = number of installed modules
- P_{module} = Nominal module power [kWp]

This value represents the maximum capacity achievable under the rooftop constraints of the dwelling. To quantify the effect of the physical limitation, the rooftop constraint factor was defined using Equation 5.

$$RCF = \frac{P_{installed}}{P_{required}} \times 100 \quad (5)$$

Where:

- RCF = Rooftop Constraint factor [%]
- $P_{installed}$ = installed PV capacity [kWp]
- $P_{required}$ = theoretical capacity required for full demand offset [kWp]

To select the necessary equipment, prices and availability in the U.S. market are evaluated. Technical drawings, including layout plans, mounting details, string configuration, and single-line diagrams, were developed using AutoCAD.

E. PVSyst energy simulation

After determining the number of modules to be installed based on roof space limitations, a simulation was performed using PVSyst software.

The PVSyst simulation includes

- local meteorological data
- module specifications
- inverter characteristics
- system losses
- and roof orientation and tilt

The software estimated annual energy production and overall system performance under real operating conditions.

F. Technical performance assessment

After running the simulation in PVSyst, a technical analysis of the solar system is conducted. The technical performance of the photovoltaic system was evaluated based on energy production, demand coverage, system efficiency, and validation of the electrical design.

The evaluation took the following indicators into account:

- Annual energy generation [kWh/year] (obtained from the PVSyst simulation)
- Demand coverage [%]
- Performance ratio (PR) [%]

The demand coverage was calculated using Equation 6.

$$Coverage = \frac{E_{PV}}{E_{load}} \times 100 \quad (6)$$

Where:

- Coverage = Percentage of coverage for the system [%]
- E_{PV} = annual photovoltaic energy generation [kWh/year]
- E_{load} = annual household electricity demand [kWh/year]

The performance ratio was calculated using Equation 7.

$$PR = \frac{Y_f}{Y_R} \times 100 \quad (7)$$

Where:

- Y_f = final yield [kWh/kWp]
- Y_r = reference yield [kWh/kWp]

The conductor sizes, protective devices, grounding system, and circuit configuration were verified in accordance with the requirements established in NEC 2023 [9]. The results of the voltage drop analysis were used to confirm that the selected conductors provided adequate electrical performance while minimizing energy losses.

G. Economic performance assessment

An economic analysis is conducted to determine the feasibility of the solar photovoltaic system. This analysis is necessary because it assesses whether, despite space constraints, the system is economically viable.

The following parameters are analyzed:

- Base annual savings
- Return on investment (ROI)
- Payback period

Additionally, the main technical and economic assumptions used in the analysis are summarized in Table I.

TABLE I
MAIN TECHNICAL AND ECONOMIC ASSUMPTIONS

Parameter	Base value	Basis/justification
Annual electricity demand	9,049 kWh/year	12 months of residential utility bills
Electricity tariff	USD 0.13/kWh	Local utility rate for the study period
Annual electricity price increase	3%/year	Historical trend in Florida residential electricity prices [10]
Module degradation	0.5%/year	Selected PV module technical specification
Analysis period	25 years	Expected useful life of PV modules and mounting system
Installed PV capacity	3.0 kWp	Maximum capacity allowed by rooftop constraints
Annual PV generation	4,053.9 kWh/year	PVSyst simulation
O&M cost	15 USD/kWp-year*	Economic assumption/source to be specified
Initial investment	USD 4,500	Market-based cost estimation

The annual savings were determined from the energy generation obtained from the PVSyst Analysis and the electricity tariff using Equation 8.

$$Annual\ savings = E_{pv} \times Tariff \quad (8)$$

Where:

- Annual savings = savings made from using solar energy [USD]
- EPV = Energy generation from solar system [kWh]
- Tariff = Electricity tariff [USD/kWh]

The return of investment was calculated using Equation 9.

$$ROI = \frac{Annual\ Savings}{System\ Cost} \times 100 \quad (9)$$

Where:

- ROI = Return on investment [%]
- Annual savings = First-year annual savings made from using solar energy [USD]
- System cost = system cost including initial investment and operational and maintenance cost [USD]

The simple payback period was determined using Equation 10.

$$Payback = \frac{System\ Cost}{Annual\ Savings} \quad (10)$$

Where:

- Payback= Amount of time required to recover system cost
- System cost = system cost including initial investment and operational and maintenance cost [USD]
- Annual savings = savings made from using solar energy [USD]

H. Environmental performance assessment

The environmental impact of the photovoltaic system was evaluated through the annual reduction of carbon dioxide emissions. Emissions were avoided using Equation 11.

$$Emissions\ avoided = E_{pv} \times EF \quad (11)$$

Where:

- Emissions avoided = Carbon dioxide emissions avoided [kg of CO_2]
- EPV = Annual electricity generation [kWh/year]
- EF = Grid emission factor [kg CO_2/kWh]

The emission factor selected corresponds to Florida's electricity grid, allowing the estimation of annual greenhouse gas emission reductions associated with photovoltaic generation.

Assumptions made in the economic assessment have been made depending on the nature of the assessed residential system and the available information both technologically and from the market perspective. The cost of electricity at USD 0.13/kWh is the cost stated by the local electricity supplier during the analyzed period. A yearly increment of 3% in the cost of electricity was assumed as a conservative estimate considering the past trends of residential electricity costs in Florida [10]. A yearly degradation of the selected PV module was estimated at

0.5%. Lastly, an analysis period of 25 years has been chosen considering the lifetime of the PV modules and the warranty of the mounting structure.

III. Results and Discussion

This section presents the results obtained and a discussion of them.

An analysis of the residence's energy consumption was conducted based on the electricity bills. A summary of consumption and costs is shown in Table II.

TABLE II
ANNUAL ENERGY CONSUMPTION AND COSTS

Parameter	Value
Annual consumption [kWh]	9,049
Maximum monthly usage [kWh]	1,060 (August)
Minimum monthly usage [kWh]	455 (January)
Annual cost [USD]	1,297.76

Using Equation 1 to estimate the required photovoltaic capacity yields a result of 5.62 kWp, assuming an approximate specific annual output of 1,610 kWh/kWp

The estimated area required to install the necessary capacity is 28–32 m², assuming 14–16 panels rated at 350–400 [W].

Assuming there are no space constraints on the roofs, a simulation was performed in PVSyst based on an installed capacity of 5.62 kWp. Table III shows a comparison of the energy consumed and the energy generated each month.

TABLE III
ENERGY CONSUMPTION VS ENERGY GENERATION

Month	Consumption [kWh]	PV generation [kWh]	Balance [kWh]
Feb	578	674	96
Mar	572	646	74
Apr	557	786	229
May	897	786	-111
Jun	991	843	-148
Jul	950	843	-107
Aug	1060	843	-217
Sep	891	843	-48
Oct	837	759	-78
Nov	668	759	91
Dec	593	646	53
Jan	455	618	163

For the system, Trina Solar Vertex Modules were selected for the system since they demonstrate a great quality and capacity that fits to the project.

The rooftop assessment revealed that the available installation area could only accommodate five photovoltaic modules due to geometric and structural constraints. As a result, the maximum feasible system size was limited to 3.0 kWp. Using equation 3, considering five Trina Solar Vertex modules (1.303 m wide) of 600 W, a spacing of 20 mm between modules, and a 100 mm safety margin at both ends the spatial impact of the installation was calculated given a result of 6.8 m. Combined with the module height of 2.172 m, the PV array occupied approximately 14.8 m².

Therefore, the available rooftop area allowed the installation of only five photovoltaic modules, corresponding to an installed capacity of 3.0 kWp.

This represents a substantial reduction compared to the 5.62 kWp theoretically required to fully offset household electricity consumption. This represents only 53.4% of the capacity theoretically required to achieve full energy offset (calculated using Equation 5). This result highlights the significant impact of rooftop availability on residential photovoltaic deployment. Although the site presented favorable solar conditions, the usable installation area prevented the implementation of a full-demand offset system.

For the photovoltaic system, a Growatt MIN 2500TL-X solar inverter and an Iron Ridge mounting structure were selected.

The analysis was performed in PVSyst, and the annual power generation was calculated to be 4,053.9 kWh with a specific yield of 1,351 kWh/kWp/year. The system achieved a Performance Ratio (PR) of 83.04%, indicating efficient operation and acceptable system losses.

The percentage of demand for coverage is 44.8%. Therefore, the installed system could supply nearly half of the household's annual electricity demand despite the rooftop constraints. Table IV summarizes the main results of the simulation.

TABLE IV
TECHNICAL PERFORMANCE INDICATORS

Parameter	Value
Annual electricity demand	9,049 kWh/year
Required PV capacity	5.62 kWp
Installed PV capacity	3.0 kWp
Annual PV generation	4,053.9 kWh/year
Demand coverage	44.8%
Specific yield	1,351 kWh/kWp/year
Performance Ratio (PR)	83.04%

The obtained PR falls within the range commonly reported for well-designed residential PV systems, demonstrating that the reduced system size did not negatively affect operational efficiency.

Figure 2 shows the string layout, which illustrates the series connection of five Trina Vertex DEG20C.20 modules, forming a single string. The layout details the path of the DC

cabling on the roof and the location of the junction box, ensuring safe and orderly routing.

Figure 3 shows the structural and anchoring plan, which illustrates the attachment points for the IronRidge XR Flush Mount system on the sloped roof. This design specifies the distances between rails, the position of the mounting clamps, and the load distribution, ensuring compliance with the Florida Building Code and wind resistance in HVHZ zones.

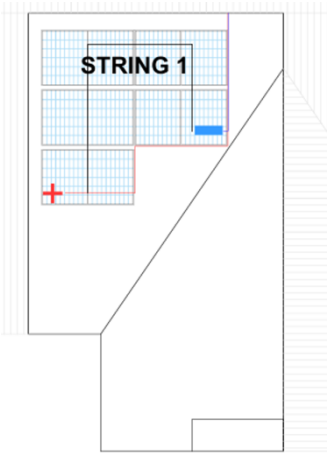


Fig. 2 Wiring Diagram

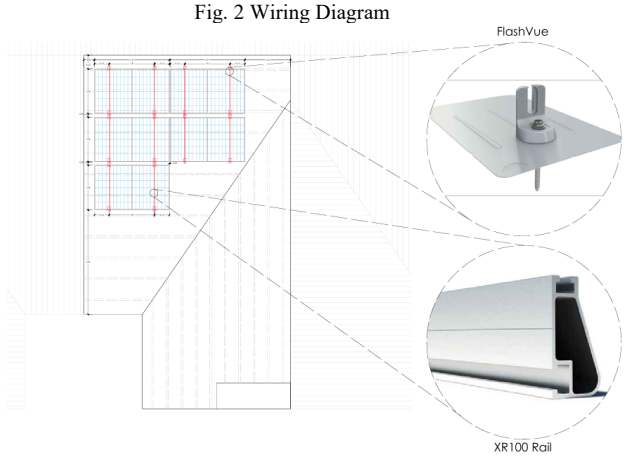


Fig. 3 Structure Diagram

Finally, Figure 4 presents the single-line diagram, which summarizes the electrical connections from the photovoltaic modules to the Growatt MIN 2500TL-X inverter and includes DC and AC protections, circuit breakers, and the interconnection with the home's main electrical panel. This diagram is essential for the system's installation, inspection, and subsequent maintenance.

The photovoltaic system was designed in accordance with current regulations in the state of Florida. From an electrical standpoint, the guidelines of the National Electrical Code (NEC 2023, Sections 690 and 705) were followed for the selection of conductors, protective devices, grounding, and system signage. Structurally, the requirements of the Florida Building Code (FBC) were considered, specifically those for sloped roofs in high-wind-speed zones (HVHZ). The IronRidge XR100 Flush Mount mounting system is UL2703-certified and approved for use in Florida, which guarantees the mechanical strength and safety of the installation.

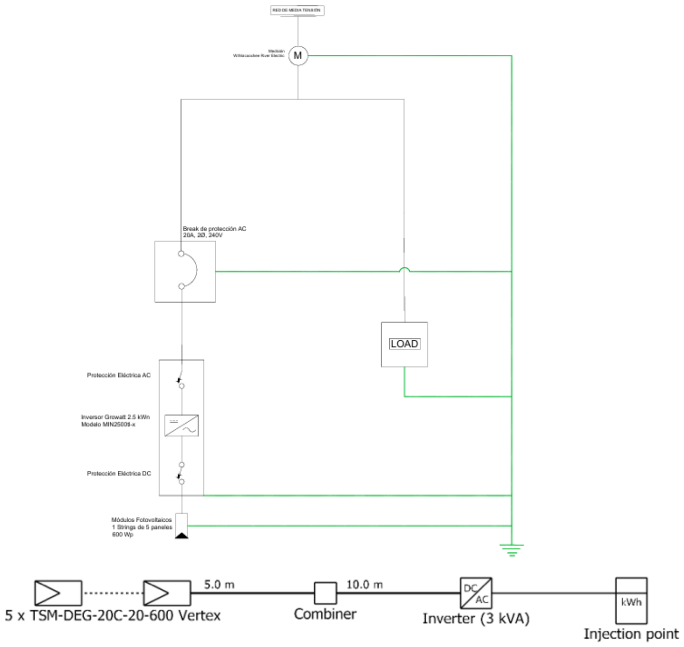


Fig. 4 Single-line diagram

The economic analysis was conducted using an electricity rate of $0.13/kWh, an inflation rate of 3%, an annual module degradation of 0.5% and an annual operation and maintenance cost of 15 USD per kWp.

Based on market prices for solar modules, inverters, mounting structures, and other electrical components, the initial investment is approximately $4,500. Table V summarizes the results of the calculated economic parameters.

TABLE V
ECONOMIC INDICATORS

Parameter	Value
Initial Investment [USD]	4,500
Annual O&M cost [USD]	45.00
ROI [%]	11.67
Simple Payback [years]	8.8
Analysis period [years]	25
Savings from first year [USD]	526.99

The results show that, although space limitations mean the installed capacity of solar photovoltaic systems does not cover the residence's entire energy demand, the system has a payback period of approximately 9 years, leaving about 16 years of savings since energy consumption from the power grid is reduced. The economic benefits stem primarily from

the substantial reduction in grid energy consumption and the increase in electricity rates.

For the environmental analysis, an emissions factor of 0.37 kg of CO_2/kWh is used, which yields a result of 1,500 kg of carbon dioxide avoided during the system's first year of operation. These results support a clean energy transition in which the use of renewable energy contributes to the reduction of greenhouse gas emissions.

It has been demonstrated that the installation of renewable technologies such as solar energy, despite space constraints on residential rooftops, is technically, economically, and environmentally feasible. This promotes the use of more sustainable energy sources and greater energy resilience for households.

The outcomes from the current research have been found to be compatible with other studies which have shown how the design of the roof as well as the building itself could play a significant role in determining the achievable photovoltaic capacity. Vecchi et al. [6] stated that there is a high level of variation in the rooftop photovoltaic potential based on the residential building typology and urban settings, with self-sufficiency levels depending upon the available rooftop resources and system settings. On the other hand, in the current research, we consider only one residential building in Florida.

IV. Conclusions

An analysis was conducted of a residential solar photovoltaic system, considering space constraints on rooftops, which limit the amount of energy that can be used for the residence. A technical, economic, and environmental analysis was carried out to determine the feasibility of the residential solar system. The following results were found:

- Annual energy consumption for the residence was calculated at 9,049 kWh. If there were no space constraints on the roof, a 5.62 kWp system would be needed to meet the residence's energy demand. However, due to space limitations, only 3 kWp can be installed, providing 44.8% coverage of the demand and generating 4,053.9 kWh in the first year with a performance ratio of 83.04%.
- From an economic perspective, the system is feasible because it has a simple payback period of 8.8 years and an ROI of 11%, demonstrating that, even though it does not meet all the demand, installing the system is still considered feasible.
- The environmental analysis shows that 1,500 kg of carbon dioxide per year can be avoided through the installation of the solar photovoltaic system. This contributes to decarbonization and the reduction of greenhouse gas emissions into the atmosphere.

This study is subject to several limitations. First, the household electricity demand was obtained from monthly utility bills rather than high-resolution load measurements, which limits the representation of hourly consumption patterns and may affect the estimation of self-consumption and grid interaction. Second, the analysis is based on a single residential case study in Wesley Chapel, Florida. Therefore, the results should not be generalized directly to other residences, since rooftop geometry, orientation, shading, electricity tariffs, climatic conditions, structural requirements, and household consumption patterns may differ substantially. Third, the economic results depend on assumptions regarding electricity price escalation, module degradation, investment cost, and operation and maintenance expenses. Sensitivity analysis is therefore necessary to assess the robustness of the economic conclusions. Future studies should evaluate multiple residential typologies and locations and incorporate high-resolution load profiles to improve the generalizability of the findings.

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