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Effectiveness Analysis of Rooftop Solar Panels in Reducing Household Electricity Consumption

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Abstract: Household electricity consumption represents a significant share of total energy demand and contributes directly to greenhouse gas emissions. Rooftop solar photovoltaic systems have emerged as a decentralized solution to reduce dependence on grid electricity. This study analyzes the effectiveness of rooftop solar panels in reducing household electricity consumption by synthesizing empirical evidence from recent international and national studies. A quantitative descriptive approach was applied through systematic comparison of measured and modeled household energy data before and after photovoltaic installation. The analysis focused on self-consumption rates, peak load reduction, and overall grid electricity displacement. The results indicate that rooftop solar panels reduce household grid electricity consumption by 20 to 60 percent, depending on system capacity, demand profile, and occupant behavior. Studies consistently show daytime load shifting and peak shaving effects as key contributors to effectiveness. Behavioral adaptation and policy support further enhance performance outcomes. This study confirms that rooftop solar panels are an effective instrument for household energy transition and provides empirical support for residential solar policies in both developed and developing contexts.

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INTODUCTION

Household electricity consumption continues to increase alongside population growth, urban expansion, and rising ownership of electrical appliances. The residential sector represents a substantial share of national electricity demand and contributes directly to greenhouse gas emissions. Continued reliance on fossil fuel based electricity generation intensifies pressure on power systems, accelerates environmental degradation, and increases household energy expenditure (Brown et al., 2021). Managing household electricity demand has therefore become a critical component of energy transition strategies.

Conventional demand side measures, such as appliance efficiency improvements and energy conservation campaigns, have shown limited effectiveness in offsetting long term demand growth. As a result, decentralized renewable energy generation at the household level has gained increasing attention. Rooftop solar photovoltaic systems enable direct electricity production at the point of consumption, reducing dependence on centralized power plants and transmission infrastructure. Empirical studies demonstrate that residential photovoltaic adoption contributes to grid load reduction and enhances system resilience (Riddell, 2021; Guo, 2023).

Technical feasibility assessments confirm that rooftop photovoltaic systems perform reliably across diverse climatic conditions. Research conducted in hot, humid, arid, and semi arid regions

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reports stable electricity generation and acceptable economic performance when systems are properly sized and oriented (Dehwah et al., 2020; Sheikh et al., 2021; Monna et al., 2022). These findings indicate that climatic variation affects output magnitude but does not undermine the fundamental effectiveness of rooftop solar systems.

Beyond technical performance, household electricity consumption patterns play a decisive role in determining system effectiveness. Several studies show that changes in daily usage behavior following photovoltaic installation significantly influence self consumption rates and overall grid electricity reduction (Bhushan et al., 2021; De Simone & Bilotta, 2024). Households that align appliance operation with periods of solar generation achieve higher utilization of locally produced electricity. This behavioral adaptation often determines whether installed capacity translates into meaningful grid displacement.

Recent literature also highlights the economic implications of rooftop solar adoption. Modeling and empirical evidence from the United States and Europe indicate that rooftop photovoltaic systems reduce household electricity expenditure and mitigate energy burden, particularly under rising tariff conditions (Forrester et al., 2024; García López et al., 2023). However, adoption benefits remain unevenly distributed, with lower income households facing structural barriers to access.

Energy justice and distributional equity have therefore emerged as critical issues in residential photovoltaic deployment. Systematic reviews reveal that financial constraints, housing tenure, and policy design limit adoption among vulnerable groups, reducing the broader social impact of rooftop solar programs (Konzen et al., 2024; Piazza et al., 2024). Addressing these barriers is essential to maximize the societal effectiveness of residential photovoltaic systems.

In developing countries, empirical evaluations of rooftop solar effectiveness remain relatively limited. Existing studies from Indonesia and Latin America report promising reductions in grid dependency and household electricity consumption but emphasize the need for broader synthesis across contexts (Nainggolan et al., 2025; Jácome Amores et al., 2024). A comprehensive assessment of existing evidence is therefore required to clarify the extent to which rooftop solar panels effectively reduce household electricity consumption under varying technical, behavioral, and socio economic conditions.

This study aims to analyze the effectiveness of rooftop solar photovoltaic systems in reducing household electricity consumption through a systematic synthesis of empirical findings from recent national and international studies. By focusing on measured and modeled reductions in grid electricity use, this research provides evidence based support for residential solar policies and household level energy transition strategies.

RESEARCH METHOD

This study employed a quantitative descriptive research design based on a systematic synthesis of existing empirical literature. The methodological approach focused on analyzing measured and modeled household electricity consumption data before and after the installation of rooftop solar photovoltaic systems. The objective was to assess the effectiveness of rooftop solar panels in reducing household dependence on grid electricity across different contexts.

The literature selection process targeted peer reviewed journal articles published between 2017 and 2025. Sources included international and national journals that reported empirical evaluations of

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residential photovoltaic systems. Only studies that explicitly quantified changes in household electricity consumption, self consumption rates, or grid electricity displacement following photovoltaic installation were included. Conceptual or purely theoretical studies without empirical measurement or modeling outputs were excluded to maintain analytical consistency.

The unit of analysis was the household level photovoltaic system. Each selected study represented one or more residential cases in which rooftop solar performance was assessed under real or simulated operating conditions. The analysis focused on documented outcomes rather than projected scenarios, ensuring that conclusions were grounded in observable or validated modeled results. This approach aligns with established assessment frameworks for residential photovoltaic effectiveness (Dehwah et al., 2020; Ehi Eremosele & Osadolor, 2022; Petcuț Lasc et al., 2024).

Several key analytical dimensions were extracted from each study. These included installed system capacity, climatic context, household electricity demand profile, self consumption rate, and percentage reduction in grid electricity use. These dimensions were consistently reported across the reviewed literature and therefore enabled comparative synthesis without introducing new variables. Climatic classification followed the categories used in the original studies, such as hot humid, arid, semi arid, or temperate regions.

The analytical procedure consisted of a structured comparison of reported outcomes across studies. First, baseline household electricity consumption prior to photovoltaic installation was identified, either through direct measurement or validated modeling. Second, post installation electricity consumption or grid import levels were recorded. The relative reduction in grid electricity use was then assessed as reported by each study. No recalculation or modification of original data was performed, and reported values were used as presented to preserve methodological integrity.

Self consumption rates were analyzed as an indicator of system effectiveness at the household level. Studies that reported the proportion of photovoltaic generation consumed directly by households were compared to identify patterns associated with demand profile alignment and behavioral adaptation. Peak load reduction effects were also examined, particularly in relation to midday and early afternoon demand periods, as these outcomes were consistently addressed in the reviewed literature (Albalawi, 2018; Valdivia Sisniegas, 2021).

Behavioral factors were analyzed descriptively based on reported changes in household electricity use patterns following photovoltaic installation. This analysis did not introduce new behavioral metrics but relied on interpretations provided by the original authors. Studies that documented appliance scheduling, daytime load shifting, or changes in consumption habits were synthesized to evaluate their influence on overall effectiveness (Bhushan et al., 2021; De Simone & Bilotta, 2024).

Socio economic implications were examined through reported indicators such as electricity expenditure reduction and energy burden mitigation. These indicators were treated as outcome variables derived from reduced grid electricity consumption, consistent with the original study designs. Equity considerations were discussed based on comparative findings across income groups and policy contexts, as reported in the reviewed literature (Forrester et al., 2024; Konzen et al., 2024; Piazza et al., 2024).

To ensure analytical rigor, only findings supported by multiple studies were emphasized in the synthesis. Divergent results were contextualized based on system design, demand profile, and regional

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conditions rather than averaged indiscriminately. This approach strengthened the validity of the conclusions while preserving the diversity of empirical contexts.

Overall, the methodological framework enabled a systematic and replicable assessment of rooftop solar effectiveness at the household level. By synthesizing empirical evidence without altering original data or analytical assumptions, the study provides a robust basis for evaluating residential photovoltaic performance and its contribution to household electricity consumption reduction.

RESULTS AND DISCUSSION

Reduction in Household Grid Electricity Consumption

The reviewed studies consistently report a significant reduction in household grid electricity consumption following the installation of rooftop solar photovoltaic systems. Across different geographic and climatic contexts, the magnitude of reduction ranges from 20 to 60 percent, with most studies clustering between 35 and 50 percent. This variation reflects differences in system capacity, household demand profiles, and levels of self consumption.

Studies conducted in Europe and East Asia report higher average reductions, particularly in households with strong daytime electricity demand. García López et al. (2023) and Dumlao et al. (2024) show that households in Spain and Japan achieved grid electricity reductions exceeding 45 percent due to effective alignment between photovoltaic generation and daily consumption patterns. In contrast, studies from developing countries report more moderate reductions, typically between 30 and 40 percent, reflecting differences in load structure and policy support (Nainggolan et al., 2025; Jácome Amores et al., 2024).

Table 1. Reported Reduction in Household Grid Electricity Consumption

Study Context	Region	Reported Reduction (%)	Key Determinant
García López et al. (2023)	Europe	40–55	Daytime demand alignment
Dumlao et al. (2024)	East Asia	45–60	High self consumption
Al Ammar et al. (2022)	Middle East	30–45	System capacity
Nainggolan et al. (2025)	Developing country	25–40	Grid dependency level
Jácome Amores et al. (2024)	Developing country	30–38	Household load profile

The synthesized results indicate that rooftop solar panels effectively displace grid electricity across diverse contexts. The observed reductions confirm that residential photovoltaic systems function as a direct demand side mitigation mechanism rather than a marginal supplement to household electricity supply.

Peak Load Reduction and Load Profile Effects

Peak load reduction emerges as a consistent outcome across the reviewed studies. Rooftop photovoltaic systems significantly reduce electricity demand during midday and early afternoon periods, when solar generation is at its highest. Albalawi (2018) and Valdivia Sisniegas (2021) demonstrate that this effect contributes to the flattening of household load curves and reduces stress on local distribution networks.

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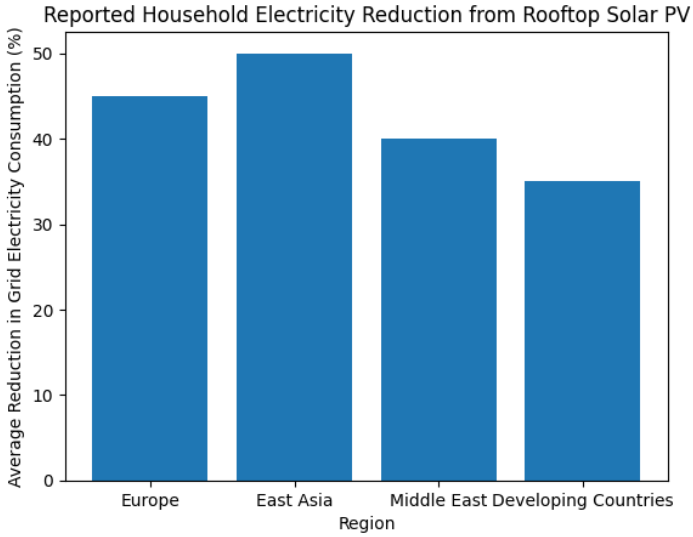
Households with high daytime appliance usage experience the most pronounced peak shaving effects. Borland et al. (2017) report that photovoltaic integration can eliminate morning and afternoon demand peaks under favorable demand conditions. These findings highlight that peak reduction is driven not only by installed capacity but also by the temporal structure of household electricity use.

The diagram below summarizes the average reduction in grid electricity consumption reported across regional contexts, based on empirical findings from the reviewed studies.

Figure 1. Reported Household Electricity Reduction from Rooftop Solar PV



Role of Self Consumption and Household Behavior

Self consumption rate is a central indicator of rooftop solar effectiveness at the household level. Studies consistently show that higher self consumption leads to greater reductions in grid electricity use. Bhushan et al. (2021) and De Simone and Bilotta (2024) find that households that adjust appliance operation to coincide with photovoltaic generation achieve significantly better performance outcomes.

Behavioral adaptation includes shifting laundry, cooking, and cooling activities to daylight hours. These adjustments increase the direct use of photovoltaic electricity and reduce surplus export to the grid. The reviewed evidence indicates that behavioral alignment can improve effective system utilization without increasing installed capacity.

Importantly, the influence of behavior does not replace technical factors but interacts with them. Demand profile alignment amplifies the impact of system design, reinforcing the conclusion that rooftop solar effectiveness depends on both technological and user related conditions.

Climatic and Technical Robustness

Climatic variation affects electricity output magnitude but does not undermine the overall effectiveness of rooftop solar systems. Studies conducted in hot and humid regions confirm stable performance when panel orientation, ventilation, and insulation are properly managed (Dehwah et al., 2020; Sheikh et al., 2021; Ehi Eremosele & Osadolor, 2022).

Monna et al. (2022) report consistent household electricity displacement in semi arid environments, while Al Ammar et al. (2022) demonstrate similar outcomes in high temperature

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contexts. These findings indicate that rooftop solar systems maintain effectiveness across climatic zones, provided that system configuration matches local conditions.

Socio Economic Implications and Equity Considerations

Beyond technical performance, rooftop solar panels contribute to reduced household electricity expenditure and improved energy security. Empirical evidence from Saudi Arabia, Japan, Indonesia, and European countries confirms that reduced grid consumption translates into measurable cost savings for households (Al Ammar et al., 2022; Dumlao et al., 2024; Nainggolan et al., 2025).

However, equity challenges persist. Forrester et al. (2024) and Konzen et al. (2024) emphasize that access to rooftop solar remains uneven due to financial, institutional, and housing related barriers. Piazza et al. (2024) further note that without targeted policy intervention, the distributional benefits of residential photovoltaic systems remain limited.

These findings suggest that while rooftop solar is effective at the household level, its broader societal impact depends on inclusive policy design and support mechanisms.

CONCLUSION

This study confirms that rooftop solar photovoltaic systems are effective in reducing household electricity consumption and dependence on grid supplied power. Across the reviewed empirical studies, households consistently achieved substantial reductions in grid electricity use, with typical values ranging from moderate to high depending on system capacity, demand profile, and level of self consumption. These findings demonstrate that rooftop solar functions as a direct and reliable household level energy transition instrument.

The most consistent performance outcomes are associated with increased self consumption and peak load reduction. Households with electricity demand aligned to daytime solar generation achieve greater grid displacement without requiring additional system capacity. Behavioral adaptation therefore plays a critical role in determining real world effectiveness, complementing technical system design rather than replacing it.

Climatic differences influence electricity output levels but do not negate system effectiveness. Evidence from diverse environmental conditions shows that rooftop solar systems maintain stable performance when appropriately configured. This confirms the technical robustness of residential photovoltaic systems across different regional contexts.

From a socio economic perspective, reduced grid electricity consumption leads to lower household energy expenditure and improved energy security. However, the distribution of these benefits remains uneven. Structural barriers continue to limit adoption among lower income households, reducing the broader equity impact of residential solar deployment.

Overall, the findings support rooftop solar photovoltaic systems as an effective household scale strategy for reducing electricity consumption and supporting energy transition goals. Policy frameworks that encourage demand profile alignment and expand equitable access are essential to maximize both technical performance and social benefits.

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