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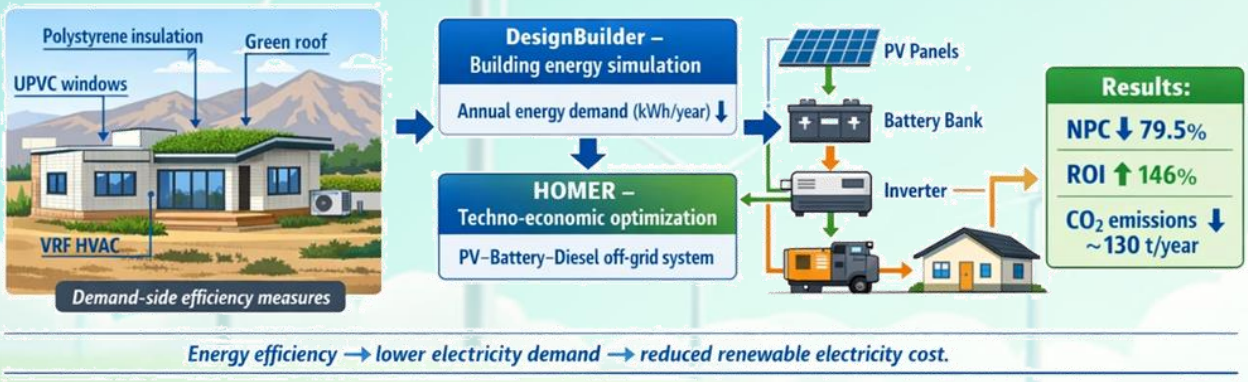
Investigating Energy Consumption Reduction Strategies and Their Effect on the Renewable Electricity Price: A Case Study of a Climate-Compatible Villa in Saman, Iran

Narges Loghmani

Highlights

- **Combining all energy efficiency measures reduced the Net Present Cost of the off-grid solar system by 79.5%, dropping it from $947,243 to approximately $194,000.**
- **Upgrading to a VRF HVAC system provided the largest single cost reduction at 63.1%, significantly outperforming insulation or window upgrades.**
- **The optimal integrated scenario increased the return on investment by 146% while reducing annual carbon emissions by roughly 130 tons.**
- **This study proves that prioritizing building energy efficiency before sizing renewable systems is crucial for cost-effective off-grid electrification.**

Graphical Abstract



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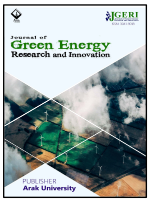

Investigating Energy Consumption Reduction Strategies and Their Effect on the Renewable Electricity Price: A Case Study of a Climate-Compatible Villa in Saman, Iran

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ABSTRACT

The main objective of this study is to evaluate the impact of building energy efficiency measures on the cost of solar electricity in a climate-compatible villa located in the suburbs of Saman, Chaharmahal and Bakhtiari Province, Iran. Enhancing building energy efficiency while lowering the cost of renewable electricity generation is particularly vital in Iran's off-grid residential sector, where growing energy demand and dependence on fossil fuels necessitate sustainable, climate-compatible solutions. A baseline case and five optimization scenarios were modeled using DesignBuilder (v6.1.0.6) to estimate annual energy consumption, followed by techno–economic–environmental assessment of an off-grid solar–battery–diesel generator system using HOMER (v2.81). Results show that the net present cost (NPC) of the baseline system is $947,243, with cost reductions of 17.6%, 5.4%, 22.7%, 63.1%, and 79.5% achieved through polystyrene insulation, green roof, UPVC windows, VRF HVAC, and all measures combined, respectively. The optimal integrated scenario also reduces annual emissions by ~130 tons and increases the return on investment (ROI) by 146%. This work uniquely couples building-level energy efficiency modeling with techno–economic–environmental optimization of a hybrid off-grid PV– Battery–Diesel generator system, quantifying for the first time how demand-side measures propagate into key renewable electricity cost metrics in off-grid residential contexts. These findings highlight the substantial economic and environmental benefits of combining building optimization strategies with renewable energy deployment in off-grid residential applications.

1. Introduction

The residential sector in Iran alone accounts for approximately 28% of the country's total energy consumption (Figure 1) [1], with the majority of this energy supplied from fossil fuel sources [2]. This dependency not only increases greenhouse gas emissions and exacerbates environmental challenges but also places a significant economic burden on the national energy sector. In a context where fuel price fluctuations, depletion of fossil resources, and international commitments to reduce pollutants have become pressing concerns, transitioning toward energy-efficient buildings and the utilization of renewable energy (RE) has emerged as a strategic necessity for Iran. This necessity is further underscored by socio-economic trends, as population growth and the growing demand for recreational living during weekends and holidays in pleasant off-grid regions continue to drive energy use upward. Consequently, enhancing efficiency, reducing energy consumption, and decreasing reliance on the national grid have become particularly important. Achieving energy independence in off-grid buildings typically involves two complementary strategies: (i) reducing energy consumption through building optimization and energy management, and (ii) meeting the remaining demand using renewable sources such as solar and wind power.

Building on this second strategy, the use of RE sources, particularly solar photovoltaic (PV) and wind power, is a top priority in off-grid regions due to their modularity, scalability, and independence from fuel supply chains. The share of RE production, comprising hydropower, wind, solar, biomass, and geothermal energy, in net-zero energy buildings has been widely examined in previous studies [3-5]. As shown in Figure 2, wind energy accounts for 24% and solar PV for 40% of the supply mix, both of which are highly adaptable for decentralized and residential-scale deployment, making them particularly attractive for off-grid applications. Their complementary seasonal and diurnal profiles, solar PV producing peak output during the day and wind often contributing more at night or in colder months, enhance system reliability. Multiple studies confirm that hybrid renewable energy systems, combining two or more sources, achieve a lower levelized cost of electricity (LCOE) and improved supply stability compared to single-source configurations [6]. This supports the multi-source integration approach adopted in the present study to ensure both economic viability and long-term resilience in off-grid villas.

Complementary to the deployment of renewable energy technologies, effective demand-side management and building energy optimization are equally critical to ensuring the technical, economic, and environmental sustainability of off-grid systems. In parallel with expanding renewable generation, managing energy consumption effectively is essential to achieving energy independence, especially in regions where grid access is unavailable or limited. Energy consumption in Iran has been rising steadily in recent years, driven by population growth, economic expansion, and industrial development [8,9]. Advanced energy monitoring, through real-time tracking and analysis of consumption, enables the identification of inefficiencies and targeted interventions [10,11]. Complementary measures such as high-performance wall and roof insulation, green roofs, double-glazed UPVC windows, intelligent lighting controls, and variable refrigerant flow (VRF) systems significantly reduce thermal losses and improve overall building efficiency [12-15].

The upward trend in total energy and electricity consumption from 2011 to 2021 is shown in Figure 3, accompanied by steady growth in renewable electricity generation from wind, hydro, and solar sources. While this indicates progress toward cleaner energy, the current pace of renewable deployment remains insufficient to meet the country's rapidly growing demand. As illustrated in Figure 4, wind and solar energy production have both expanded significantly since 2013, with solar showing particularly strong growth after 2017. This complementary generation pattern reinforces the technical and economic rationale for hybrid RE systems, directly aligning with the multi-scenario analysis conducted in this study.

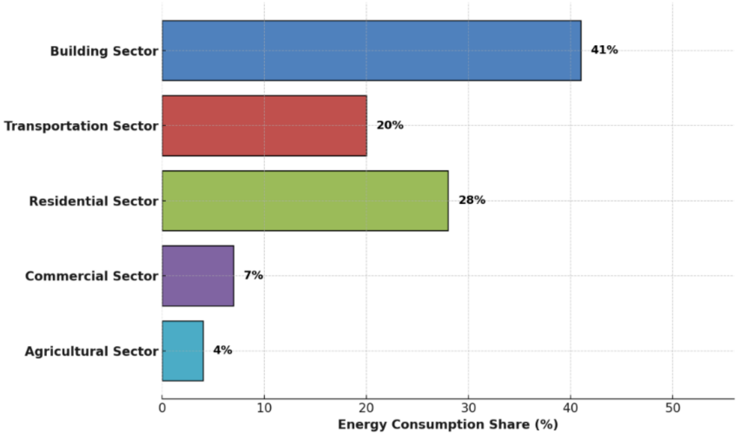


Figure 1. Energy consumption share of various sectors in Iran [2].

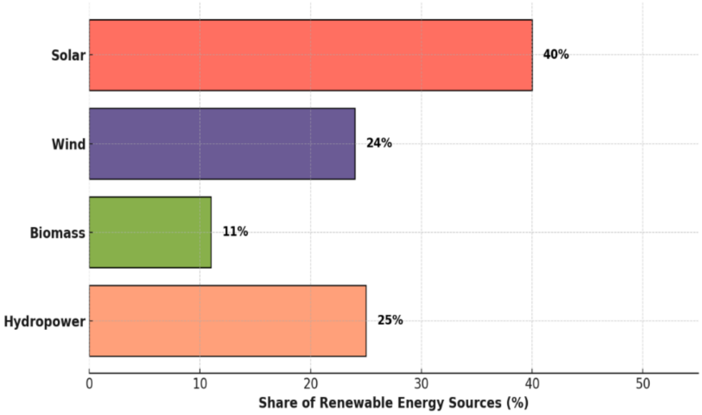


Figure 2. Share of RE sources in power supply in off-grid areas [7].

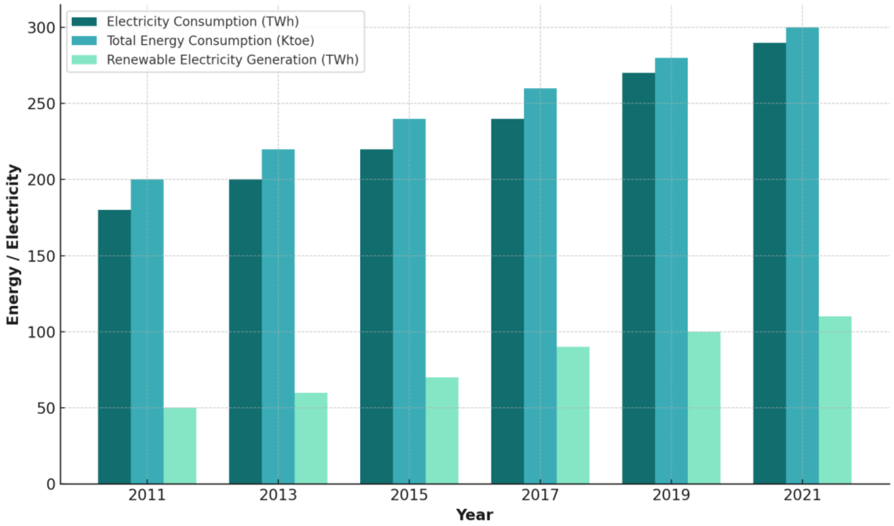


Figure 3. Growth in energy consumption, electricity generation, and the share of renewable electricity production in Iran from 2011 to 2021 [16].

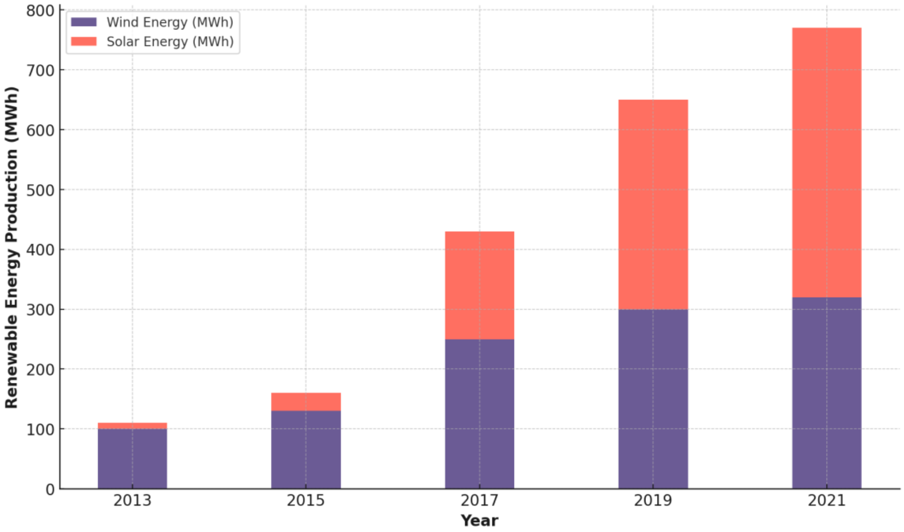


Figure 4. Growth of wind and solar energy in Iran from 2013 to 2021 [16].

A review of existing studies reveals that the use of appropriate materials and construction techniques has a significant impact on a building's energy performance [17-21]. According to the literature review focused on off-grid building energy, categorized in Table 1 based on location, energy sources, methodology, findings, and distinction from the present study, it is evident that no previous research has been conducted on reducing the cost of renewable electricity through physical optimization of an off-grid building. The physical optimizations investigated in this study include external envelope insulation, double-glazed windows, smart control of electrical and thermal systems, and the implementation of green roofs.

Taken together, prior studies consistently report the advantages of hybrid configurations for off-grid applications and the effectiveness of envelope/operational measures in curbing building demand [3-5, 12-15, 22-30]. However, a gap remains regarding how building-level optimizations quantitatively translate into renewable electricity cost metrics (e.g., NPC, LCOE, ROI) in off-grid villas. The present work directly addresses this gap by coupling DesignBuilder-based demand reductions with HOMER-driven techno–economic–environmental analysis, thereby linking envelope/operation measures to electricity cost and emissions outcomes.

2. Study location

In the present work, the cost of RE supply is initially estimated for a sample villa located in the suburbs of Saman city, near the historical Zaman Khan Bridge, in an off-grid condition. This site lies within the jurisdiction of Chaharmahal and Bakhtiari Province, situated in western Iran (Figure 5). Saman, with a population of 14,192 in the year 2016, is located at coordinates 32.45°N and 50.91°E. This city is known for its tourism appeal and is situated 22 km northeast of Shahrekord [31]. Passive strategies such as south-facing skylight windows, wall materials adapted to the local climate, and earth-sheltered architectural techniques were employed in the base case design. Subsequently, optimization strategies were applied, and the renewable electricity supply cost was re-evaluated to estimate the potential cost reduction in energy provisioning. As shown in the classification presented in Figure 5, Saman County is located in a relatively cold region. However, based on the Köppen climate classification, and as referenced in Table 2, Saman has a Mediterranean climate characterized by one warm month with an average temperature above 25°C and one cold month with an average of around 0°C [32].

Table 1. Analysis of existing research on energy management, reduction, and optimization in off-grid villa homes.

Reference	Location	Renewable energy type	Methodology	Findings	Different from the present work
Zebra et al. [22], 2021	Mozambique	PV, Wind Turbines (WT)	Review-PESTEL	A hybrid system combining RE sources and a DG provided the best scenario.	Different geographical location, no energy optimization performed, different methodology, and objective
Zhang et al. [23], 2022	Various climate zones	Combined Heat and Power (CHP), PV, Solar Thermal Collectors (STC), WT, Battery Energy Storage (BES), and Thermal Energy Storage (TES)	Multi-Objective Genetic Algorithm (MOGA)	MOGA is used to determine the optimal combination of distributed energy resources and the size of each component to minimize system cost and CO2 emissions for various locations.	Different geographical location, no energy optimization performed, different methodology
Pulido et al.[24], 2019	Netherlands	PV, BES, Fuel cell (FC)	DEMkit	A 30 kW solar PV system with a 45 kWh sea salt battery and a 15 kWh glycerol FC operating year-round can remain completely off-grid.	Different geographical location, no energy optimization performed, different methodology, no use of physical tools for solar cost reduction
Cao et al. [25], 2022	China	PVT solar panels, thermal storage tanks, WT, Absorption chiller, Heat pump (HP)	TRNSYS	The highest and lowest unit product cost of the system for January and July were $32.77/GJ and $8.38/GJ, respectively.	Different geographical location, no energy optimization performed, thermal insulation not examined, different objective
Kim et al. [26], 2019	South Korea	PV, STC, HP, TES	TRNSYS	Increasing the solar fraction of the proposed system leads to a primary energy saving of up to 73% compared to a centralized heat pump system.	Different geographical location, no energy optimization performed, different methodology, building envelope optimization not considered
Vichos et al. [27], 2022	Greece	REs, Hydrogen storage	HOMER PRO	The use of RE and energy storage is recommended for maximum energy efficiency.	Different geographical location, no energy optimization performed, different methodology
Muh & tabet [28], 2019	Cameroon	REs	HOMER PRO	A small-scale PV/DG/Hydro/BES, with an energy cost of $0.443/kWh, is identified as the most economically viable system for southern Cameroon.	Different geographical location, no energy optimization performed, different methodology, different objective
Suresh et al. [29], 2020	India	Biogas, Biomass, PV, WT, FC, BES	HOMER	The energy cost is $0.163/kWh.	Different geographical location, no energy optimization performed, different methodology, different objective
Odou et al. [30], 2020	Benin	PV, Diesel generator (DG), BES	HOMER	A hybrid PV/DG/BES (150 kW/62.5 kVA/ 637 kWh) is the most cost-effective optimized system.	Different geographical location, no energy optimization performed, different methodology, different objective
Present work, 2025	Iran	PV, DG, BES	HOMER	A reduction in total NPC (79.5%) and a decrease in CO2 emissions (130 tons/year) compared to the baseline scenario.	-

Table 2. Geographical and Climatic Characteristics of Saman City [32].

Item	Description
Country / Province	Iran / Chaharmahal and Bakhtiari
Distance to provincial capital (Shahrekord)	20 km
Geographical coordinates	50.9117° E, 32.4514° N
Elevation above sea level	1,996 m
Köppen climate classification	Csa
The coldest month and the recorded temperatures	January holds the record as the coldest month, with an average high temperature of 4.3 °C and an average low of -3.8 °C.
Warmest Month and Recorded Temperatures	July holds the record as the warmest month, with an average high temperature of 31.6 °C and an average low of 18.2 °C.

To provide a better understanding of the examined villa's layout, various sectional views of the villa are presented in Figure 6. One noteworthy point is the use of earth-sheltered architecture, a climate-responsive design technique commonly employed in cold regions. It should be noted that the present study is conceptual in nature and based on a hypothetical case study; no physical construction has been carried out. The building is designed for residential use and intended to be occupied throughout the year.

3. Methodology

For modeling and energy analysis of the building in this study, DesignBuilder software was employed. This software allows users to first model the building using architectural plans (base scenario). Then, by applying various building materials (2 scenarios), window configurations (1 scenario), and modifications to occupancy and usage patterns (1 scenario), it is possible to perform detailed energy analyses.

In addition to the base scenario, which is based on climate-adaptive architectural recommendations, five optimization scenarios were investigated:

- Scenario 1: Application of polystyrene insulation in the external envelope of the building.
- Scenario 2: Implementation of a green roof to assess its impact on energy performance.
- Scenario 3: Use of UPVC double-glazed windows to evaluate their effect on thermal losses.
- Scenario 4: Installation of a VRF HVAC system to enhance energy efficiency.
- Scenario 5: A combined scenario integrating all four previous optimizations to assess their cumulative effect.

Figure 7 presents the solar resource input data required by HOMER software for evaluating solar power potential. It also illustrates the software outputs. HOMER, developed by the U.S. National Renewable Energy Laboratory (NREL), is used for the simulation and optimization of hybrid RE systems, ranking configurations based on comprehensive financial analysis [33,34].

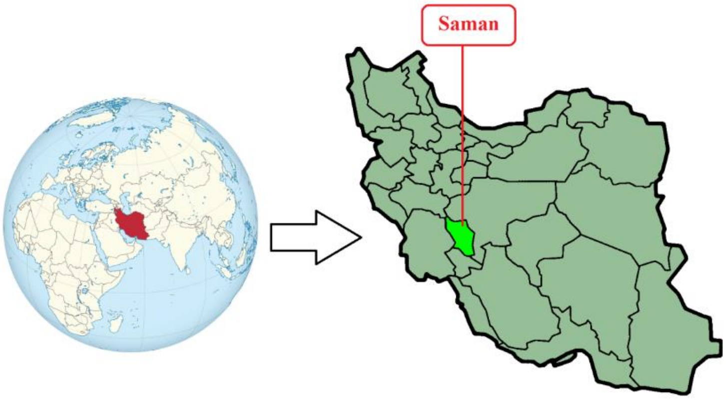
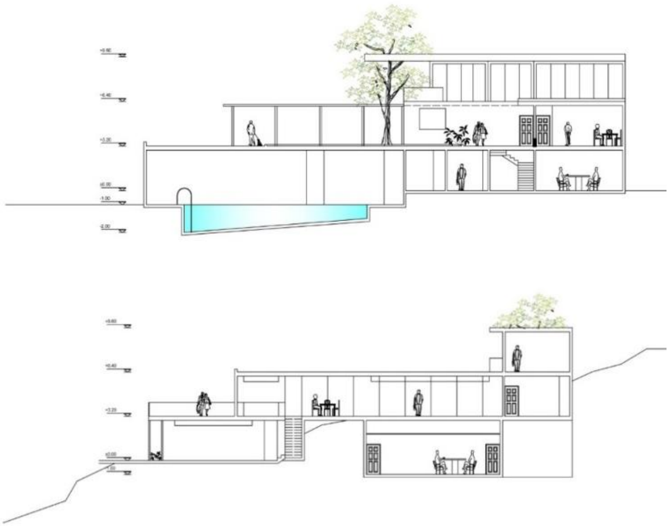


Figure 5. Geographical location of the study area.


Cross-sections A_A

Cross-sections B_B

Figure 6. Southern and Eastern cross-sections of the investigated building.

The governing equations used in the software, including the power output of PV cells, diesel generator efficiency, BES performance equation, and economic calculations, are presented in Table 3. The schematic of the system investigated in this study is presented in Figure 8. For backup in emergencies, BES storage and a diesel generator are employed, to supply electricity to a residential villa [41].

Table 3. Governing Equations for the Investigated System.

Reference	Parameter	Equation
[35]	Power output from PV cells	$P_{PV} = Y_{PV} \,.\, f_{PV} \cdot \frac{\overline{H}_T}{\overline{H}_{T,STC}}$
[36]	DG efficiency	$\eta_{gen} = \frac{3.6\ P_{gen}}{\dot{m}_{fuel} .\, LHV_{fuel}}$
[37]	BES performance	$P_{batt,max} = \frac{Min(P_{batt,kbm\ or\ mcr\ or\ mcc})}{\eta_{batt,c}}$
[38]	Net present cost (NPC) calculation	$total\ NPC = \frac{C_{ann,total}}{\frac{i(1+i)^N}{(1+i)^N - 1}}$
[39]	Cost of electricity per kWh	$COE = \frac{C_{ann,total}}{E_{load\ served}}$
[40]	ROI	$\mathrm{ROI} = \frac{\text{cumulative nominal cash flow of (final year} - \text{zero year)}}{\text{lifetime} \times \text{zero year cumulative nominal cash flow}}$

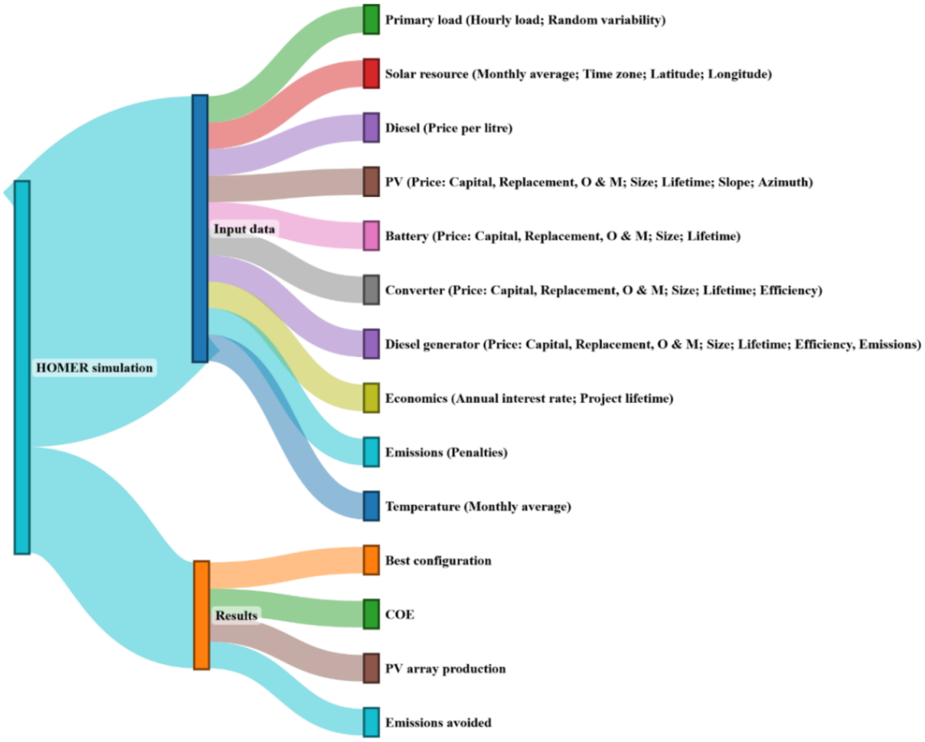


Figure 7. Input and output parameters diagram from HOMER software.

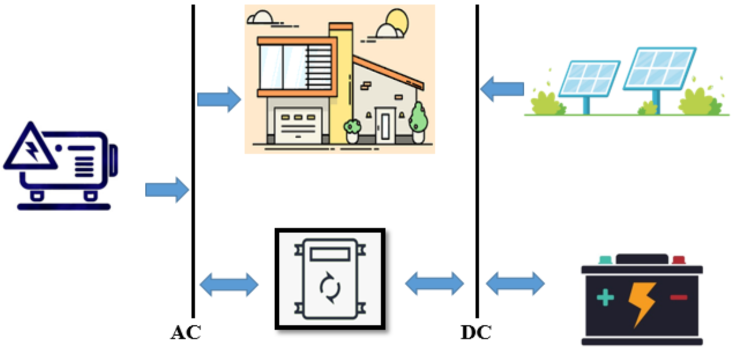


Figure 8. Schematic Diagram of the System Investigated in the Present Study.

In a RE system, management of surplus electricity, capacity factor, and electrical losses is critically important. Optimizing these factors can significantly enhance system efficiency and reduce costs, ultimately resulting in more sustainable and economically viable energy production.

Surplus electricity refers to the electrical energy that remains after meeting the consumers' demand. It can be either fed into the grid or stored in energy storage systems. In RE systems, this is particularly significant because power generation from sources such as solar and wind is variable and may at times exceed demand.

The capacity factor is defined as the ratio of actual energy produced to the maximum possible output at the rated capacity of the equipment. It reflects the efficiency and productivity of RE systems.

Electrical losses refer to the energy lost during the transmission and distribution of electricity due to resistance in wires and equipment. These losses may result from various factors, including conductor resistance, equipment quality, and unbalanced loads.

4. Input data

The simulation requires a comprehensive set of technical, cost, and climatic inputs to ensure accurate modeling. Table 4 summarizes the key equipment specifications and associated economic parameters, including capital, replacement, and operating costs, as well as performance characteristics such as lifetime, efficiency, and derating factors.

In addition to these equipment-specific data, Figure 9 presents the monthly average global horizontal radiation (GHI) and clearness index for the study site. The annual average GHI is 5.06 kWh/m^2/day, while the clearness index averages 0.59, indicating a generally favorable solar resource with minor seasonal variability. Higher GHI values are observed from May to August, coinciding with peak system generation potential, whereas lower values occur during winter months, which can impact battery depth-of-discharge cycles and diesel generator utilization.

The cost of diesel fuel was set at $0.006 per liter [44], the project lifetime at 25 years, and the real annual interest rate at 18%. Emission penalties were included to internalize environmental costs: $3.10/ton CO_2, $57/ton CO, $560/ton SO_2, and $184/ton NO_x [45]. These values directly influence the economic optimization performed by HOMER.

Figures 10 through 15 display the hourly electricity demand profiles for the baseline and five optimization scenarios. These profiles incorporate stochastic variability, modeled with a 15% daily and 20% hourly randomness factor [46], to account for real-world fluctuations in residential load.

- Figure 10 (Baseline): The demand profile shows high winter peaks exceeding 150 kW, primarily due to electric heating loads, and moderate summer loads. This pattern reflects poor building envelope performance and inefficient HVAC systems.
- Figure 11 (Scenario 1 – Polystyrene Insulation): Peak winter demand is reduced to approximately 120 kW, indicating substantial thermal load reduction from improved wall and roof insulation. Summer demand remains largely unchanged, as cooling loads are not directly impacted.
- Figure 12 (Scenario 2 – Green Roof): Similar winter demand reduction is observed, with an additional slight decrease in summer cooling demand due to enhanced roof thermal resistance and heat rejection.
- Figure 13 (Scenario 3 – UPVC Windows): Both winter and summer peaks are moderately reduced compared to the baseline, owing to minimized air infiltration and improved thermal performance of the glazing.
- Figure 14 (Scenario 4 – VRF HVAC): This scenario yields the largest winter demand reduction among single-measure cases, dropping peak loads to around 80 kW. The high seasonal efficiency of VRF systems significantly decreases both heating and cooling electricity requirements.
- Figure 15 (Scenario 5 – All Measures Combined): The integrated scenario produces the most pronounced demand reduction, with peaks rarely exceeding 35 kW in winter and under 15 kW in summer. This combination of measures results in optimal thermal performance and minimized HVAC energy use.

By analyzing these demand profiles in conjunction with the solar resource data, HOMER's optimization algorithm determines the optimal sizing of PV, BES, and DG components. Lower and more stable demand patterns (as in Scenario 5) reduce PV capacity requirements, extend battery life, and minimize diesel operation, thereby lowering both net present cost (NPC) and lifecycle emissions.

Table 4. Required Simulation Data for HOMER.

Equipment	Price ($)			Size (kW)	Technical information
	Capital	Replacement	Operating and Maintenance		
PV [42]	350	350	10	0-800	Lifetime: 25 years, Derating factor: 80%, Slope = Azimuth [222]
BES [42]	174	174	5	0-1000	Type: Trojan T-105, Lifetime: 845 kWh
Converter [42]	138	138	10	0-800	Lifetime: 15 years, Efficiency: 95%
DG [43]	200	200	0.5	0-800	Lifetime: 15000 hr, Efficiency: 31% CO factor: 6.5 g/L, Destination of fuel Carbon: $CO_2 = 99.5\%, CO = 0.4\%$

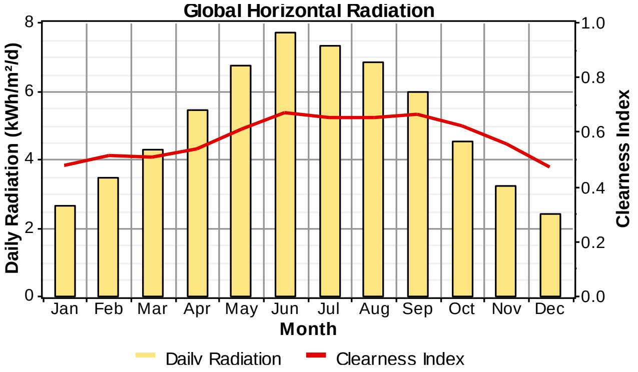


Figure 9. Monthly Average Solar Irradiance.

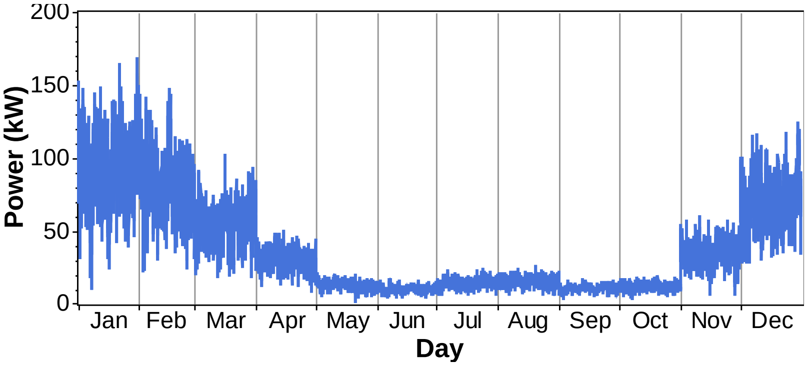


Figure 10. Annual Electricity Consumption Profile for the Base Scenario.

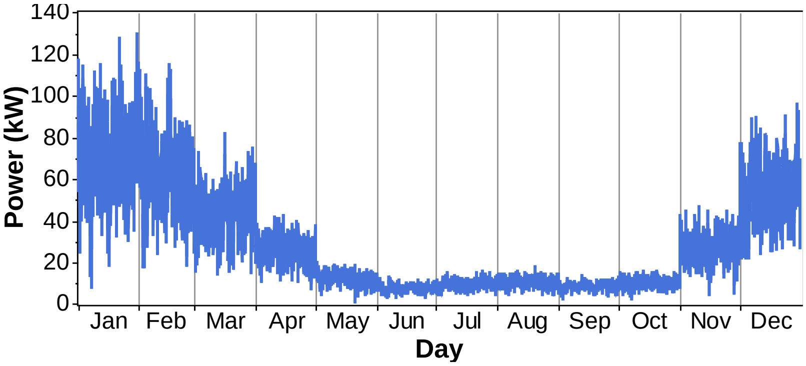


Figure 11. Annual Electricity Consumption Profile for Scenario 1.

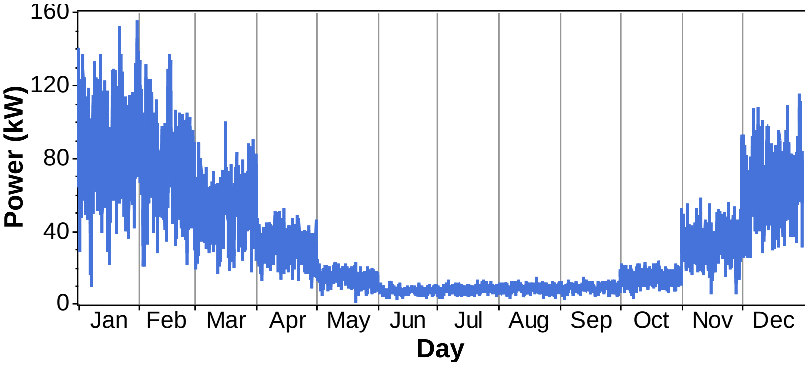


Figure 12. Annual Electricity Consumption Profile for Scenario 2.

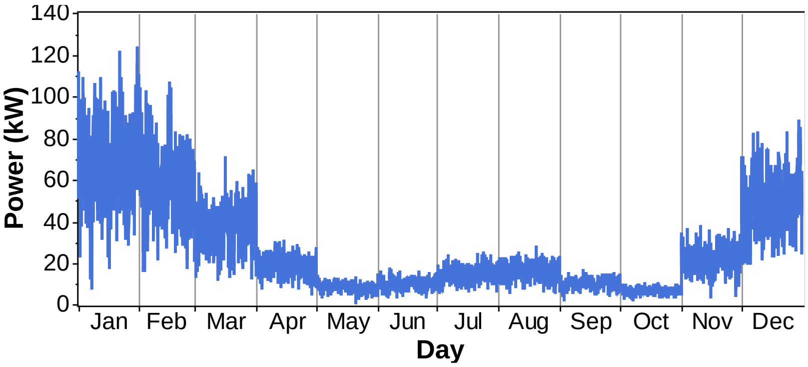


Figure 13. Annual Electricity Consumption Profile for Scenario 3.

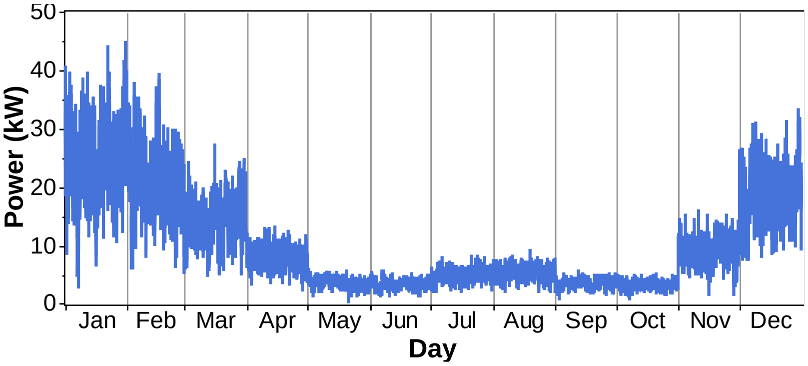


Figure 14. Annual Electricity Consumption Profile for Scenario 4.

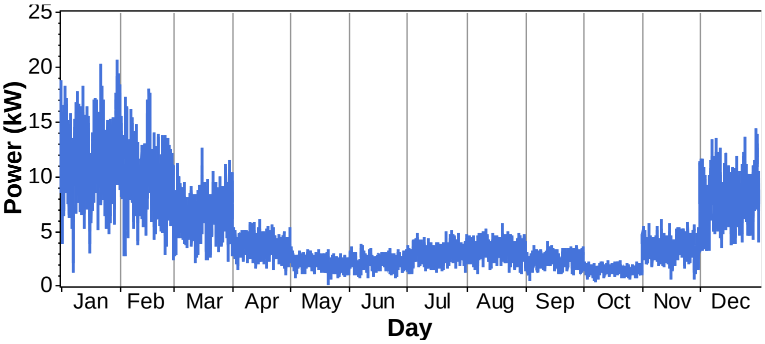


Figure 15. Annual Electricity Consumption Profile for Scenario 5.

5. Results

The simulation results for the base case of the climate-responsive villa (the selected case study), along with the four energy improvement scenarios and the optimized case (combined Scenario 1 to 4), are presented in Table 5. The analysis shows that the diesel generator and power converter capacities are identical in all scenarios, set at 100 kW, while the primary differences lie in the number of PV panels and batteries. The lowest PV capacity, at 100 kW, and the lowest number of batteries, at 30 units, both occur in Scenario 5, the optimized configuration.

From an economic perspective, an interesting observation is that as the demand for electricity decreases, the total NPC decreases; however, the cost per kWh of generated electricity increases. In other words, the higher the electricity demand, the lower the unit cost of electricity. The highest total NPC occurs in the base scenario, while the highest unit electricity cost appears in Scenario 5. Through the implemented optimizations (Scenarios 1–5), the NPC is reduced from $947,243 to a range of $896,305–$193,796, while the cost of electricity per kWh increases from $0.557 to a range of $0.557–$0.867. This scale effect is consistent with HOMER-based case studies in off-grid settings, where greater effective demand and hybridization typically yield lower LCOE due to improved asset utilization [29,30].

Present results confirm this trend: while demand-side measures compress NPC substantially, unit costs can rise when fixed components are amortized over a smaller annual energy throughput, a nuance often underemphasized in purely supply-side studies. The magnitudes and directionality of these improvements accord with prior building-scale studies on envelope upgrades and efficient HVAC, which document significant reductions in heating/cooling loads and total energy use [12-15]. By explicitly propagating these demand reductions into a hybrid off-grid sizing/dispatch model (HOMER), the present results extend this line of work to quantify downstream impacts on NPC, LCOE, and ROI.

Regarding renewable electricity generation, depending on the number of PV panels, annual production ranges from 157,483 to 629,930 kWh, covering 77% to 97% of the total electricity demand. As the system is off-grid, a significant amount of surplus electricity is generated annually, the highest being 434,096 kWh/year in Scenario 3, and the lowest being 115,181 kWh/year in Scenario 5. The share of surplus electricity ranges from 44.4% to 71.1%, with Scenario 5 showing the lowest and the base scenario showing the highest surplus. On high-solar days, a significant portion of this surplus electricity could be utilized for auxiliary applications such as hydrogen production through electrolysis, which could further enhance the system's overall energy autonomy and economic value. This observation is in line with studies that integrate power-to-hydrogen pathways in off-grid or net-zero contexts, where surplus PV is routed to electrolysis to enhance autonomy and provide seasonal storage [11,34,41]. Our findings thus reinforce the sector-coupling potential reported in the literature and indicate a practical avenue for valorizing surplus generation in high-irradiance periods.

The capacity factor for the PV system remains at 18% across all scenarios. The highest capacity factors for the diesel generator, inverter, and rectifier are 16.5% (base), 22.1% (base), and 3.1% (Scenario 2), respectively. In Scenarios 1 and 3, the rectifier is used minimally, resulting in a zero capacity factor.

Losses in the BES, inverter, and rectifier systems are also analyzed. The lowest BES losses, at 3,460 kWh/year, occur in Scenario 5 due to the reduced number of batteries. Fewer batteries not only lower initial investment costs but also reduce storage-related energy losses by limiting the number of charge/discharge cycles, as seen in the substantially lower BES loss values in Scenario 5 compared to all other configurations. The highest BES losses, at 19,789 kWh/year, are observed in the base scenario, which uses 1,000 batteries, the highest among all configurations. Inverter and rectifier losses, which are directly related to their capacity factors, fall within 2,062–10,169 kWh/year and 6–1,450 kWh/year, respectively.

In terms of emissions, which result from the operation of the diesel generator, lower energy demand leads to lower emissions. The highest total emissions, at around 136 tons/year, occur in the base case, while the lowest, at 6.3 tons/year, occur in Scenario 5. The generator operating hours, which correlate with diesel fuel consumption, range from 1,786 hours/year (base) to 150 hours/year (Scenario 5).

A particularly important and unexpected result relates to the diesel generator dispatch strategy. In the base scenario, Scenario 2, and Scenario 4, the generator operates in cycle charging mode, while in Scenarios 1, 3, and 5, it operates in load following mode. In cycle charging mode, the generator runs at full capacity and stores surplus power in batteries, increasing rectifier activity and consequently its losses, clearly observed in the results. In load following mode, the generator only produces as much electricity as needed, avoiding excess generation and BES charging, thus minimizing the need for rectifier operation. In Scenario 5, the load following dispatch strategy allows the diesel generator to operate only when strictly necessary, preventing unnecessary charging of the battery bank. This operational behavior is visible in Figure 16, where generator activity is minimal despite fluctuations in load and PV generation, resulting in both reduced operating hours and lower associated emissions. Such behavior is consistent with HOMER-driven analyses in off-grid hybrids, where load-following logic curtails unnecessary charging cycles, shortens generator operating hours, and reduces associated emissions compared to cycle-charging regimes [29,30]. The pattern observed here (minimal generator activity in Scenario 5) corroborates these operational advantages.

Analysis of the ROI, a key financial indicator in RE studies, shows that Scenario 5, which combines all optimizations, has the best performance, with an ROI of 434%, equivalent to a payback period of 0.234 years. The least favorable scenario in terms of ROI is Scenario 1, with 267%.

Figure 16 illustrates the system performance in Scenario 5, identified as the most technically, economically, and energy-efficient configuration, during the first week of January. As shown, on days with high solar radiation and sufficient BES charge, or when the electricity demand is low, the diesel generator is either not used or minimally engaged. On January 4 and 5, due to low solar radiation and insufficient BES charge, the diesel generator operates at approximately 30 kW to meet demand. The sequential supply of demand is evident in the figure: during daylight, PV production is prioritized; in the absence of solar generation, the system switches to battery discharge, and only when the battery state of charge drops below the threshold does the diesel generator engage. This layered dispatch minimizes fuel consumption and emissions. Figure 16 also illustrates the sequential supply of demand, PV priority during daylight, followed by battery discharge, and DG engagement only below a SOC threshold, which is a canonical feature of efficient off-grid hybrid operation reported in the literature [27,29,30]. This layered dispatch underpins the low DG hours and emissions achieved in the optimized scenario.

Table 5. Simulation Results for Different Scenarios.

	Equipment								Capacity factor (%)			
Scenario	PV (kW)	DG (kW)	BES	Converter (kW)	NPC ($)	LCOE ($/kWh)	PV production (kWh/yr)	Excess electricity (kWh/yr)	PV	DG	Inverter	Rectifier
Base	300	100	1000	100	947243	0.557	472447	274091	18	16.5	22.1	2.9
Polystyrene	400	100	1000	100	780205	0.582	629930	428265	18	7.68	20.3	0
Green roof	300	100	1000	100	896305	0.572	472447	285534	18	14.9	21.1	3.1
UPVC	400	100	1000	100	732224	0.586	629930	434096	18	6.38	19.7	0
VRF	200	100	700	100	349401	0.742	314965	229090	18	1.52	9.3	0.9
Optimized	100	100	300	100	193796	0.867	157483	115181	18	0.51	4.5	0.3

Table 5 continued

	Losses (kWh/year)			Emission (kg/year)						
Scenario	EBS	Inverter	Rectifier	CO2	CO	SO2	NOx	ROI (%)	Dispatch strategy	DG (hour)
Base	19789	10169	1318	132582	327	266	2920	288	CC	1786
Polystyrene	13383	9376	7	69151	171	139	1523	267	LF	1180
Green roof	19278	9749	1450	119983	296	241	2643	291	CC	1621
UPVC	13279	9090	6	58148	144	117	1281	270	LF	1013
VRF	8052	4275	400	13359	33	26.8	294	208	CC	219
Optimized	3460	2062	137	6122	1501	1203	135	434	LF	150

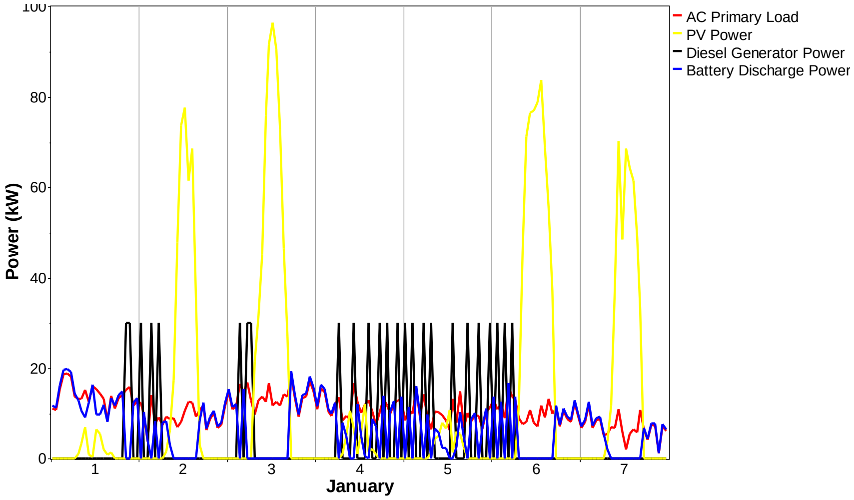


Figure 16. System Performance in Scenario 5 During the First Week of January.

6. Discussion

The primary objective of this study was to quantitatively assess how building-level energy efficiency measures influence the techno–economic–environmental performance of an off-grid solar–battery–diesel generator system in a climate-compatible villa. The findings strongly support this objective by demonstrating that demand-side optimizations, such as advanced insulation, efficient glazing, green roofing, and VRF-based HVAC, can substantially reduce the net present cost, lower emissions, and improve ROI compared to the baseline configuration. These outcomes confirm the initial hypothesis that integrated building optimization strategies not only reduce energy demand but also enhance the cost-effectiveness and environmental performance of renewable energy systems in off-grid residential applications. Additionally, the observed trade-off between reduced total costs and increased unit electricity costs in low-demand scenarios provides a nuanced refinement to the initial assumptions, highlighting the importance of balancing demand reduction with optimal capacity utilization in system design.

The results of this study offer several practical implications for stakeholders involved in off-grid and hybrid renewable energy deployment. For policymakers, the demonstrated potential of combining building envelope improvements and high-efficiency HVAC systems with a hybrid PV–DG–BES configuration, yielding up to 79.5% reduction in total NPC and approximately 130 tons/year reduction in emissions, provides strong justification for targeted policy instruments such as subsidies, tax incentives, and low-interest financing schemes that jointly address demand- and supply-side optimization.

For grid operators and energy planners, although the analysis focuses on an off-grid case, operational strategies such as load-following dispatch and surplus PV utilization for hydrogen production are transferable to weak-grid and microgrid contexts, where they can reduce generator runtime, improve asset utilization, and enhance system resilience under high renewable penetration. For building designers, developers, and EPC contractors, the quantified linkage between building-level energy optimization and renewable electricity cost metrics (LCOE, ROI) enables more informed investment decisions, demonstrating that optimal sizing of PV arrays and battery storage not only prevents over-dimensioning but also reduces storage-related losses while increasing energy autonomy in remote locations. Finally, a cross-cutting insight emerges: while demand-side measures substantially reduce total system costs, they may also increase unit electricity cost when fixed-capacity components are amortized over a smaller annual energy throughput, highlighting the importance of integrated techno–economic optimization in design practice.

The findings of this study have broader implications that extend beyond the specific case of the climate-responsive villa examined. For grid operators, the results indicate that implementing building-level energy efficiency measures can reduce the required capacity of distributed generation or off-grid systems, thereby alleviating stress on generation and storage infrastructure, improving peak load management, and enhancing network resilience. For policymakers, the study provides both quantitative and qualitative evidence to support the formulation of incentives, building standards, and supportive programs that facilitate the effective integration of renewable energy in the residential sector, particularly in remote or rural areas. For researchers, the integrated framework employed, combining consumption modeling via DesignBuilder with techno–economic–environmental assessment using HOMER, is adaptable to various climates, load profiles, and technologies (e.g., hybrid wind–solar systems or hydrogen production scenarios) and can serve as a decision-support tool at different scales. Overall, the model is transferable to regions with diverse energy resource profiles, subsidy policies, and levels of grid connectivity, making it suitable for international comparative studies and the strategic design of energy transition pathways across varied contexts.

7. Future works

This study, while offering valuable insights into the techno–economic–environmental impacts of building energy efficiency measures in off-grid PV–battery–diesel systems, is subject to several limitations.

First, the analysis relies on simulation-based results from DesignBuilder and HOMER, which assume idealized operational conditions, fixed component efficiencies, and static economic parameters; real-world performance may deviate due to degradation, partial shading, equipment downtime, or fluctuating fuel prices [47,48].

Second, the study focuses on a single case study in the climate of Saman, Chaharmahal and Bakhtiari Province, Iran; the generalizability of the results to other climates, building typologies, and load profiles requires additional validation [49,50].

Third, the surplus electricity utilization pathway (e.g., hydrogen production) was discussed conceptually but not modeled in detail; including techno–economic modeling of such sector-coupling strategies could provide more precise estimates of benefits [51,52].

Finally, the study did not perform an uncertainty analysis for key input parameters such as PV yield, diesel price volatility, or battery degradation rate, which could influence the robustness of the reported NPC, LCOE, and ROI values [53,54].

Future research should address these limitations by incorporating experimental validation [55], expanding the scope to multiple climate zones and hybrid configurations [56,57], modeling surplus utilization pathways in detail [58], and applying sensitivity/uncertainty analysis to strengthen the reliability of the conclusions [59,60].

Future work could adapt the causality analysis methodologies presented in [61-63] to the energy domain, enabling a clearer attribution of the effects of individual building optimization measures on system sizing, cost, and emissions. Approaches from [61] and [62] could help model non-linear and probabilistic relationships between demand reduction strategies and hybrid system performance, while techniques from [63] could improve robustness by accounting for uncertainty in climatic and load variations. Integrating these methods with the current DesignBuilder–HOMER framework would provide deeper, more generalizable insights for off-grid energy system planning.

Future research could integrate the current off-grid building optimization framework with advanced Distribution Network Expansion Planning (DNEP) methodologies to simultaneously assess demand-side and supply-side impacts. Multi-objective optimization approaches that explicitly incorporate uncertainties in electricity price and load demand, as demonstrated in [64-66], could enable more comprehensive scenario evaluation. The inclusion of risk-based performance metrics such as flexibility and robustness, as introduced in [64,65], would further allow assessment of the resilience of off-grid systems under fluctuating renewable resources and demand profiles. Moreover, adopting integrated planning of medium-voltage (MV) and low-voltage (LV) networks in the presence of distributed generators and renewable sources, as developed in [66], could facilitate joint evaluation of technical and economic impacts across multiple infrastructure layers. Finally, the comprehensive review of DNEP challenges and future trends in [67] highlights promising directions such as incorporating energy storage systems, refining solution techniques for non-linear/non-convex problems, and modelling stakeholder conflicts, all of which could be adapted to expand the scope and applicability of the present model.

8. Conclusions

Implementing effective strategies to reduce energy consumption not only helps protect the environment but also enhances the sustainability and reduces the energy costs of residential buildings. Despite their significance, the direct influence of these strategies on lowering the cost of renewable electricity has not been thoroughly studied. The present study addresses this gap by examining the impact of four energy-saving strategies on the cost of a solar system in a climate-adaptive villa located in Saman, Chaharmahal and Bakhtiari Province, Iran. The energy analysis of these strategies and the evaluation of the solar system's performance were carried out using DesignBuilder v6.1.0.6 and HOMER v2.81, respectively. The energy simulations in DesignBuilder span one year, while HOMER provides a 25-year energy-economic-environmental analysis. Six scenarios were investigated in total: Scenario 1, a climate-responsive design without optimization; Scenario 2, applying polystyrene insulation to the envelope; Scenario 3, implementing a green roof; Scenario 4, installing UPVC windows; Scenario 5, incorporating a VRF air conditioning system; and Scenario 6, which combines Scenarios 2 to 5. This study confirms the economic and environmental value of implementing energy-saving strategies in climate-adaptive buildings and provides a practical foundation for future decision-making in this domain.

- The solar PV capacity in the off-grid system was 400 kW in Scenarios 2 and 4, 300 kW in Scenarios 1 and 3, 200 kW in Scenario 5, and the lowest, 100 kW, in Scenario 6.

- In all scenarios, a 100 kW diesel generator was used as a backup power source, remaining constant across all configurations.

- The number of batteries used was 1,000 units in Scenarios 1 through 4, 700 units in Scenario 5, and only 300 units in the most optimized case, Scenario 6.

- The total NPC of the solar system ranged from $947,243 in Scenario 1 (the base case) to $193,796 in Scenario 6 (the optimized case), indicating a significant reduction in total system cost with energy-saving strategies.

- The cost of electricity increased as energy demand decreased, ranging from $0.557/kWh in Scenario 1 to $0.867/kWh in Scenario 6, highlighting the inverse relationship between total electricity consumption and the unit cost of renewable electricity.

- The solar system was capable of supplying between 77% and 97% of the total electricity demand across the scenarios, with surplus electricity generation ranging from 44.4% to 71.1% of total output, a notable consequence of off-grid system design.

- Annual system losses were also considerable, varying from 31,276 kWh in Scenario 1 to just 5,659 kWh in Scenario 6, driven primarily by the number of batteries and inverter utilization.

- Emissions from diesel generator operation ranged from approximately 136.1 tons/year in the base scenario to as low as 6.3 tons/year in the fully optimized Scenario 6, showing a strong correlation between system design and environmental performance.

- The optimal generator dispatch strategy varied by scenario: Scenarios 1, 3, and 5 followed a cycle charging strategy, while Scenarios 2, 4, and 6 followed a load following approach, which significantly influenced both generator usage and energy losses.

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Declaration of competing interest

The author declare that she has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, have been completely observed by the author.

Bibliography

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