Research Square

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The Security Premium of Reliable Energy: Quantifying the Trade-off Between Load Criticality and Economic Viability in Off-Grid Systems

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Abstract

Achieving deep decarbonization in off-grid industries is often hindered by the strict reliability requirements of critical loads, a factor frequently overlooked in standard techno-economic assessments. This study quantifies the "Security Premium" as the economic penalty incurred to guarantee 100% reliability by contrasting non-critical and critical load scenarios under identical climatic conditions in Ibri, Oman. Using SAM and RETScreen simulations, the results reveal a stark divergence in viability determined by load criticality. The non-critical PV-Wind-Battery system is highly profitable, achieving a Net Present Value (NPV) of $86.5 million and a competitive LCOE of 27 ¢/kWh. In contrast, the critical industrial system requires a 5.0 MW diesel baseload to prevent supply interruption. This configuration yields a negative NPV of -$31.8 million, effectively quantifying the Security Premium required to support essential industrial operations. While the critical system is economically challenging, it delivers a massive environmental benefit by reducing CO_2 emissions by over 19,000 tons/year. These findings demonstrate that without specific policy interventions, such as reliability tariffs or carbon credit mechanisms to offset the Security Premium, the hybridization of critical off-grid sectors will remain financially unviable.

1 Introduction

Access to reliable and affordable electricity remains a persistent challenge in off-grid and remote regions worldwide, where grid extension is often technically complex or economically unfeasible. In such contexts, electricity supply has traditionally relied on diesel generators due to their dispatchability, operational simplicity, and relatively low initial capital cost. However, diesel-based generation is associated with high fuel and maintenance costs, vulnerability to fuel price volatility, logistical challenges in remote locations, and significant greenhouse gas (GHG) emissions. These limitations have intensified the global interest in alternative energy solutions capable of delivering secure, cost-effective, and environmentally sustainable power for off-grid applications [1, 2].

Hybrid Renewable Energy Systems (HRES), which combine two or more renewable energy sources with energy storage, have emerged as a practical approach to overcoming the intermittency of standalone technologies. Solar photovoltaic (PV) and wind energy systems are among the most widely deployed technologies in these off-grid hybrid configurations due to their modularity, technological maturity, and declining costs [3–5]. When appropriately integrated, these hybrid systems can enhance supply adequacy, improve energy utilization, and reduce reliance on fossil fuels, thereby supporting global decarbonization targets [1, 6].

The design, optimization, and techno-economic performance of such systems have been studied extensively, especially in rural electrification, islanded communities, telecommunication systems, and remote industrial facilities [7–9]. These studies typically evaluate system performance based on indicators such as the Levelized Cost of Electricity (LCOE), Net Present Value (NPV), and reliability. Furthermore, environmental studies consistently show that hybrid renewable systems in areas of high

resource availability can cause significant reductions in GHG emissions compared to diesel-only power generation [8, 10].

However, a critical limitation in this extensive body of literature is the tendency to treat demand load as a homogeneous variable. This approach often ignores the strict reliability requirements of industrial applications. Non-critical loads, such as auxiliary infrastructure, can tolerate limited power losses. This flexibility allows for cost-optimized systems with high renewable fractions. In contrast, critical loads like oil extraction pumps demand 100% supply continuity, where even momentary outages result in technical failure. This disparity creates a "blind spot" in standard assessments. By not explicitly differentiating between critical and non-critical loads, many studies underestimate the **"Security Premium"**, defined here as the additional investment and operational cost required to maintain dispatchable backup diesel generation for critical loads.

To address this gap, this study provides a comparative assessment of two HRES configurations in Ibri, Oman, designed to quantify the trade-off between load criticality and economic viability. Unlike previous works that focus on single-configuration optimization, this research analyzes a renewable-only system for non-critical loads against a PV-Diesel hybrid for critical loads under identical climatic conditions. The primary objective is to isolate and quantify the Security Premium, identified as the spread between the profitability of flexible systems and the losses incurred by critical systems. By defining this cost, the study aims to provide policymakers with the financial evidence needed to justify specific interventions, such as reliability tariffs or carbon credits, to render the decarbonization of critical off-grid industries financially feasible.

2 Literature Review

2.1 Off-grid hybrid renewable energy system architectures

Extensive research has been conducted on off-grid hybrid renewable energy systems (HRES) as potential alternatives for providing energy access to remote areas with no grid connectivity (where extensions are neither feasible nor cost-effective). Most literature reports systems that combine solar photovoltaic (PV) and wind energy with some form of storage (often supplemented by dispatchable sources such as diesel generators to boost supply reliability) [1, 5, 6, 9, 11]. For applications with high renewable penetration and low fuel usage, especially islanded or rural areas with moderate reliability constraints, PV–wind–battery configurations are often proposed [9–11].

In contrast, PV–diesel and PV–wind–diesel–battery systems remain prevalent where load continuity is critical and supply interruptions are unacceptable, such as for industrial facilities, public infrastructure, and essential services[2, 12–15]. These hybrid configurations balance renewable integration with dispatchable backup to mitigate intermittency and ensure operational robustness.

Figure 1 helps to integrate the current research with the diverse configurations of off-grid HRES systems by providing a conceptual classification of the main system architectures found in previous research,

and pinpointing the two configuration families that are the focus of the present analysis, which are: a renewable-dominant PV–wind–battery system and a PV system with diesel back-up. This classification shows that design choices are in many instances more tied to the load and reliability than to the available resources.

2.2 Modelling, Sizing, and Optimization Approaches

Several optimization-based techno-economic evaluation studies look at off-grid HRES and focus on trying to determine the appropriate size. Most of these studies focus on trying to meet the technical and reliability requirements while minimizing the LCOE or NPC of the system [2–4, 11, 12]. To tackle the trade-offs between cost and renewables (and penetration and emissions and system reliability), these studies propose the use of multi-target optimization and metaheuristic algorithms [16–19].

Some studies look at the importance of control logic and dispatch strategies. Operational decisions are, for example, explained as having a large impact on system performance, fuel consumption, and storage utilization [20–23]. Studies that look at varying system feasibility based on parameters that are uncertain, like fuel prices, costs of components, and load growth, are also quite abundant [15, 23, 24].

Table 1 captures a synthesis of these varying works by providing representative studies on off-grid HRES based on system design, specific methodology, application, reliability, and other parameters. From this synthesis, it is evident that while there are multiple studies focused on varying designs and configurations and optimization processes, there is an absence of a focus on systematic classification based on load criticality.

Table 1
Summary of representative off-grid hybrid renewable energy system studies

Ref.	System Configuration	Application Context	Methodology / Tool	Reliability Treatment	Key Findings
[11]	PV–Wind–Battery–Diesel	Rural village (Nigeria)	HOMER optimization	LOLP considered	Improved reliability but increased diesel dependency
[25]	PV–Wind–Diesel–Battery	Remote locations	Comparative economic analysis	Basic reliability metrics	Grid-connected systems showed lower LCOE
[26]	PV–Diesel–Battery	Rural electrification (Zambia)	Techno-economic assessment	Diesel backup ensured continuity	High fuel cost sensitivity
[27]	PV–Wind–Diesel–Battery	Remote village (Nigeria)	HOMER Pro	Reliability constraint imposed	Diesel dominance under low-RES availability
[10]	PV–Wind–Battery	Rural communities	Environmental sustainability assessment	Limited reliability discussion	Focused primarily on environmental impacts
[23]	PV–Wind–Diesel–Battery	Educational institution	Techno-economic & sensitivity analysis	Reliability embedded implicitly	Did not differentiate load criticality
[28]	PV–Diesel–Battery	University buildings	Comparative grid vs off-grid study	Backup-based reliability	Lacked explicit load prioritization
[29]	PV–Diesel	Urban off-grid (Somalia)	Economic feasibility analysis	Diesel-based reliability	Renewable penetration constrained
[30]	PV–Wind–Battery	Remote applications	Exergetic & techno-financial optimization	Dispatch strategy driven	Reliability linked to dispatch, not load type
[31]	Multiple hybrid systems	Review (global)	Review & classification	Discussed generally	No explicit system selection rule

2.3 Reliability, Dispatch, and Load Characteristics

The design of off-grid energy systems relies heavily on considerations of reliability, yet the way these considerations are treated really is quite varied in the literature. For example, many studies implicitly address reliability when talking about additional storage or conservative sizing, while not actually differentiating critical from non-critical loads [9, 11, 26, 32]. In contrast, some studies address certain dispatching strategies and control methods to enhance system stability and lower the risk of unserved loads when the system is supplied by renewables [20, 21, 30].

Very few studies have examined the impact of load characteristics on the resultant system design. However, studies that incorporate analysis of industrial or mission-critical loads show that there are strong reliability considerations that, even in quite favourable renewable resource conditions, necessitate the inclusion of dispatchable backup generation [13, 33, 34]. The implications of these studies are that in the optimization of the system, load criticality cannot be decoupled, as there are fundamental differences in the loss-of-load considerations that are acceptable for the non-critical residential or commercial demand as compared to critical loads.

This is still a key differentiating feature, yet many studies that compare different configurations still do so, focusing on the costs or renewable fraction, and do not frame their findings in the context of a reliability-driven design approach.

2.4 Emerging Hybridization Pathways

Besides standard PV–wind–diesel configurations, literature reviews show that hybridization with bioenergy, micro-hydro, and cutting-edge storage systems is gaining traction. Bioenergy and biogas hybrids have been studied in order to improve dispatchability and utilize local biomass. Also, micro-hydro integration is frequently suggested in areas where water resources are available [35–39].

Recently, studies have been done on hydrogen-based power-to-power systems. These systems are capable of long-duration energy storage and provide the potential to increase the share of renewables in off-grid and islanded systems. These systems may have the flexibility and seasonal balancing benefits that are often needed, but the complexity and cost should warrant paying special attention to the coordination of system design and the operational profiles [40–45].

2.5 Research Gap

The studied references demonstrate that although there exist many studies pertaining to off-grid Hybrid Renewable Energy Systems (HRES) in various contexts, comparative studies appear to be carried out in system selection with little or no emphasis to load criticality. Most studies either concentrate on renewable dominant systems or, as a matter of course, consider diesel as a backup reliability $enhancer$ without differentiation between non-critical and critical demand and on the same resources and location [2, 11, 15, 26, 34, 46].

Thus, there is a research gap in the analysis of structured comparisons of off-grid HRES architectures where load criticality is the dominant design parameter. The current research attempts to fill this gap by comparative analysis of a PV–wind–battery system for non-critical load and a PV–diesel system for critical load by employing the same case scenario with consistent techno-economic and environmental performance parameters.

3 Methodology

3.1 Study Area and Renewable Resource Assessment

The selected study area, Ibri (23.23° N, 56.52° E), Sultanate of Oman, is a potential site for the integration of renewables. Ibri is also near the industrial sites, which can be used for renewables. The area is mainly arid desert (very dry) with a lot of solar exposure and some moderate winds, giving the area a lot of potential for renewables [47].

To assess the satellite location for large installations, a satellite survey was conducted. The selected site for the study is shown in the satellite image of Ibri in Fig. 2. The area is mainly flat with a lot of sand, and it also has a low number of obstacles (not too many plants, buildings, and other things), which means there will not be a lot of preparatory civil work for the installations.

High-resolution meteorological data from the Global Solar Atlas and Global Wind Atlas databases [48, 49] were used in the renewable resource assessment. The site has Global Horizontal Irradiance (GHI) of 6.12 kWh/m²/day and Direct Normal Irradiance (DNI) of 5.50 kWh/m²/day. Wind resource assessments at the 100 m hub height show mean winds of about 6.47 m/s, which is sufficient for contemporary low-speed wind turbine systems.

These resources' temporal variation must be considered for system sizing. Monthly climatic profiles used for the simulations, along with daily solar radiation and air temperature, are provided in Fig. 3. The data shows that solar irradiance is most intense between May and July during the hottest temperatures (over 35°C) while winds are calm year-round. The solar PV will be the primary energy generator, and wind energy will be used for energy supplementation during hours outside of peak solar generation.

3.2 Load Profile Definition and Criticality Classification

In order to analyze the effect of various reliability requirements on the system design, the authors elect to model a load profile from a cluster of remote oil production wells, a highly relevant industrial application for the region. Total peak demand is scaled to 5.0 MW. The authors set two different load scenarios for system sizing:

Case A (Non-Critical Load): Represents auxiliary industrial infrastructure. Here, the system is optimized to sustain the highest possible Internal Rate of Return (IRR) with a focus on renewable penetration, while absorbing a small Loss of Load Probability (LLP) so as to incur lower expenses on storage.

Case B (Critical Load): Represents essential extraction pumps (Electrical Submersible Pumps – ESPs). This load is challenging given the high inrush currents as well as the 100% power "must have" constraint. The economic consequence of supply interruption is tremendous given production would be deferred, and equipment would be damaged [50].

3.3 System Architectures and Electrical Configuration

Two separate configurations for Hybrid Renewable Energy Systems (HRES) were modeled for each respective load scenario. The electrical interconnection adheres to an AC-coupled bus topology, which accommodates flexible coupling topologies for multiple generation sources.

- Configuration A (PV–Wind–Battery): Intended for the non-critical load, this configuration is fully renewable and employs a battery energy storage system (BESS) to shift excess generation from peak solar hours to address nighttime demand.
- Configuration B (PV–Diesel): Intended for the critical load, this system uses a parallel topology. The diesel generator maintains baseload power and grid-forming capacity for stability, while the PV system operates in a fuel-saving mode. To mitigate engine glazing, and to promote longevity, the control logic governs the diesel generator to operate above a minimum load ratio of 30%.

Figure 4 shows the specific electrical design of the hybrid system in the Single Line Diagram (SLD). The figure shows the coupling of the PV strings and wind turbines to the AC bus through the DC/AC inverters. It also shows the coupling of the diesel generator and the point of common coupling (PCC) to the load. For the off-grid network to be safe, circuit breakers and relays are used to contain faults and avoid cascading failures.

3.4 Component Modelling and Techno-Economic Parameters

System simulations were conducted using the System Advisor Model (SAM) and RETScreen, to estimate energy yield, costs, and impacts on the environment.

An important consideration for the economic analysis is the price of traditional methods of power generation in remote locations, which is notably high. Figure 5 shows the costs associated with the benchmark energy production for the different methods in Oman. In addition, it shows that the costs for the generation of power through diesel in the grid central is around 0.45$ per kWh. In remote locations where the grid is not available, the costs associated with the generation of power through diesel are considerably higher, and not only due to the lack of available infrastructure, but also because of the logistical complexities that come with the transportation of the fuel. Thus, for the purposes of this study, we assume that the off-grid diesel LCOE is around $0.77 per kWh. Given this, it becomes easier to justify the economy behind the investment in the HRES systems for that price.

The specific technical and financial input parameters used for the simulation are summarized in Table 2. The criteria were based on the specifics of the regional market and the industry-standard technology specs. The financial model is based on a project life of 20 years with an assumed inflation of 1.0% yearly.

Table 2
Input Parameters for System Simulation

Category	Parameter	Value / Assumption
Financial	Project Lifetime	20 Years
	PPA Price Escalation	1.00% / year
	Diesel Fuel Price Benchmark	~$0.77 / kWh
	Debt Ratio (Case B)	~ 88%
PV System	Specific PV Output	5.07 kWh/kWp/day
	Capacity Factor (Simulated)	~ 19.0%
	Tilt Angle	26° (Fixed)
Wind System	Turbine Hub Height	100 m
	Mean Wind Speed	6.47 m/s
	Capacity Factor (Simulated)	~ 20.2%
Storage	Technology	Lithium-Ion Battery
	Roundtrip Efficiency	89.02%
Diesel Gen	Rated Capacity (Case B)	5,000 kW
	Minimum Load Ratio	30%

3.5 Simulation Framework and Performance Evaluation Criteria

The simulation employed a time-step analysis to manage the balancing of supply and demand. In Case A, the objective of the optimization analysis was to maximize the Internal Rate of Return (IRR) and simultaneously minimize the Levelized Cost of Electricity (LCOE) without the 100% reliability constraint. For **Case B**, the optimization was constrained by a "zero unmet load" requirement, which forced the inclusion of the diesel generator despite its negative impact on the Net Present Value (NPV).

The environmental impact was assessed by calculating the reduction in Greenhouse Gas (GHG) emissions relative to a base case of 100% diesel generation, using standard emission factors for the region.

4 Results and Discussion

4.1 Technical Performance and Energy Yield

The simulation results indicate that various operational attributes are influenced by the specific load criticality requirements. Table 2 provides a summary of the annual operational energy output, as well as the system performance indicators for the two configurations.

Case A (Non-Critical / PV–Wind–Battery) had total annual electricity generation of 16.98 GWh. The system takes advantage of the complementarity of the site's resources, operationally achieving 19.0% capacity factor for solar PV and 20.2% for the wind turbines. While battery storage systems allow for the shifting of loads, total system energy output is still restricted by the level of renewable energy generation. This finding is consistent with Khan et al. [51], where fully renewable off-grid systems in dry areas are technically feasible, and yet still limited by the availability of triggering intermittent winds.

Case B (Critical load / PV–Diesel) realized an even higher annual generation of 47.99 GWh. The critical load system generates almost three times more than the non-critical system, as shown in Fig. 6. This increase is due to the 5.0 MW diesel generator, which is dispatchable and operates as a baseload generator to guarantee 100% reliability for the oil well pumps. The technical results corroborate that renewable-only systems (Case A) are possible for flexible demands, while for industrial critical loads (Case B), the higher energy density achieved by hybridizing with conventional generation is a necessity, a position that Mulenga et al. [26] affirm in comparable studies on off-grid electrification.

4.2 Economic Viability and Trade-offs

Analysis of the economic performance of the systems shows a clear separation between the profit from the investments and the security of the operations. The financial data for the two setups are presented in Table 3, and their project lifetime cumulative cash flow is compared in Fig. 7.

Table 3
Comparative Technical and Economic Results

Indicator	Case A (Non-Critical)	Case B (Critical)
Annual Generation	16,978 MWh	47,993 MWh
LCOE (Nominal)	27.04 ¢/kWh	12.62 ¢/kWh
Net Present Value (NPV)	$86.5 Million	-$31.8 million
Internal Rate of Return (IRR)	143.71%	N/A (Negative)
Payback Period	1 Year	N/A

Figure 7 shows cash flows side by side for both scenarios. Case A, for example, shows in Fig. 7a, the non-critical case of the PV-Wind-Battery (B) system, demonstrates a strong positive cash flow (NPV = $86.5 million, IRR = 143.71%) with less than 1 year payback period for all money invested. Positive cash flow is driven by no variable fuel costs, accompanied by high initial costs (CAPEX) which get payed back quickly by sales of electricity. The LCOE is 27.04 ¢/kWh. This is cheaper than the baseline costs of $0.77/kWh of diesel consumption for off-grid systems. Even though the price is higher than the

connected-grid options, it proves a competitive price for the off-grid diesel systems. This also proves that for non-critical load systems, renewables only systems. This also supports the findings of Tjahjana et al. [52], who also noticed high profit systems for renewables hybrids in some remote Indonesian areas.

In contrast, the critical load system (Case B) exhibits different financial characteristics, as shown in Fig. 7 (b). Although the nominal LCOE of 12.62 ¢/kWh is lower (likely a result of economies of scale for a project size of 5.0 MW), the project still has an NPV of -$31.8 million. This is a result of the cash flow diagrams, where the revenue stream under the assumed PPA is below the operational cost associated with the OPEX incurred by continuous diesel fuel consumption.

This negative financial performance should not be interpreted as a system failure, but rather as the quantified Security Premium, the inherent cost of maintaining a dispatchable 5.0 MW backup to guarantee 100% reliability for the oil wells. Basnet et al. [31] noted that these hybrid systems with large, integrated, and thermal components often fail to achieve positive NPVs unless there are specific industrial tariffs or subsidies with regard to the value of the uninterruptible power.

4.3 Environmental Impact and Decarbonization Potential

The assessment describes how effective each design option is in terms of reducing remote power generation-related carbon emissions. Figure 8 shows GHG emissions in the critical load scenario as compared to the diesel-only base case.

In the analysis, an interesting paradox was discoverd between the “cleanliness” of energy produced and the total emissions reduced. While Case A (PV-Wind-Battery) is the only case with direct emissions, running it will reduce emissions by ~ 8,500 tCO_2/year. However, given that the system has a small operational scale, its direct emissions impact was also small.

On the other hand, Case B (PV-Diesel) has much more impact, reducing emissions by 19,191.3 tCO_2/year. As show in Fig. 8, for the case where diesel generators run oil well pumps, this is a 93% reduction from the diesel-only base case. Case B has this impact not because it is “cleaner” per kWh produced, but because it displaced much more (over twice) the conventional generation attributed to Case A (16.9 GWh) than to Case B (47.9 GWh).

Still, Case B depends on fossil fuels for baseload stability, thus total decarbonization remains unattainable. This constraint corroborates with Icaza and Borge-Diez [47], who stress that although hybrid-diesel systems must be incorporated to mitigate, on a large scale, the carbon produced from industrial applications, they are merely transitional technologies. To bring zero-emission targets within reach for critical loads, current technological cost constraints would necessitate the inconsistent scaling of renewable capacity and storage to economically unfeasible levels.

Conclusion and Policy Implications

This study presented a techno-economic feasibility analysis of hybrid renewable energy systems (HRES) for the electrification of remote oil and gas facilities in Oman. By contrasting a non-critical load scenario (Case A) with a critical industrial load scenario (Case B), the research quantified the trade-offs between economic profitability, supply reliability, and environmental sustainability.

The main insights from the simulations are as follows:

1. Feasibility of Fully Renewable Systems: The case study of the PV-Wind-Battery System (Case A) shows a high degree of feasibility. A net present value (NPV) of 86.5 million USD with 143% internal rate of return (IRR), and payback period of less than one year are indicative of strong economic performance. This demonstrates that configurations that are 100% renewable are great alternatives to diesel for ancillary facilities as well as for staff housing and flexible pumping operations.
2. “Security Premium” for Essential Loads: For essential industrial loads (Case B), where all of the loads need to be served, including the 5.0 MW diesel baseload generator, in spite of its economic unfeasibility, it becomes a technical necessity. This means, there is no less diesel generator in the system, although it has a nominal levelized cost of energy (LCOE) equal to 12.62 ¢/kWh which seems to be lower than that of the rest of the compounded system. A result of the absence of generator is NPV of -31.8 million USD. This phenomenon is what is referred to as the “security premium” which involves the costs of remote production where no active and flexible pumping operations are available.
3. Potential for Decarbonization: Critical load system (Case B) failed to yield any positive economic outcome; however, it offered the greatest level of environmental benefits which were quantified to be 19,000 tons of CO2 / year representing a 93% reduction when compared to the diesel-only baseline. This is indicative of the high level of effectiveness hybridization as an interim solution for the decarbonization of the fossil fuel industry.

Policy Recommendations: The data indicates that Oman's existing tariff frameworks do not encourage private funding for significant-scale hybridization of critical loads. To address the financial shortfall identified in Case B, we recommend the following to policymakers:

1. Off-grid hybrid projects that underpin critical industrial infrastructure should be provided “Reliability Tariffs” or capacity payments.
2. Providing Carbon Credits for the 19,000 tons of emissions avoided in order to address the negative NPV in the critical load scenario should be considered.

Limitations and Future Work

This study relied on fixed battery costs and current diesel prices. Future research should investigate the integration of **Green Hydrogen** as a potential replacement for the diesel baseload component to achieve a truly zero-emission critical power system. Additionally, sensitivity analysis regarding future battery cost reductions could identify the "tipping point" where the diesel generator can be economically phased out entirely.

Declarations

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Author Contribution

Al Hinai Al Waleed: Conceptualization of the study, Methodology, Software simulation (SAM & RETScreen), Data analysis, and prepared the original draft of the manuscript. **MAA Ghani:** Supervision, Validation, Project administration, and critical revision of the manuscript. **WNW Zakaria:** Validation, Resources, and discussion on emerging production techniques. **Farrukh Jamil:** Data curation and supervision, and contributed to manuscript review, editing, and proofreading. **Murid Hussain:** Supervision and was involved in revising and formatting the manuscript, as well as manuscript review. **FR Wong:** Review and editing of the manuscript.

Data Availability

Data Availability StatementThe datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Figures

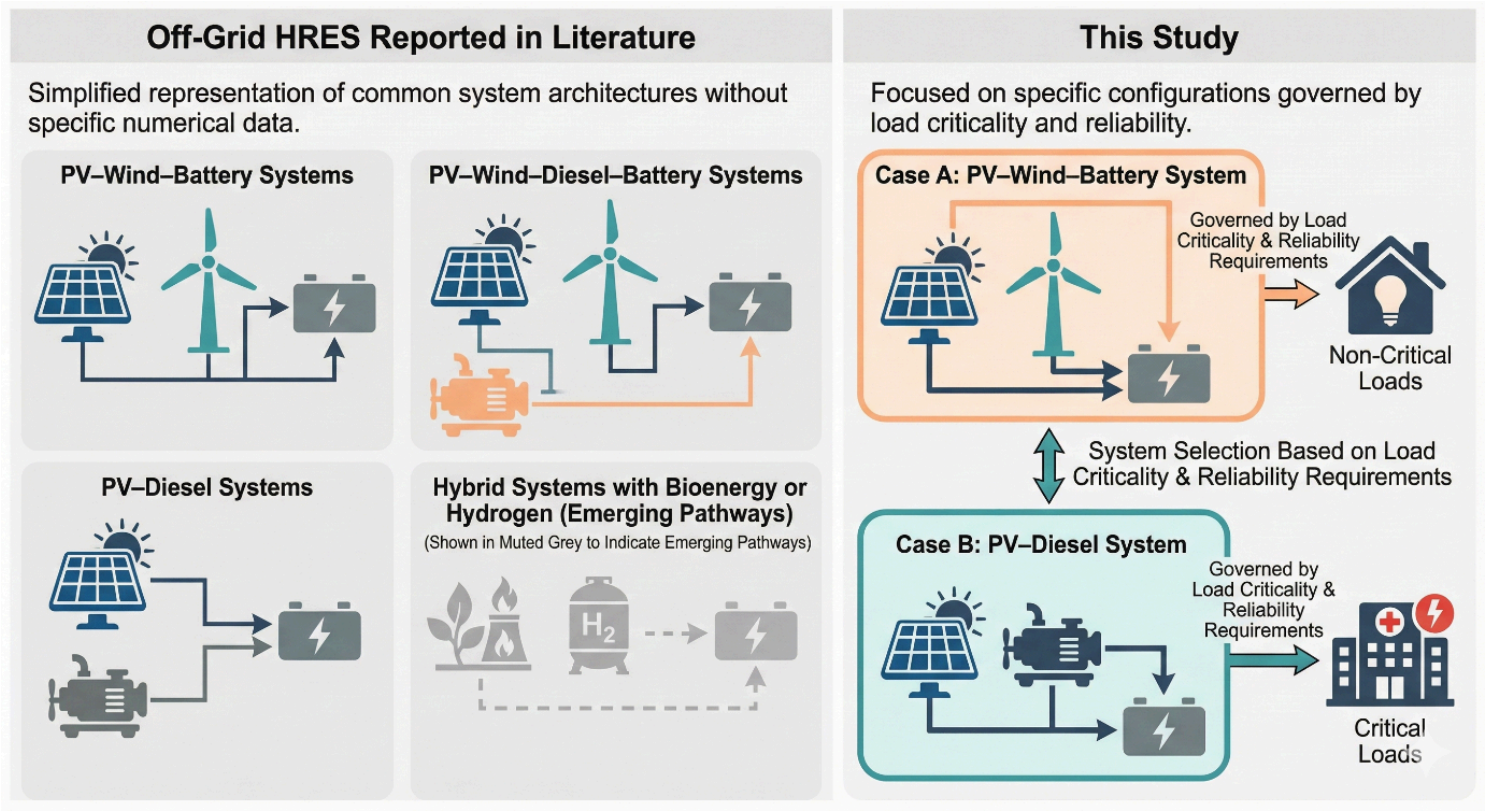


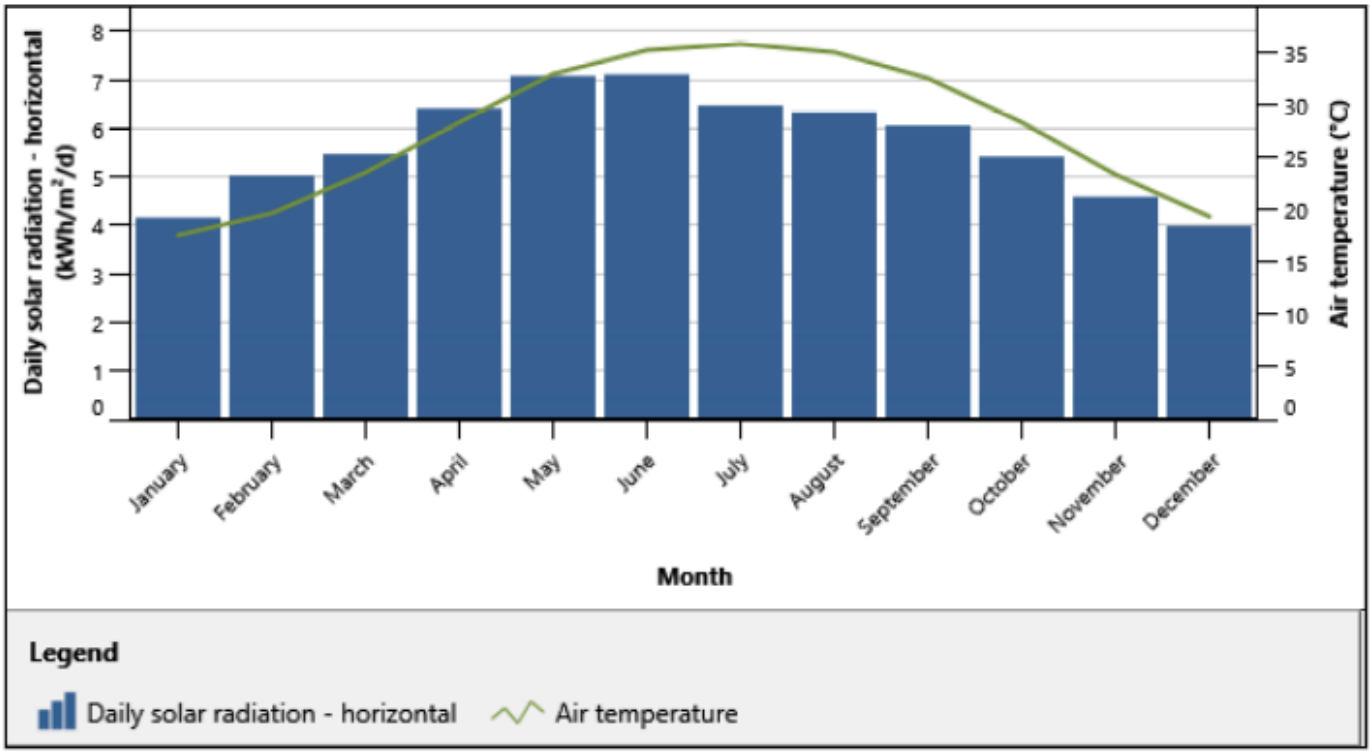
Figure 1

Conceptual classification of off-grid HRES architectures reported in the literature and positioning of the system configurations investigated in this study.



Figure 2

Satellite imagery of the proposed site in Ibri, Oman, demonstrates flat terrain suitable for PV and wind turbine installation.



Heating design temperature	13.3	
Cooling design temperature	41.6	
Earth temperature amplitude	21.8	

Month	Air temperature	Relative humidity	Precipitation	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days	Cooling degree-days
	°C	%	mm	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
January	17.6	47.4%	7.75	4.16	95.2	2.7	18.8	12	236
February	19.7	40.2%	10.36	5.03	95.1	3.0	21.1	0	272
March	23.6	30.9%	11.16	5.47	94.9	3.1	25.3	0	422
April	28.4	23.4%	9.00	6.41	94.7	2.9	30.6	0	552
May	33.0	17.6%	4.34	7.08	94.3	3.0	35.5	0	713
June	35.3	18.5%	4.50	7.11	93.8	3.0	38.5	0	759
July	35.9	24.3%	9.30	6.47	93.6	2.8	39.4	0	803
August	35.1	26.7%	8.99	6.34	93.8	2.5	38.8	0	778
September	32.6	25.1%	4.50	6.06	94.3	2.3	35.9	0	678
October	28.4	26.0%	3.10	5.42	94.8	2.1	30.8	0	570
November	23.4	38.6%	4.50	4.59	95.1	2.1	25.2	0	402
December	19.4	46.8%	7.13	3.99	95.3	2.4	20.7	0	291
Annual	27.7	30.4%	84.63	5.68	94.6	2.7	30.1	12	6,476

Figure 3

Monthly climatic profile for Ibri, Oman, derived from RETScreen meteorological databases, showing daily solar radiation (bars) and average air temperature (line).

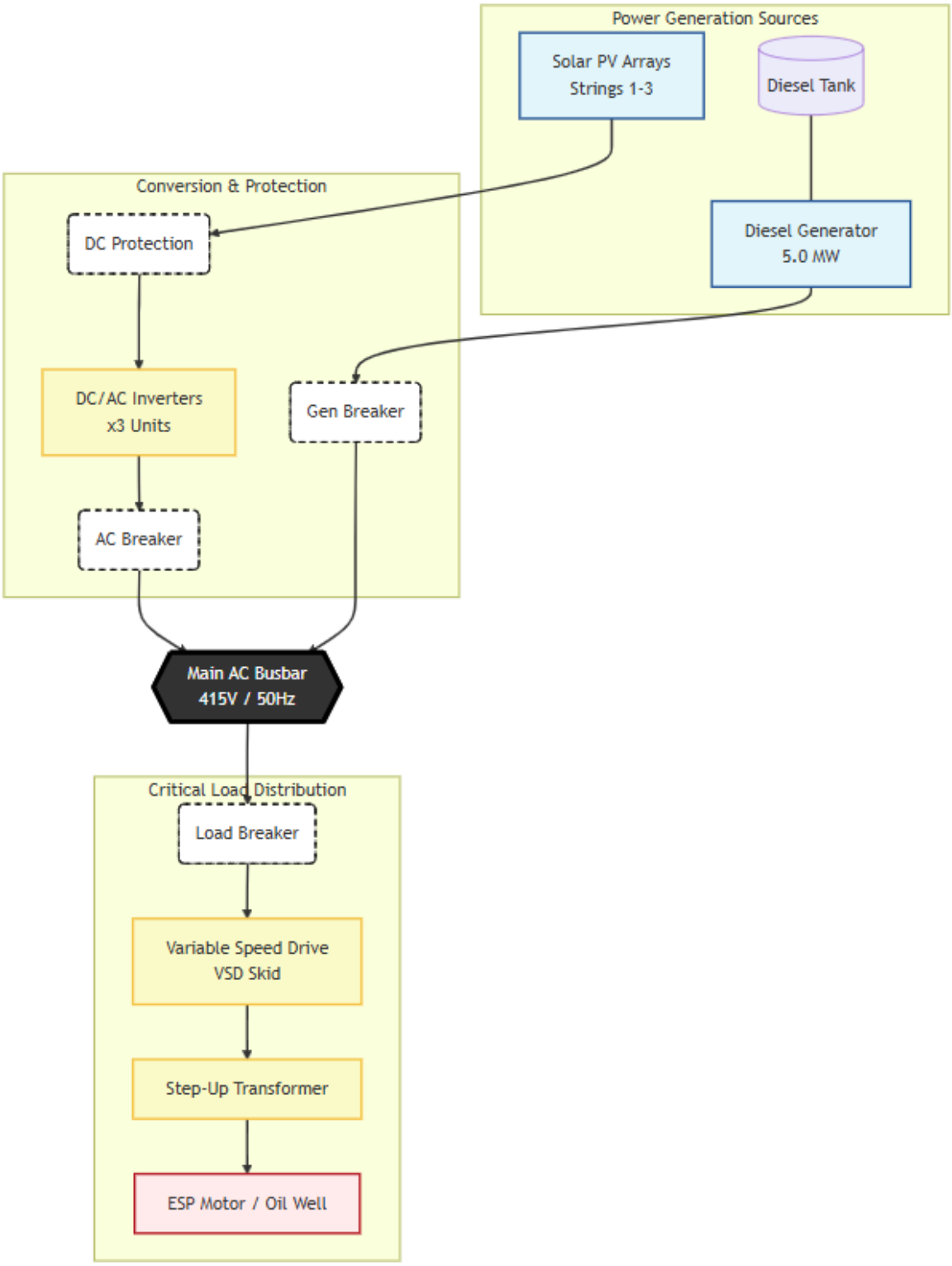


Figure 4

Single Line Diagram (SLD) of the proposed PV–Diesel hybrid system

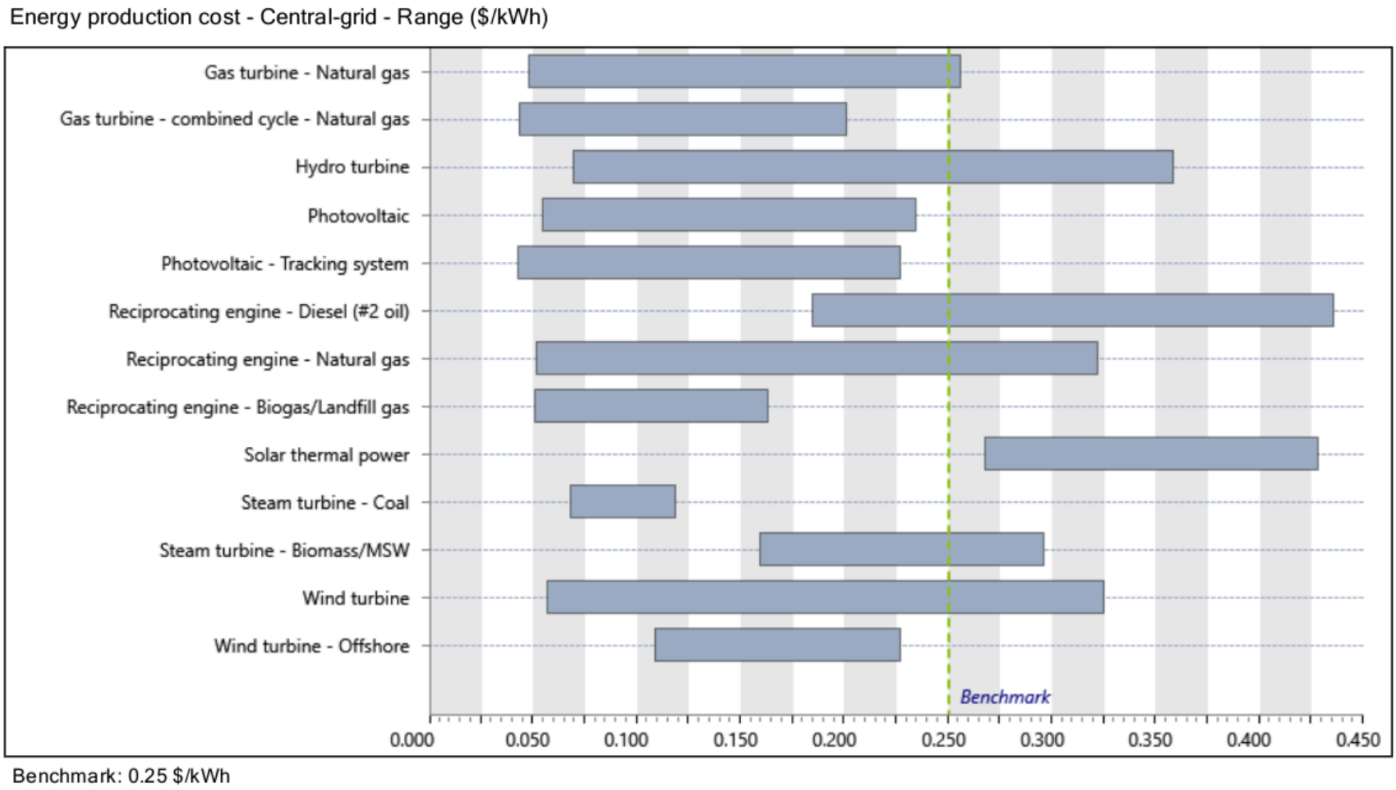


Figure 5

Benchmark comparison of energy production costs for various power generation technologies in Oman (Central-grid), highlighting the baseline costs before off-grid logistical adjustments are applied.

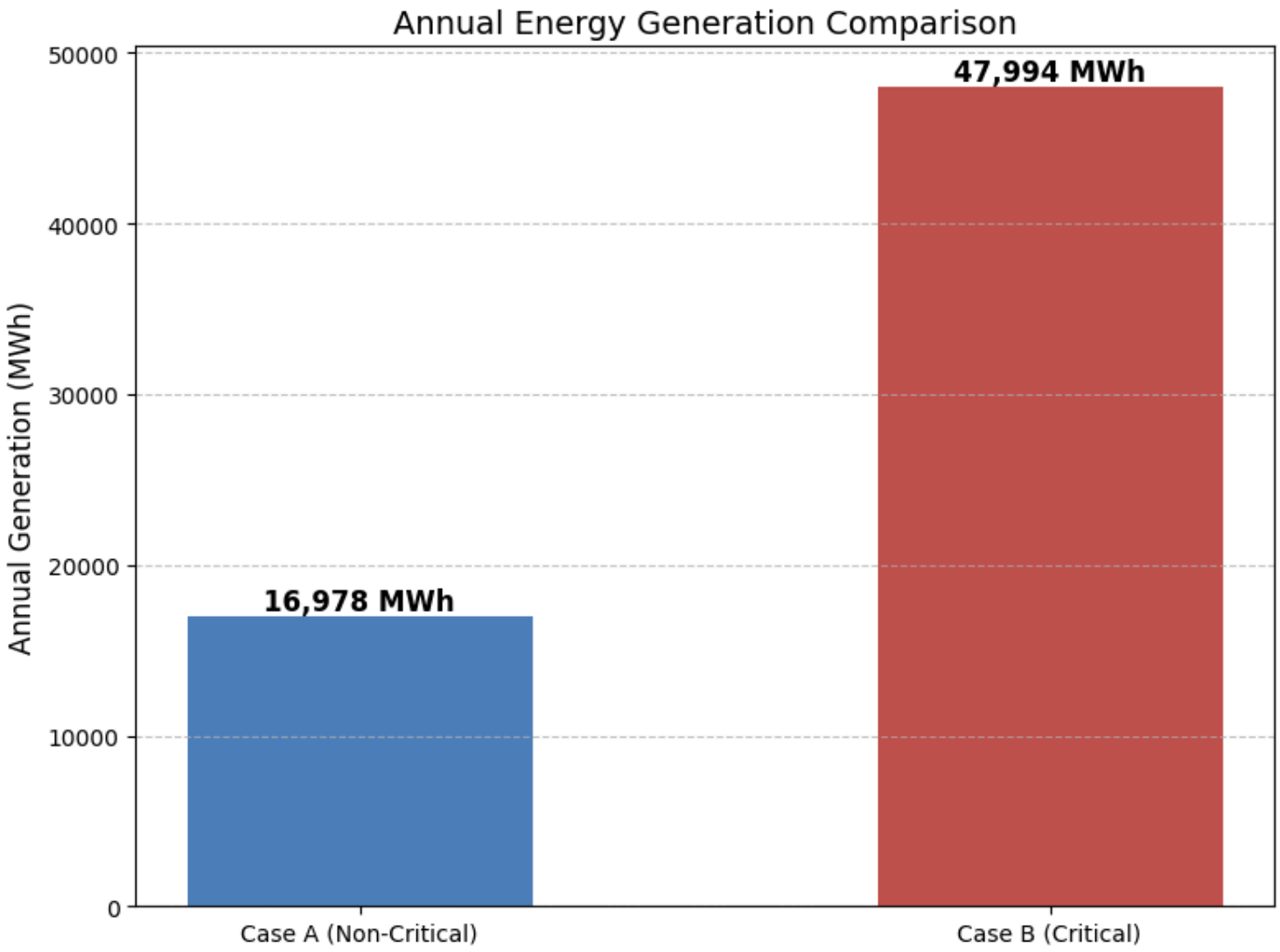


Figure 6

Comparison of annual energy generation between the non-critical (Case A) and critical (Case B) systems. The critical system requires nearly 3x the generation volume to maintain baseload stability.

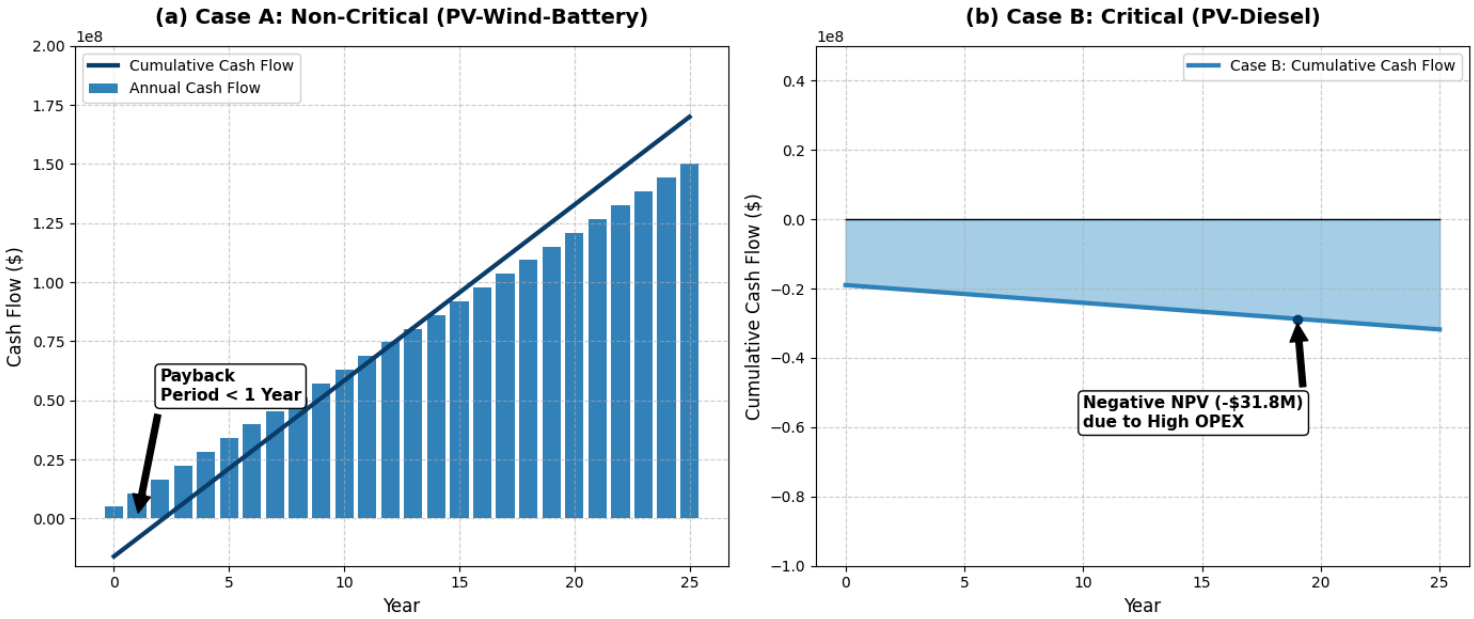
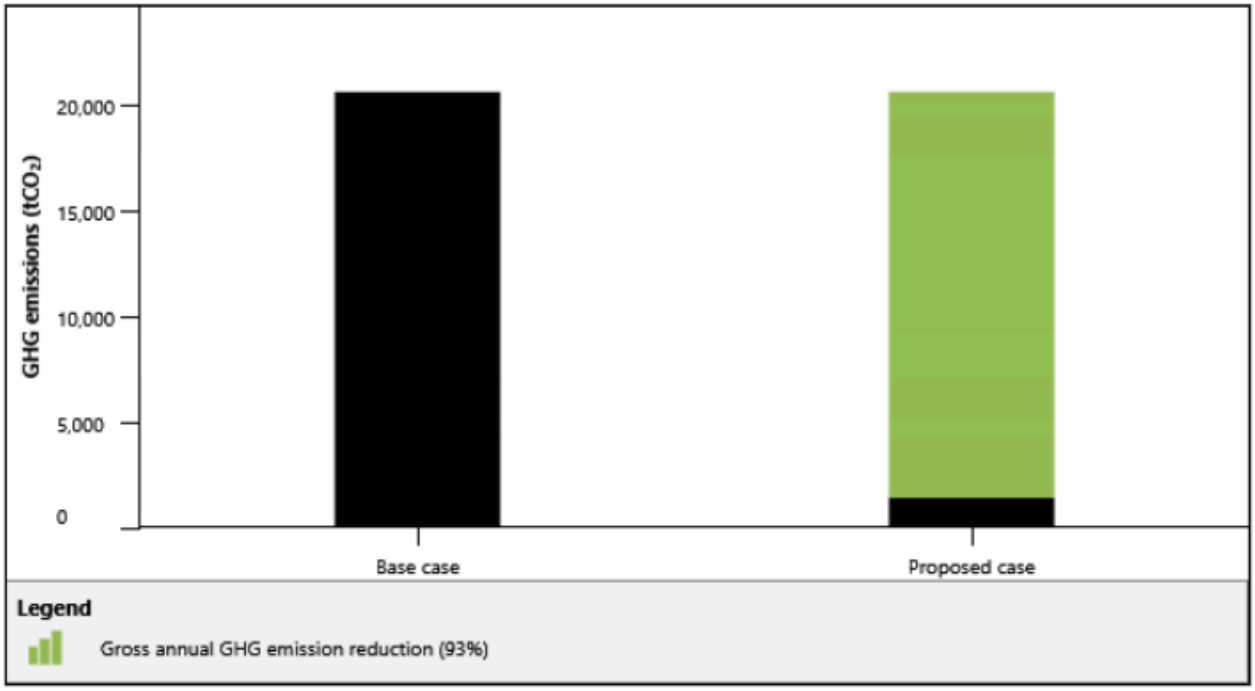


Figure 7

Comparative cumulative cash flow analysis over the 20-year project lifetime. (a) Case A (Non-Critical) shows rapid capital recovery and high profitability due to zero fuel costs. (b) Case B (Critical) shows a negative financial trajectory driven by the high OPEX of the diesel generator required for baseload stability.

GHG emissions



GHG equivalence



19,191.3 tCO_2 is equivalent to 3,514.9

Cars & light trucks not used

GHG emissions		
Base case	20,635.8	tCO_2
Proposed case	1,444.5	tCO_2
Gross annual GHG emission reduction	19,191.3	tCO_2

Figure 8

Environmental impact assessment for the Critical Load scenario (Case B). The integration of solar PV reduces annual GHG emissions by 19,191.3 tCO_2, equivalent to removing over 3,500 light vehicles from the road, representing a 93% decrease compared to the conventional diesel base case.