



Technical, Economic, and Environmental Assessment of Hybrid Renewable Energy Systems for Off-Grid Electricity Supply: A Case Study of Goharan, Bashagard

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Abstract

This study aimed to technically, economically, and environmentally evaluate alternative hybrid renewable energy system configurations for off-grid electricity supply in Goharan, Bashagard County, Iran, and identify the configuration providing the most favorable balance among energy performance, life-cycle cost, renewable energy penetration, fossil-fuel dependence, and environmental impacts. Six off-grid configurations combining photovoltaic (PV) arrays, wind turbines, lithium-ion batteries, diesel generators, and power converters were modeled and optimized using HOMER Pro. Local electrical-load and renewable-resource data were incorporated, and configurations were compared using technical, economic, and environmental criteria, including optimal component capacities, annual energy production, renewable energy fraction (REF), fuel consumption, net present cost (NPC), levelized cost of energy (LCOE), and pollutant emissions. Multi-parameter sensitivity analyses examined changes in diesel-fuel price, discount rate, equipment capital costs, and electrical load. Scenario 1, comprising 4,733 kW PV, 13,000 kWh battery storage, and a 1,671 kW converter, emerged as the preferred base-case configuration, achieving 100% renewable energy, an NPC of approximately USD 6.20 million, and an LCOE of USD 0.098/kWh without direct fossil-fuel consumption. Its NPC was approximately 22% lower than Scenario 3, 29% lower than Scenario 5, and nearly 55% lower than Scenario 6. Scenario 2 showed the highest NPC at approximately USD 27.44 million and an LCOE exceeding four times that of Scenario 1. Among diesel-backed configurations, Scenario 6 achieved a 97.6% REF and limited diesel generation to 2.4%. Sensitivity analysis indicated that fuel price, equipment capital cost, and electrical load substantially influenced economic performance, while Scenario 1 remained the least-cost option across the examined discount-rate range. A PV–battery configuration provides the most economically and environmentally favorable solution for the studied off-grid system, whereas PV–wind–battery–diesel integration offers a strong alternative when dispatchable backup is required; therefore, scenario-based multi-criteria optimization can support robust planning of renewable off-grid electrification under changing economic and demand conditions.

Keywords: Hybrid renewable energy system; Off-grid electrification; Photovoltaic; Wind turbine; Lithium-ion battery; Diesel generator; HOMER Pro; Techno-economic analysis; Sensitivity analysis.

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1. Introduction

Reliable access to electricity is a fundamental prerequisite for socioeconomic development, particularly in remote and sparsely populated areas where connection to centralized power grids is technically difficult or economically unjustifiable. In such regions, electricity supply is often constrained by long distances from existing transmission and

distribution infrastructure, low population density, difficult terrain, and the high capital cost of grid extension. Conventional off-grid solutions based primarily on diesel generators can provide dispatchable electricity, but their long-term use is associated with substantial fuel consumption, recurring operating costs, logistical dependence on fuel transportation, and adverse environmental consequences. These limitations have



increased interest in decentralized renewable energy systems as alternatives for supplying isolated communities and critical loads. Renewable resources such as solar and wind energy are particularly relevant to off-grid electrification because they can exploit locally available energy resources, reduce dependence on transported fuels, and support more sustainable electricity provision. Nevertheless, the performance of an autonomous energy system depends not only on resource availability but also on the temporal correspondence between generation and demand, the sizing of system components, storage requirements, conversion losses, reliability constraints, and economic assumptions [1, 2].

Solar photovoltaic and wind technologies are among the most widely considered renewable options for decentralized electricity generation. Solar energy is especially attractive in regions characterized by high levels of solar irradiance because photovoltaic systems are modular, scalable, relatively simple to operate, and increasingly competitive in terms of life-cycle cost. The energy output of a photovoltaic system is, however, governed by the magnitude and temporal distribution of solar radiation, cell temperature, array orientation, system efficiency, and local climatic conditions. Consequently, accurate characterization of the solar resource and appropriate sizing of photovoltaic capacity are essential for designing technically feasible stand-alone systems [3]. Wind energy can complement photovoltaic generation because wind-resource patterns may differ temporally from solar-resource patterns, potentially reducing periods of simultaneous renewable-energy shortage. However, wind systems may involve higher capital expenditure, greater sensitivity to site-specific wind-speed distributions, and more complex mechanical and maintenance requirements. For this reason, the relative contribution of PV and wind technologies in an optimal hybrid system cannot be established in general terms and must be evaluated for each location using local resource, demand, and cost data [4].

The intermittency of renewable energy generation represents one of the principal technical challenges in off-grid applications. Solar and wind generation vary across hours, days, and seasons and therefore do not necessarily coincide with the electrical load profile. In isolated systems without a grid connection, even relatively short mismatches between renewable generation and electricity demand can affect the continuity of supply. Hybrid renewable energy systems address this limitation by combining multiple generation technologies with energy-storage systems and,

where necessary, dispatchable backup generators. Batteries can store excess renewable electricity during periods of high generation and release stored energy during periods of insufficient generation, thereby reducing short-term imbalances and increasing renewable-energy utilization. Diesel generators can additionally serve as dispatchable backup sources during extended periods of low renewable generation or depleted battery storage. The resulting architecture can improve energy security and operational flexibility, but it also creates an optimization problem involving trade-offs among installed renewable capacity, battery size, diesel-generator operation, fuel consumption, capital cost, replacement cost, and reliability [2, 4].

The design of hybrid renewable energy systems is therefore intrinsically multidimensional. Increasing renewable generation capacity may reduce fuel dependence and direct operating emissions but simultaneously increase initial capital expenditure and, in some cases, the amount of surplus electricity. Increasing battery capacity can enhance autonomy and reduce reliance on dispatchable fossil-fuel backup, yet large battery banks may substantially increase capital and replacement costs. Conversely, reducing renewable and storage capacities can lower initial investment while increasing diesel-generator operating hours, fuel consumption, maintenance requirements, and exposure to future fuel-price fluctuations. Thus, system selection cannot be based solely on installed capacity or initial investment. A meaningful evaluation requires simultaneous consideration of technical performance, total life-cycle cost, energy cost, renewable-energy fraction, fuel consumption, storage behavior, and environmental consequences. System optimization is particularly important in off-grid applications because over-sizing can make projects economically unattractive, whereas under-sizing can compromise energy adequacy and operational reliability [5, 6].

Techno-economic assessment provides an analytical basis for identifying configurations that achieve an acceptable balance between system performance and cost. Among the most widely used economic indicators are net present cost (NPC) and levelized cost of energy (LCOE). NPC represents the present value of system expenditures over the project lifetime and can incorporate initial capital investment, replacement costs, operation and maintenance expenditures, fuel costs, and salvage values. LCOE translates the annualized system cost into the average cost of electricity supplied and therefore facilitates comparison among configurations with different technologies and cost

structures. These indicators are particularly useful in hybrid-energy analysis because configurations with relatively low initial capital costs may generate high recurring fuel and maintenance expenditures, whereas capital-intensive renewable configurations may have substantially lower operating costs over the project horizon. Consequently, optimization should focus on life-cycle performance rather than initial expenditure alone [5, 6]. HOMER Pro has become one of the most extensively applied platforms for this purpose because it can simulate the hourly interaction among electrical load, renewable generation, storage, converters, and dispatchable generators and compare feasible configurations on the basis of economic and technical criteria [7].

The usefulness of HOMER-based analysis is particularly evident in studies of rural and isolated electricity systems where local conditions strongly determine the optimal solution. Previous research in Iran has demonstrated that autonomous hybrid systems can offer technically and economically viable alternatives to conventional electricity supply in remote areas. Ataei et al. evaluated autonomous hybrid wind and solar systems for Moheydar Village and showed that the economic feasibility of hybrid renewable configurations is influenced by local renewable-resource conditions and the interaction among system components [8]. Similarly, Ganjei et al. designed and performed sensitivity analysis on an off-grid wind-solar system incorporating a diesel generator and battery backup for a rural area in Iran. Their analysis emphasized that optimal system design is affected not only by renewable-resource availability but also by economic parameters and configuration characteristics, highlighting the importance of sensitivity analysis when assessing stand-alone systems [9]. These studies collectively indicate that findings from one location should not be transferred directly to another because even within a single country, differences in solar irradiance, wind speed, demand profile, component costs, and fuel conditions can substantially alter the preferred configuration.

Recent research has also moved beyond simple cost minimization toward integrated evaluation of technical, economic, and sustainability performance. Samatar et al. examined hybrid off-grid renewable energy systems for sustainable rural electrification and demonstrated the importance of comparing configurations across several dimensions rather than relying on a single performance indicator [10]. This approach is consistent with broader reviews of hybrid renewable energy systems, which show

that system design increasingly requires the simultaneous consideration of renewable penetration, system reliability, storage requirements, environmental impact, and economic feasibility [2, 5]. The growing technical diversity of HRES configurations also reinforces the importance of scenario-based analysis. A solar-battery system, a wind-battery system, a renewable-diesel-battery configuration, and a combined solar-wind-diesel-storage system may all be technically feasible, yet they can exhibit substantially different cost structures, renewable-energy fractions, battery autonomy, fuel requirements, and emissions. A systematic comparison among such configurations is therefore necessary to determine whether additional technological complexity produces sufficient technical or environmental benefits to justify its associated cost.

Sensitivity analysis is another essential component of robust hybrid-system evaluation. Optimization results are typically generated under a defined set of baseline assumptions, including fuel price, discount rate, equipment cost, project lifetime, battery characteristics, and electrical demand. However, these parameters may change considerably over a project's operating life. Fuel prices can fluctuate, equipment costs may decline or increase, financing conditions can alter discount rates, and electrical demand may grow as population, economic activity, or appliance ownership changes. A configuration identified as optimal under baseline assumptions may therefore become less favorable under alternative economic or demand conditions. Sensitivity analysis provides a means of assessing whether the ranking of candidate systems remains stable when key inputs vary and helps identify which parameters have the greatest effect on NPC, LCOE, and system selection [6, 9]. This is especially important for configurations incorporating diesel generators, because their economic performance can be strongly influenced by fuel consumption and fuel-price variation.

Environmental performance must likewise be incorporated into the evaluation of off-grid hybrid systems. Diesel generators remain valuable as controllable backup sources because they can improve supply adequacy during prolonged periods of low renewable generation; nevertheless, diesel operation produces direct emissions, including carbon dioxide and local air pollutants. Increasing the renewable-energy fraction can reduce generator operating hours and fuel use, thereby decreasing operational emissions. Yet a system with the highest renewable-energy fraction is not automatically the most appropriate configuration if the required additional generation and

storage capacity results in disproportionately high life-cycle costs. The relevant decision problem is therefore not simply to maximize renewable penetration or minimize diesel use in isolation but to determine an acceptable balance among economic feasibility, renewable utilization, backup requirements, and environmental performance. Hybrid-system evaluation should consequently compare fossil-fuel dependence and direct emissions alongside conventional technical and economic indicators [4, 10].

The case of Goharan in Bashagard County, Hormozgan Province, provides an appropriate context for such an integrated evaluation because off-grid electricity supply in remote areas requires solutions that are compatible with local energy resources and demand conditions. The technical and economic performance of candidate configurations in this location cannot be inferred solely from general evidence on solar, wind, storage, or diesel technologies. Instead, local load characteristics, renewable-resource data, equipment sizing, and project economic assumptions must be incorporated into an integrated simulation framework. The broader research on hybrid systems indicates that PV and wind resources may complement one another, batteries can mitigate short-term variability, and diesel backup can enhance dispatchability, but the optimal balance among these components depends on the specific system context [1, 3, 7]. Accordingly, a locally calibrated scenario-based analysis is necessary to determine whether a relatively simple renewable-storage configuration is preferable to more complex hybrid arrangements incorporating wind generation and/or diesel backup.

The underlying doctoral research by Rashidi Mehrizi provides the technical and economic basis for investigating cost-effective hybrid renewable energy solutions for off-grid electricity supply under the conditions of the study area [11]. Building on that framework, the present study extends the comparative assessment by considering multiple system architectures and evaluating their technical, economic, and environmental implications in an integrated manner. Six configurations incorporating different combinations of photovoltaic generation, wind power, lithium-ion battery storage, diesel generation, and power conversion are examined. In addition to optimal component sizing and annual energy production, the analysis considers renewable-energy fraction, battery performance, diesel-generator contribution, fuel use, NPC, LCOE, and direct operational pollutant emissions. Furthermore, sensitivity analysis is used to determine how variations in fuel price, discount rate, equipment cost, and electrical load influence the economic

performance and comparative ranking of the configurations. Such an approach responds to the need identified in the hybrid-energy literature for location-specific assessment, life-cycle economic evaluation, explicit consideration of renewable and fossil contributions, and robustness testing under changing assumptions [5, 9, 10].

Accordingly, the aim of this study was to technically, economically, and environmentally evaluate and compare alternative hybrid renewable energy system configurations for off-grid electricity supply in Goharan, Bashagard, and to identify the configuration that provides the most appropriate balance among life-cycle cost, renewable-energy utilization, storage requirements, diesel dependence, and environmental performance.

2. Methodology

The present study was conducted to evaluate and compare different configurations of a hybrid renewable energy system (HRES) for off-grid electricity supply. The methodological framework is based on the simultaneous assessment of the technical, economic, and environmental dimensions of the system. The main system components included a photovoltaic (PV) system, wind turbine, lithium-ion battery, diesel generator, and power converter, while system simulation, equipment-capacity optimization, and scenario comparison were performed using HOMER Pro software.

The research process involved identifying the study area and electrical demand profile, collecting climatic and load data, defining the technical and economic specifications of the equipment, developing six different scenarios, simulating and optimizing the configurations in HOMER Pro, and finally evaluating and comparing the results. Identical baseline economic conditions were assumed across all scenarios so that differences in performance would primarily reflect the structure and composition of the system components.

During the simulation stage, HOMER Pro uses load data, renewable energy resources, the technical and economic specifications of the equipment, and the defined constraints to examine feasible configurations and determine the optimal capacity of the components in each scenario. The optimal configurations are evaluated in terms of technical indicators, including energy generation, renewable energy fraction, battery performance, and the extent of diesel-generator utilization. From an economic perspective, net present cost (NPC) and levelized cost of energy (LCOE) are

used, taking into account capital, operation and maintenance, fuel, and equipment-replacement costs. Fuel consumption and pollutant emissions resulting from diesel-generator operation are also compared as the principal environmental indicators.

To assess the robustness of the results and the extent to which configuration selection depends on economic conditions and energy demand, a multi-parameter sensitivity analysis was conducted. This analysis examined the effects of changes in five key parameters—diesel fuel price, photovoltaic panel cost, load growth, discount rate, and equipment lifetime—on the economic indicators and configuration selection.

The baseline project lifetime was assumed to be 25 years, with a baseline discount rate of 6%. For scenarios incorporating a diesel generator, the baseline fuel price was assumed to be USD 0.16/L.

Study Area

The study area was Goharan, located in Bashagard County, Hormozgan Province, Iran. The area was selected in accordance with the study objective of evaluating hybrid renewable energy systems for off-grid electricity supply. Its geographical characteristics include a latitude of approximately 26.6° N, a longitude of approximately 57.9° E, and an elevation of approximately 700 m above sea level.

Load Characteristics

The regional electrical load characteristics were defined as a time series in HOMER Pro and used as one of the primary model inputs. Peak load was assumed to be 1,815 kW in all scenarios, whereas daily energy consumption varied according to the data used for each scenario. Daily energy consumption for Scenarios 1 through 6 was 14,098, 13,574, 14,098, 14,098, 13,866, and 14,098 kWh/day, respectively.

Table 1. Electrical Load Characteristics in the Study Scenarios

Scenario	Daily Energy Consumption (kWh/day)	Peak Load (kW)	System Configuration
Scenario 1	14,098	1,815	PV + Battery + Converter
Scenario 2	13,574	1,815	Wind + Battery + Converter
Scenario 3	14,098	1,815	PV + Diesel + Battery + Converter
Scenario 4	14,098	1,815	Wind + Diesel + Battery + Converter
Scenario 5	13,866	1,815	PV + Wind + Battery + Converter
Scenario 6	14,098	1,815	PV + Wind + Diesel + Battery + Converter

Renewable Energy Resource Data

The climatic data required for renewable energy resource modeling were obtained from the NASA POWER database. For the solar resource, monthly global horizontal irradiance (GHI), expressed in kWh/m²/day, was used as an input to the photovoltaic generation model. For the wind resource, wind-speed data expressed in m/s and corresponding to the geographical coordinates of the study area were used in HOMER Pro.

System Components and Scenario Configurations

The HRES consisted of a photovoltaic array, wind turbine, lithium-ion battery, diesel generator, and power converter. The PV model was defined as Generic Flat Plate PV, and the wind turbine was an EWT DW 61 with a rated capacity of 900 kW. The energy-storage component was a Generic 100 kWh Li-Ion battery, and the diesel generator

was modeled as an Autosize Genset with a capacity of 2,000 kW.

The presence and capacity of system components varied according to the six defined scenarios. The configurations included PV–Battery, Wind–Battery, PV–Diesel–Battery, Wind–Diesel–Battery, PV–Wind–Battery, and PV–Wind–Diesel–Battery systems. The optimal component capacities for each scenario were determined using HOMER Pro and are presented in Table 10.

The battery was incorporated into the model as an energy-storage device to compensate for the temporal mismatch between renewable energy generation and load demand, and its capacity was determined by HOMER Pro according to the specific scenario. The converter was included to facilitate energy exchange among the generation sources, storage system, and electrical load.

Table 2. Annual Energy Generation by Generation Sources in the Selected Scenarios

Scenario	PV Generation (kWh/year)	Wind Generation (kWh/year)	Diesel Generation (kWh/year)	Total Generation (kWh/year)
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1	8,347,769	0	0	8,347,769
2	0	15,046,386	0	15,046,386
3	7,166,702	0	565,948	7,732,650
4	0	1,880,798	3,855,041	5,735,839
5	6,217,688	1,880,798	0	8,098,486
6	6,217,688	1,880,798	197,059	8,295,545

Definition of the Six Scenarios

To investigate the effects of different combinations of generation sources, energy storage, and backup generation on the performance of the off-grid electricity-supply system, six independent scenarios were defined and simulated in HOMER Pro. The scenarios were differentiated according to the type of renewable energy resources, the presence or absence of a diesel generator, and the manner in which the storage system was utilized. In all scenarios, the system was modeled as off-grid, and a power converter was used to facilitate energy exchange between the AC and DC sections.

Scenarios 1 and 2 were based on solar and wind energy, respectively, each combined with battery storage. In Scenarios 3 and 4, a diesel generator was combined with solar and wind systems, respectively. Scenario 5 incorporated both solar and wind resources without a diesel generator, whereas Scenario 6 incorporated both renewable resources together with battery storage and a diesel generator as a backup source. This structure enables a systematic technical, economic, and environmental comparison of the different configurations.

Table 3. Structure and Equipment Capacities of the Six Simulated Scenarios

Scenario	System Configuration	PV (kW)	Wind (kW)	Battery (kWh)	Diesel (kW)	Converter (kW)	Daily Load (kWh/day)	Peak Load (kW)
1	PV + Battery	4,733	0	13,000	0	1,671	14,098	1,815
2	Wind + Battery	0	7,200	13,600	0	1,465	13,574	1,815
3	PV + Diesel + Battery	4,063	0	13,600	2,000	1,737	14,098	1,815
4	Wind + Diesel + Battery	0	900	4,400	2,000	1,438	14,098	1,815
5	PV + Wind + Battery	3,525	900	13,300	0	1,962	13,866	1,815
6	PV + Wind + Diesel + Battery	3,525	900	10,300	2,000	1,526	14,098	1,815

Modeling and Optimization in HOMER Pro

To evaluate and compare the different hybrid renewable energy system configurations, system simulation and optimization were conducted in HOMER Pro. The software enables simultaneous modeling of electrical load, renewable energy resources, energy storage, power conversion, and backup generation. In the present study, the system was defined as off-grid, and its main components consisted of a photovoltaic array, wind turbine, lithium-ion battery, diesel generator, and power converter. The active components and capacity search ranges were specified according to the structure of each scenario.

The model was developed based on the connection of the generation sources to the system bus, storage system, converter, and electrical load. PV and wind turbines were modeled as climate-dependent generation sources, whereas the diesel generator was modeled as a dispatchable backup source in the relevant scenarios. System operation was simulated at an hourly time resolution to account for the interaction among variable renewable generation, energy

storage, and backup generation in meeting the electrical load.

This structure enables the interaction among variable renewable energy generation, energy storage, and backup generation to be examined at an hourly time resolution.

Model Input Data

The principal inputs to the HOMER Pro model included the time-series electrical load profile, solar irradiance data, wind-speed data, technical and economic equipment specifications, and parameters related to diesel fuel. The load profile was entered as time-series data, while solar irradiance and wind-speed data were used to calculate hourly renewable energy generation.

The equipment incorporated into the model included the photovoltaic array, EWT DW 61 wind turbine, Generic 100 kWh Li-Ion battery, Autosize Genset diesel generator, and power converter. The technical and economic specifications of these components were entered into HOMER Pro according to the parameters defined in the model.

Decision Variables

During the design and optimization process, photovoltaic-array capacity, the number or capacity of wind turbines, battery-bank capacity, diesel-generator capacity, and converter capacity were considered decision variables. The optimal values of these variables were determined according to the structure of each scenario and the HOMER Pro simulation results.

Not all variables were active in every scenario; for example, in Scenario 5, the diesel generator was not included in the system configuration and its capacity was therefore set to zero.

HOMER Pro simulates the performance of each configuration based on time-series data for electrical load and generation resources. During each time interval, energy generated by renewable sources is used to meet the load, and when surplus energy is available, it is used to charge the battery. Under generation-deficit conditions, the battery supplies part of the energy shortfall, and in scenarios incorporating a diesel generator, the diesel unit is dispatched as a backup source when stored energy is insufficient. Simulation outputs include indicators such as energy generation by each source, storage status, fuel consumption, and unmet load.

The principal economic criterion used to compare the configurations was net present cost (NPC). This indicator represents the present value of the total system costs over the study period and includes initial capital investment, equipment replacement, operation and maintenance, fuel, and equipment salvage value.

In addition to NPC, the levelized cost of energy (LCOE) was calculated to compare the average cost of electricity generation across the different configurations. LCOE is obtained by dividing the annualized system cost by the annual energy served.

The general form of net present cost can be expressed as follows:

$$NPC = C_{cap} + C_{rep} + C_{O\&M} + C_{fuel} - C_{salvage}$$

where:

C_{cap} is the initial capital investment cost,

C_{rep} is the equipment replacement cost,

$C_{O\&M}$ is the operation and maintenance cost,

C_{fuel} is the fuel cost, and

$C_{salvage}$ is the salvage value of the equipment at the end of the study period.

In addition to NPC, the LCOE indicator is used to compare the average electricity-generation cost.

$$LCOE = \frac{C_{annualized}}{E_{served}}$$

where $C_{annualized}$ is the annualized system cost and E_{served} is the annual energy served.

Technical Indicators

The HOMER Pro outputs formed the basis for the comparative evaluation of the six scenarios. The technical indicators included annual energy generation, renewable energy fraction, loss of power supply probability (LPSP), unmet load, capacity factor, excess energy, installed equipment capacity, and resource utilization. These indicators enable simultaneous assessment of the system's ability to meet the load, the extent of renewable-energy utilization, and dependence on backup sources.

Annual energy generation was calculated as one of the principal technical-performance indicators for comparing solar, wind, and diesel electricity generation across the different configurations. The numerical results for this indicator for all six scenarios are presented and analyzed in the Results section.

3. Findings and Results

This section presents the results of the scenario simulations conducted in HOMER Pro, together with the report and analysis of each scenario.

Results for Scenario 1

Scenario 1 consists of a photovoltaic system, lithium-ion battery, and power converter and does not include a diesel generator or grid connection. The optimal PV capacity was 4,733 kW, and the optimal battery capacity was 13,000 kWh. In this configuration, electricity is supplied by renewable energy and battery storage, resulting in a renewable energy fraction of 100%.

Costs

The initial capital cost, annual operation and maintenance cost, and periodic replacement costs of each system component, based on the 25-year cash-flow table provided in the HOMER output file, are presented below.

Table 4. Life-Cycle Cost Breakdown for Scenario 1

System Component	Life-Cycle Cost, NPC (USD)
PV	≈ 2,165,000

Battery	≈ 3,362,000
Converter	≈ 672,000
Total System	≈ 6,199,000

Results for Scenario 2

In Scenario 2, the optimal configuration consists of EWT DW 61 wind turbines, each with a rated capacity of 900 kW, Generic 100 kWh lithium-ion batteries, and a power converter. The optimal wind-farm capacity was 7,200 kW, and the optimal battery capacity was 13,600 kWh. The daily

load in this scenario was 13,574 kWh, with a peak demand of 1,815 kW. Given the absence of both a diesel generator and grid connection, electricity supply in this configuration is based on renewable energy and battery storage, resulting in a renewable energy fraction of 100%.

Table 5. Life-Cycle Cost Breakdown for Scenario 2

System Component	Life-Cycle Cost, NPC (USD)
Wind Farm	≈ 23,378,000
Battery	≈ 3,477,000
Converter	≈ 589,000
Total System	≈ 27,444,000

Results for Scenario 3

In Scenario 3, the optimal configuration consists of a 2,000-kW diesel generator, photovoltaic array, lithium-ion battery, and power converter. The optimal PV capacity was 4,063 kW, and the optimal battery capacity was 13,600 kWh.

The daily load was 14,098 kWh, with a peak demand of 1,815 kW. Renewable generation and storage were added to the existing diesel infrastructure to reduce fuel dependence and operating costs.

Table 6. Life-Cycle Cost (NPC) Breakdown for Scenario 3

System Component	Life-Cycle Cost, NPC (USD)
Diesel Generator	≈ 1,500,000
PV	≈ 1,859,000
Battery	≈ 3,509,000
Converter	≈ 698,000
Total System	≈ 7,567,000

Results for Scenario 4

In Scenario 4, a 900-kW wind turbine and lithium-ion battery were added to the existing 2,000-kW diesel generator. The objective of this scenario was to evaluate the effect of wind energy and battery storage on the performance and cost of the diesel-based system. The optimal configuration for Scenario 4 consists of a 2,000-kW diesel

generator, one EWT DW 61 wind turbine with a rated capacity of 900 kW, a lithium-ion battery with a capacity of 4,400 kWh, and a power converter. The daily load was 14,098 kWh, with a peak demand of 1,815 kW. In this configuration, the diesel generator plays a major role in directly supplying the load and reducing the required storage capacity.

Table 7. Life-Cycle Cost Breakdown for Scenario 4

System Component	Life-Cycle Cost, NPC (USD)
Diesel Generator	≈ 8,140,000
Wind Turbine	≈ 2,925,000
Battery	≈ 2,148,000
Converter	≈ 578,000

Results for Scenario 5

In Scenario 5, the optimal configuration consists of a 3,525-kW photovoltaic array, one 900-kW EWT DW 61

wind turbine, a 13,300-kWh lithium-ion battery, and a power converter. The daily load in this scenario was 13,866 kWh, with a peak demand of 1,815 kW. Given the absence of a

diesel generator and grid connection, electricity supply in this configuration relies on renewable resources and battery storage, and a renewable energy fraction of 100% was reported.

Results for Scenario 6

In Scenario 6, the optimal configuration consists of a 2,000-kW diesel generator, a 3,525-kW photovoltaic array,

one 900-kW EWT DW 61 wind turbine, a 10,300-kWh lithium-ion battery, and a power converter. The daily load in this scenario was 14,098 kWh, with a peak demand of 1,815 kW. In this configuration, the diesel generator is used as a backup source alongside renewable generation and battery storage.

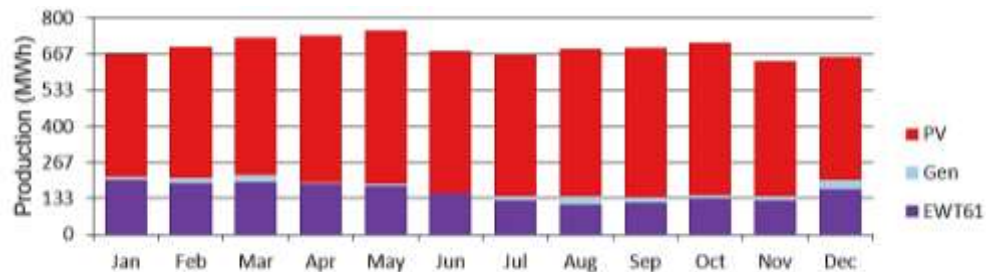


Figure 1. Annual Energy Generation Pattern

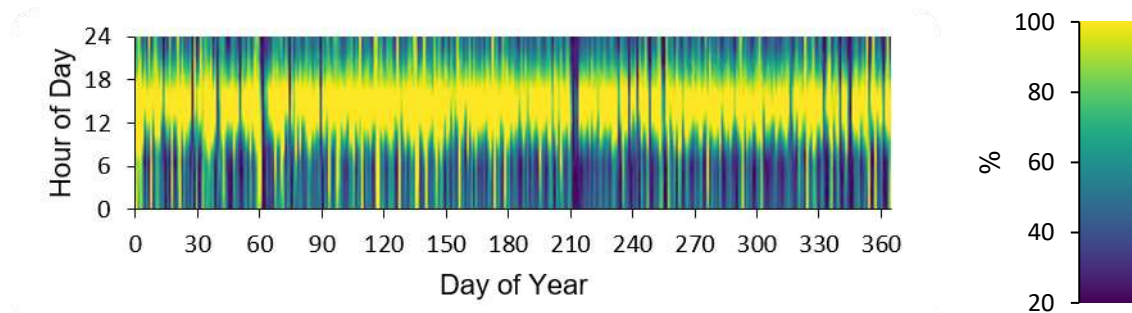


Figure 2. Variations in Battery State of Charge

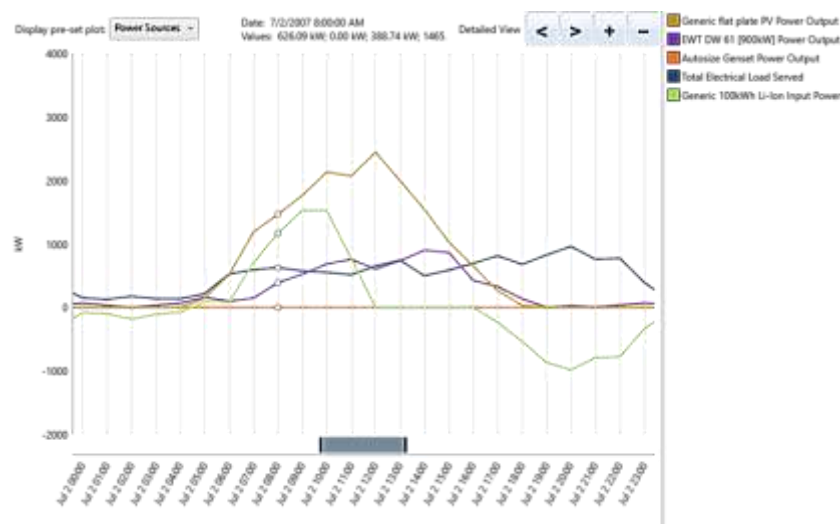


Figure 3. System Operation and Dispatch Pattern

Technical Analysis of the Results

In terms of capacity sizing, Scenario 2 has the highest renewable generation capacity; however, this increased

capacity results in substantially higher capital costs. In contrast, Scenario 4 has the smallest battery bank because the diesel generator directly supplies a large proportion of

the load. These differences indicate that, in off-grid system design, storage capacity depends on the role of the backup source and the renewable generation profile.

Annual Energy Generation

The simulation results indicated that the annual energy-generation profile differed according to the resource configuration in each scenario. Scenario 2, with annual wind generation of 15,046,386 kWh, had the highest total generation among all scenarios. In Scenario 1, PV generation was 8,347,769 kWh. In Scenario 6, renewable resources generated 8,098,486 kWh, whereas diesel generation was only 197,059 kWh; therefore, the role of the diesel generator in this configuration was limited.

Renewable Energy Fraction

Scenarios 1, 2, and 5 have a renewable energy fraction of 100%. This fraction reaches 97.6% in Scenario 6, whereas approximately two-thirds of the energy in Scenario 4 is supplied by the diesel generator. Therefore, among configurations incorporating backup generation, Scenario 6 has very limited operational dependence on fossil fuels.

Battery Performance

Battery autonomy in Scenarios 1, 2, 3, and 5 is approximately 18 hours, whereas it is 5.99 hours in Scenario 4 and 14 hours in Scenario 6. This difference indicates that, in diesel-assisted scenarios, the role of energy storage varies according to the degree of reliance on the backup source.

Diesel Generator Performance

Scenario 4 exhibits the greatest dependence on diesel generation and is substantially less favorable than the other two diesel-assisted configurations in terms of fuel consumption. Despite retaining a 2-MW generator, Scenario 6 obtains only 2.4% of its electricity generation from diesel and is therefore the most successful hybrid configuration incorporating backup generation in this respect. Scenario 3, with a diesel contribution of 7.3%, also achieves an acceptable balance between fossil-fuel backup and solar generation.

System Reliability

Because indicators such as the loss of power supply probability (LPSP) and unmet load were not explicitly reported in the baseline outputs for all scenarios, reliability assessment in this study was based on battery autonomy, PV penetration, resource diversity, and the presence of a backup source. Scenarios with approximately 18 hours of battery autonomy have adequate capacity to compensate for short-term fluctuations, while Scenarios 3, 4, and 6 also benefit from diesel backup. Scenario 1, with 17.7 hours of autonomy and PV penetration of 162%, demonstrates acceptable

performance based on the available indicators; however, before practical implementation, it should be validated against multi-day low-irradiance events using a direct LPSP measure.

Economic Analysis

The economic comparison of the scenarios was based on initial capital cost, life-cycle cost (NPC), levelized cost of energy (LCOE), fuel cost, and operation and maintenance (O&M) cost. Scenario 4 has the lowest initial capital cost, whereas Scenario 2 has the highest, primarily because of the high cost of the wind farm. Nevertheless, capital expenditure (CAPEX) alone is not an adequate criterion for system selection, and both recurring and life-cycle costs must also be considered.

Based on NPC, Scenario 1 is the least-cost option over the 25-year study horizon. Its NPC is approximately 22% lower than that of Scenario 3, 29% lower than that of Scenario 5, and nearly 55% lower than that of Scenario 6. Scenario 2, with an NPC of approximately USD 27.44 million, has a substantial economic disadvantage relative to the other configurations.

In terms of LCOE, Scenario 1 also has the lowest electricity-generation cost under the baseline load. Scenario 3 is only slightly more expensive, whereas the LCOE of Scenario 2 is estimated to be more than four times that of Scenario 1. These results indicate that, under the study conditions, the high cost of the wind-based system does not generate sufficient economic benefit to offset its initial investment requirement.

In the diesel-assisted scenarios, generator operating time is the principal factor explaining differences in fuel cost. Scenario 4 has the highest fuel cost, whereas in Scenario 6 this cost is limited to less than USD 9,000 per year. O&M costs also increase in scenarios incorporating more equipment, particularly a wind farm and diesel generator; in contrast, Scenario 1 has the lowest O&M cost.

Overall, based on life-cycle cost and energy-generation cost, Scenario 1 is the most economical configuration. Scenario 3, with an NPC approximately 22% higher than that of Scenario 1, represents a suitable option when diesel backup is required. Scenario 6, with a renewable energy fraction of 97.6% and limited diesel operation, is attractive in terms of reducing fuel dependence but has a higher life-cycle cost. Therefore, final system selection should reflect project priorities concerning cost, renewable energy fraction, and the need for diesel backup.

Environmental Analysis

Given fossil-fuel consumption and combustion-related pollutant emissions from diesel generators, environmental performance was considered one of the criteria for evaluating the study scenarios. Scenarios 1, 2, and 5 do not include diesel generators; therefore, according to the HOMER Pro outputs, direct fuel-combustion emissions during the operational phase are zero in these scenarios. In

contrast, Scenarios 3, 4, and 6 produce pollutant emissions because they incorporate diesel generators.

Environmental Comparison of the Scenarios

Annual pollutant emissions for the scenarios incorporating diesel generators are presented in the following table.

Table 8. Comparison of Annual Pollutant Emissions in Scenarios Incorporating Diesel Generators

Pollutant	Scenario 3	Scenario 4	Scenario 6
Carbon dioxide	1,622,516	2,536,827	142,078
Carbon monoxide	10,227	15,991	896
Unburned hydrocarbons	446	698	39.1
Particulate matter	62.0	96.9	5.43
Sulfur dioxide	3,973	6,212	348
Nitrogen oxides	9,608	15,022	841

Scenario 4 exhibits the highest emissions for all pollutants examined, whereas Scenario 6 has the lowest emissions among configurations incorporating diesel generation. Quantitatively, pollutant emissions in Scenario 6 are approximately 91% lower than those in Scenario 3 and approximately 94% lower than those in Scenario 4, demonstrating the decisive role of reduced diesel-generator operation in improving environmental performance.

Overall, Scenarios 1, 2, and 5 exhibit the most favorable performance in terms of direct combustion-related emissions during operation, whereas Scenario 6 has the lowest emissions among the configurations incorporating a fossil-fuel backup source. Therefore, increasing the renewable

energy fraction while reducing diesel-generator utilization can simultaneously reduce emissions and preserve the backup role of the fossil-fuel source.

To assess the robustness of the economic results, the sensitivity of the scenarios to changes in fuel price, discount rate, equipment cost, and electrical load was examined. This analysis enables evaluation of the extent to which economic indicators depend on changes in the principal model assumptions.

Among the six scenarios, only Scenarios 3, 4, and 6 incorporate diesel generators and consume fuel and are therefore sensitive to fuel-price changes; Scenarios 1, 2, and 5 do not consume fuel.

Table 9. Sensitivity Analysis Results for the Economic/Load Parameter: Effect of Changes in Fuel Price

Scenario	-30%	-15%	Baseline: USD 0.16/L	0.15	0.3	0.5
Scenario 3 — NPC (USD million)	7.48	7.52	7.57	7.61	7.65	7.71
Scenario 4 — NPC (USD million)	13.21	13.50	13.79	14.08	14.38	14.76
Scenario 6 — NPC (USD million)	8.96	8.98	8.99	9.01	9.03	9.05

Scenario 4 shows the largest change in NPC in response to changes in fuel price, which is consistent with its higher share of diesel generation, whereas Scenario 6 exhibits the lowest sensitivity because diesel accounts for only 2.4% of its electricity generation.

The baseline discount rate in the HOMER models was assumed to be 6%. The results obtained by varying this rate are presented in the following table.

Table 10. Sensitivity Analysis Results for the Economic/Load Parameter: Effect of Changes in the Discount Rate

Scenario	4%	Baseline: 6%	8%	10%
Scenario 1 — NPC (USD million)	6.60	6.20	5.89	5.66
Scenario 2 — NPC (USD million)	29.27	27.44	26.01	24.89
Scenario 3 — NPC (USD million)	8.15	7.57	7.12	6.77
Scenario 4 — NPC (USD million)	16.06	13.79	12.09	10.79
Scenario 5 — NPC (USD million)	9.27	8.72	8.29	7.96

Scenario 6 — NPC (USD million)	9.62	8.99	8.50	8.12
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An increase in the discount rate reduces NPC across all scenarios. Scenario 4 shows the greatest sensitivity; however, Scenario 1 remains the least-cost option throughout the entire range examined. Therefore, the overall ranking of the scenarios in terms of NPC remains stable.

In this analysis, capital costs—including equipment purchase, replacement, and salvage value—were varied within a range of −20% to +20% relative to the baseline value, while O&M and fuel costs were held constant.

Table 11. Sensitivity Analysis Results for the Economic/Load Parameter: Effect of Changes in Equipment Costs

Scenario	−20%	−10%	Baseline	+10%	+20%
Scenario 1 — NPC (USD million)	5.08	5.64	6.20	6.76	7.32
Scenario 2 — NPC (USD million)	22.78	25.11	27.44	29.78	32.11
Scenario 3 — NPC (USD million)	6.37	6.97	7.57	8.17	8.77
Scenario 4 — NPC (USD million)	12.39	13.09	13.79	14.49	15.20
Scenario 5 — NPC (USD million)	7.18	7.95	8.72	9.50	10.27
Scenario 6 — NPC (USD million)	7.54	8.27	8.99	9.72	10.45

Increasing capital costs increases NPC in all scenarios. This effect is more pronounced in configurations in which capital investment and equipment replacement account for a larger proportion of life-cycle cost.

The results of the LCOE sensitivity analysis with respect to changes in electrical load are presented in the following table.

Table 12. Sensitivity Analysis Results for the Economic/Load Parameter: Effect of Changes in Electrical Load

Scenario	80% Load	90% Load	100% Baseline Load	110% Load	120% Load
Scenario 1 — LCOE (USD/kWh)	0.122	0.109	0.098	0.089	0.081
Scenario 2 — LCOE (USD/kWh)	0.542	0.482	0.433	0.394	0.361
Scenario 3 — LCOE (USD/kWh)	PV + Diesel + Battery	0.128	0.115	0.105	0.096
Scenario 4 — LCOE (USD/kWh)	0.262	0.233	0.210	0.191	0.175
Scenario 5 — LCOE (USD/kWh)	0.169	0.150	0.135	0.123	0.112
Scenario 6 — LCOE (USD/kWh)	0.171	0.152	0.137	0.124	0.114

Assuming that system size and configuration remain fixed, increasing the load reduces LCOE, whereas decreasing the load increases it because fixed costs are distributed over a larger or smaller amount of generated energy. This analysis represents a scaling assessment; if the actual load changes, re-optimization of equipment capacities in HOMER would be necessary to determine the optimal configuration.

In summary, Scenario 1 achieved the lowest NPC and LCOE among the six alternatives while simultaneously attaining a renewable energy fraction of 100%. Scenario 3 is slightly more expensive but introduces a fossil-fuel backup layer through the addition of diesel generation. Scenario 6 also has the highest renewable energy fraction among the alternatives incorporating diesel, while its generator operates only to a very limited extent. These findings indicate that the “best” scenario depends on the definition of project priorities; nevertheless, based on the economic and

environmental criteria available in the study data, Scenario 1 represents the superior reference option.

Based on the available data, Scenario 1 is recommended as the selected configuration: a 4,733-kW PV array, a 13,000-kWh lithium-ion battery, and a 1,671-kW converter. Its principal advantage is the simultaneous achievement of an NPC of approximately USD 6.20 million, an LCOE of approximately USD 0.098/kWh, a 100% renewable energy fraction, and the elimination of fuel consumption and fuel costs. However, before a final implementation decision is made, multi-day low-irradiance events and the LPSP/unmet-load indicators should be examined.

The principal reasons for selecting Scenario 1 are its lowest life-cycle cost, lowest energy-generation cost, elimination of direct fuel dependence, full renewable energy fraction, low maintenance cost, and battery autonomy of nearly 18 hours. Nevertheless, this selection does not imply that the diesel-assisted scenarios should be disregarded;

Scenario 3 may be considered an alternative and more conservative option when fossil-fuel backup is mandatory.

For Goharan, the principal finding is that substantial solar capacity combined with energy storage can prevent routine dependence on diesel generation. Implementation of such a system requires careful design of the battery room, thermal management, electrical protection, maintenance accessibility, and a clearly defined strategy for managing storage capacity during periods of low solar irradiance.

The scenario configurations cannot be directly generalized to other off-grid villages because the optimal HOMER solution is highly dependent on the load profile, solar irradiance, wind conditions, fuel price, equipment costs, and local constraints. Nevertheless, the scenario-based framework used in this study is transferable, provided that climatic, economic, and load inputs are recalibrated for each locati

4. Discussion and Conclusion

The present study compared six hybrid renewable energy system configurations for off-grid electricity supply in Goharan, Bashagard, from technical, economic, and environmental perspectives. The findings indicated that Scenario 1, consisting of a 4,733-kW photovoltaic array, 13,000 kWh of lithium-ion battery storage, and a 1,671-kW converter, provided the most favorable overall performance under the baseline conditions. This configuration achieved a 100% renewable energy fraction, eliminated direct diesel-fuel consumption, and produced the lowest net present cost (NPC) and levelized cost of energy (LCOE) among the six configurations. Its NPC was approximately USD 6.20 million and its LCOE was approximately USD 0.098/kWh. These findings demonstrate that, under the solar-resource, load, and economic conditions considered for Goharan, a PV–battery configuration can satisfy off-grid electricity demand without routine dependence on fossil-fuel generation. This result is consistent with the general argument in the hybrid renewable energy literature that the economic attractiveness of autonomous systems depends strongly on matching the dominant local renewable resource with appropriately sized storage capacity [1, 3]. It also supports the broader conclusion that solar-based hybrid systems can be particularly competitive in regions where adequate solar irradiance permits high photovoltaic utilization and where storage can compensate for temporal mismatches between generation and demand [2, 4].

The superiority of Scenario 1 in terms of NPC is particularly important because the comparison was based on life-cycle cost rather than initial capital expenditure alone. Although some alternative configurations incorporated dispatchable diesel generation or diversified renewable resources, their additional components increased capital, replacement, operation, maintenance, or fuel expenditures. Scenario 1 had an NPC approximately 22% lower than Scenario 3, 29% lower than Scenario 5, and nearly 55% lower than Scenario 6. These differences illustrate why hybrid-system selection should be based on total life-cycle economics rather than equipment cost at the installation stage. Reviews of HOMER-based optimization studies have similarly emphasized that the lowest-capital-cost configuration is not necessarily the most economical over the project lifetime because fuel, maintenance, and replacement costs can materially alter the ranking of alternatives [5, 6]. The present findings therefore reinforce the usefulness of NPC as a comprehensive economic decision criterion for off-grid system planning.

The LCOE results were consistent with the NPC findings. Scenario 1 yielded the lowest LCOE at approximately USD 0.098/kWh under the baseline load, whereas Scenario 2 had an LCOE more than four times higher. Scenario 3 was only moderately more expensive than Scenario 1, suggesting that the addition of diesel backup may be economically acceptable when enhanced dispatchability is considered essential, but it is not the least-cost solution under the modeled baseline conditions. The comparatively poor economic performance of Scenario 2 can largely be attributed to the very high installed wind capacity required to satisfy demand reliably. Scenario 2 required 7,200 kW of wind capacity and 13,600 kWh of battery storage, which resulted in an NPC of approximately USD 27.44 million. This finding is consistent with previous evidence that wind-based autonomous systems are highly sensitive to local wind-resource quality, turbine economics, and capacity requirements, and that high installed capacity may offset the benefits of renewable generation when wind conditions are not sufficiently favorable [4, 8]. The result also confirms that renewable-resource abundance alone does not ensure economic optimality; resource quality, system sizing, and technology cost must be assessed jointly.

From a technical perspective, Scenario 2 produced the greatest annual amount of renewable electricity, with approximately 15.05 million kWh generated from wind. Nevertheless, its superior energy production did not translate into superior economic performance. This is an important

finding because it demonstrates that maximizing annual renewable production is not equivalent to optimizing the system. Excessive generation capacity may result in underutilization, curtailment, surplus energy, or unnecessarily high capital expenditure. HOMER-based optimization is designed precisely to evaluate such trade-offs by linking resource availability and system operation to economic criteria [7]. The present results therefore support the view that technical indicators must be interpreted alongside economic indicators rather than independently. A configuration may appear technically strong because of large renewable generation capacity but remain unattractive if the additional output does not justify the cost of installing and maintaining the required equipment [6].

The results for Scenario 5 further illustrate the importance of this trade-off. Scenario 5 combined PV, wind, and battery storage without diesel generation and achieved a renewable energy fraction of 100%, but its NPC was higher than that of Scenario 1. Although adding wind generation increased resource diversity and theoretically reduced dependence on a single intermittent resource, this benefit was accompanied by additional capital and maintenance requirements. The finding is consistent with studies emphasizing that hybridization is most advantageous when complementary renewable-resource profiles materially improve reliability or reduce storage requirements; otherwise, increasing the number of technologies may simply increase system complexity and cost [2, 4]. In Goharan, the modeled results suggest that the economic contribution of wind generation was insufficient to offset the added investment relative to the PV–battery configuration.

Among the systems incorporating a diesel generator, Scenario 6 showed the strongest overall technical and environmental performance. The system combined PV, wind, battery storage, and a 2,000-kW diesel generator, but diesel generation accounted for only approximately 2.4% of annual electricity production. The renewable energy fraction reached approximately 97.6%, indicating that the diesel generator functioned mainly as a backup rather than a primary generation source. This result is consistent with the rationale underlying hybrid renewable–diesel systems, in which the dispatchable generator is retained to improve reliability during periods of insufficient renewable production while renewable generation and storage minimize generator operating hours [9, 10]. The present findings indicate that this architecture can effectively preserve dispatchable backup while substantially reducing direct fossil-fuel dependence.

Scenario 3 also represented a relatively balanced diesel-assisted configuration. In this scenario, the diesel share was approximately 7.3%, substantially lower than in Scenario 4. Its NPC was approximately 22% higher than Scenario 1, but the presence of diesel backup provides an additional operational safeguard during prolonged renewable-energy shortages. This pattern is comparable with the findings of Ganjei et al., who showed that combining wind and solar resources with battery storage and diesel backup can reduce dependence on diesel while maintaining the technical adequacy of off-grid systems [9]. Likewise, the rural electrification analysis of Samatar et al. highlighted the value of configurations that achieve high renewable penetration without entirely sacrificing dispatchability [10]. Thus, although Scenario 3 was not the least-cost option in the present study, it may remain relevant where reliability requirements justify some additional cost.

Scenario 4 performed less favorably because of its comparatively high reliance on diesel generation. Approximately two-thirds of its electricity was supplied by the diesel generator, resulting in higher fuel expenditure and substantially greater emissions. Its battery autonomy was also only 5.99 hours, considerably lower than in the renewable-dominant configurations, reflecting the greater role of dispatchable generation in meeting the load. The result illustrates the functional substitution between storage and diesel backup: when the system relies more heavily on diesel generation, the required battery capacity may decrease, but this reduction is accompanied by higher fuel use and environmental burdens. This trade-off is consistent with the broader HRES literature, which describes battery storage and backup generation as partially substitutable flexibility resources with markedly different economic and environmental implications [2, 5]. In the present study, reduced storage requirements did not compensate for the higher operating costs and emissions associated with frequent diesel operation.

Battery autonomy was approximately 18 hours in Scenarios 1, 2, 3, and 5, whereas Scenario 6 provided approximately 14 hours and Scenario 4 only 5.99 hours. The relatively high autonomy in Scenario 1 is significant because it partly explains how a PV-only generation system can operate without diesel backup under the modeled conditions. Energy storage is essential in stand-alone solar systems because daytime generation must be shifted to periods when solar input is insufficient or absent. Theoretical and engineering analyses of solar systems have long emphasized the importance of matching storage capacity with the

temporal behavior of solar irradiance and demand [3]. The present results confirm this principle in a practical optimization context: sufficiently large battery storage enables high renewable penetration and reduced dependence on dispatchable fossil-fuel resources, although the economic implications of battery investment and replacement must also be considered.

The reliability interpretation should nevertheless be treated cautiously. Scenario 1 demonstrated favorable battery autonomy and a PV penetration of approximately 162%, but direct reliability indicators such as loss of power supply probability (LPSP) and unmet load were not consistently reported for all scenarios in the baseline outputs. Therefore, the finding that Scenario 1 is technically acceptable is based on indirect indicators rather than a complete probabilistic reliability assessment. This issue is particularly important for stand-alone systems because several consecutive days of low solar irradiance may challenge even a system that performs well under typical hourly or annual conditions. HOMER-based analyses are capable of evaluating such interactions at fine temporal resolution, but robust implementation requires that reliability constraints be explicitly included in system assessment [6, 7]. Consequently, Scenario 1 should be interpreted as the preferred configuration under the modeled assumptions rather than as evidence that diesel backup is unnecessary under every possible operating condition.

The environmental results strongly favored renewable-dominant configurations. Scenarios 1, 2, and 5 produced no direct fuel-combustion emissions during operation because they did not include diesel generators. Among the diesel-assisted systems, Scenario 6 had by far the lowest pollutant emissions. Compared with Scenario 3, its emissions were approximately 91% lower, and compared with Scenario 4, they were approximately 94% lower. These reductions closely correspond to the much smaller contribution of diesel generation in Scenario 6. The result supports the well-established relationship between higher renewable penetration, lower diesel operating time, reduced fuel consumption, and lower operational emissions in hybrid systems [2, 10]. It also demonstrates that retaining a diesel generator does not necessarily result in high emissions if renewable generation and storage are sufficiently sized to restrict diesel use primarily to backup operation.

The sensitivity analysis provides additional support for the robustness of the main economic findings. Increasing the discount rate reduced NPC across all scenarios, as would be expected because future expenditures are discounted more

heavily at higher rates. Nevertheless, Scenario 1 remained the lowest-NPC configuration throughout the investigated discount-rate range. This indicates that its economic superiority was not dependent on a single discount-rate assumption. Sensitivity analysis is particularly important in long-term hybrid-energy planning because investment decisions are exposed to uncertainty in financing conditions and future cost streams [6, 9]. The stability of Scenario 1 across different discount rates therefore increases confidence in its economic ranking within the modeled range.

Fuel-price sensitivity differed substantially across the diesel-assisted scenarios. Scenario 4 exhibited the largest NPC response to changing fuel prices, whereas Scenario 6 showed the smallest response. This finding is directly explained by their respective diesel-generation shares. A system that frequently operates its diesel generator is inherently more vulnerable to fuel-price fluctuations, whereas a renewable-dominant configuration with limited diesel use is largely insulated from such changes. Similar conclusions have been reported in sensitivity analyses of hybrid renewable–diesel systems, where the economic competitiveness of configurations shifts according to fuel consumption and fuel-price assumptions [9]. The present findings therefore show that reducing diesel dependence not only lowers emissions and routine fuel costs but also decreases exposure to fuel-price uncertainty.

Changes in equipment capital costs also affected all configurations, but the impact was strongest in systems with larger or more expensive renewable and storage capacities. Scenario 2 was particularly sensitive because of the high capital cost of the wind farm. This observation reinforces the broader conclusion that technology prices can materially influence the optimal structure of HRES configurations [5, 6]. As renewable and storage technologies continue to evolve, the economic ranking observed in the present study may change. For example, substantial reductions in wind-turbine or battery costs could improve the competitiveness of scenarios that are currently disadvantaged by high capital requirements.

The load sensitivity analysis showed that, when system size and configuration were held constant, LCOE decreased as load increased because fixed system costs were spread over a larger quantity of supplied electricity. Conversely, lower load increased LCOE. This result is consistent with the basic economics of capital-intensive energy systems, in which greater utilization of installed assets reduces average unit cost. However, this finding should not be interpreted to

mean that increasing demand inherently improves system performance, because a genuine increase in electricity consumption would require re-optimization of component capacities to maintain adequacy and reliability. This distinction is important in interpreting HOMER sensitivity results and is consistent with the emphasis in previous studies on re-evaluating configurations when load assumptions change substantially [7, 8].

Overall, the findings support the central conclusion that the optimal off-grid energy system is highly site-specific. Although hybrid renewable configurations have been shown to be technically and economically feasible in other rural areas of Iran, their optimal component combinations differ according to local renewable resources, demand patterns, and cost parameters [8, 9]. In the case of Goharan, the strong performance of the PV–battery configuration indicates that local solar conditions and the modeled economics favor solar generation supported by storage over more complex PV–wind or diesel-assisted alternatives. The present findings are also consistent with the technical and economic framework developed in the underlying work of Rashidi Mehrizi, which emphasizes cost-effective hybrid renewable solutions for off-grid electricity supply in the study context [11]. More broadly, the results confirm the value of scenario-based multi-criteria assessment because no single technical indicator, such as renewable fraction or annual energy generation, was sufficient to identify the preferred system. The most appropriate configuration emerged only when technical performance, life-cycle economics, storage behavior, fuel dependence, and environmental impacts were considered simultaneously.

This study has several limitations that should be considered when interpreting the findings. First, the analysis was based on modeled load and renewable-resource data and therefore may not fully represent short-term operational anomalies, unexpected demand peaks, prolonged low-irradiance periods, or extreme climatic events. Second, direct reliability indicators, particularly LPSP and unmet load, were not consistently available for all scenarios, limiting the ability to make a complete probabilistic comparison of supply adequacy. Third, the economic analysis was based on specified assumptions regarding equipment costs, discount rate, project lifetime, and fuel price, all of which may change over time. Fourth, the environmental analysis focused primarily on direct operational emissions from diesel combustion and did not include complete life-cycle emissions associated with manufacturing, transportation, installation, replacement,

recycling, or disposal of PV modules, wind turbines, batteries, and other equipment. Finally, the study was conducted for a single location, and the resulting optimal configuration should therefore not be generalized directly to other off-grid areas without recalibration of local resource, demand, and economic inputs.

Future studies should extend the deterministic sensitivity analysis by incorporating probabilistic uncertainty analysis and stochastic simulation of solar irradiance, wind speed, electricity demand, fuel prices, and equipment costs. Reliability assessment should explicitly include LPSP, unmet load, expected energy not served, and multi-day extreme-event simulations. Multi-objective optimization approaches could also be applied to identify Pareto-optimal solutions that simultaneously minimize NPC, LCOE, emissions, and reliability risk. Future research may further compare advanced storage technologies, including different lithium-ion chemistries, flow batteries, hydrogen storage, and hybrid storage architectures. Detailed degradation models for batteries and photovoltaic modules should also be incorporated. In addition, future analyses could examine demand growth, electric mobility, demand-side management, flexible loads, and intelligent energy-management strategies. Comparative studies across multiple rural locations would be valuable for identifying the climatic and economic thresholds under which PV–battery, PV–wind–battery, or renewable–diesel hybrid architectures become preferable.

For practical implementation in Goharan, planners should prioritize detailed engineering assessment of the PV–battery configuration identified as the preferred baseline option while validating its performance under prolonged low-solar conditions before final investment. The battery system should be designed with appropriate thermal management, ventilation, electrical protection, fire-safety measures, monitoring, and maintenance accessibility. Local operators should receive training in battery management, inverter operation, fault detection, preventive maintenance, and system monitoring. Procurement decisions should consider not only initial equipment prices but also warranties, replacement schedules, spare-part availability, after-sales support, and life-cycle costs. Where uninterrupted supply is considered critical, decision-makers may also evaluate a limited backup generator or other emergency source rather than relying exclusively on routine diesel operation. Finally, continuous monitoring of load growth, battery state of health, renewable generation, and system efficiency should be incorporated into the operational plan so that component

capacities and control strategies can be adjusted as local electricity demand evolves.

Authors' Contributions

Authors equally contributed to this article.

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Declaration of Interest

The authors report no conflict of interest.

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All procedures performed in this study were under the ethical standards.

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