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COMPARATIVE MULTI-CRITERIA PERFORMANCE ASSESSMENT OF BATTERY AND HYDROGEN-BASED ENERGY STORAGE SYSTEMS IN OFF-GRID HYBRID MICROGRIDS

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Abstract: This study comparatively analyzes the impacts of different energy storage approaches on the technical, economic, and environmental performance of off-grid hybrid renewable energy systems. System modeling and optimization were carried out using HOMER Pro software. Two alternative system configurations were evaluated under real resource data and a representative load profile. The first configuration included a hydrogen-based long-term storage infrastructure consisting of photovoltaic panels, a wind turbine, battery storage, an electrolyzer, a hydrogen tank, and a fuel cell. The second configuration was based solely on battery energy storage. The results demonstrate that the hydrogen-supported system increased renewable energy penetration to 84.7%, eliminated capacity shortages, fully met the load demand without interruption, and enabled long-term storage of surplus renewable energy. Although the battery-based system required lower initial capital investment and yielded a lower levelized cost of energy, it experienced a 5.2% capacity shortage and was unable to utilize 129,782 kWh of excess energy annually. A multi-criteria assessment conducted from a life-cycle cost perspective revealed that energy supply reliability and renewable energy utilization efficiency play a more decisive role in optimal system selection than approaches based solely on economic indicators. These findings indicate that hydrogen-based long-term energy storage infrastructure in off-grid settlements should be regarded not merely as a storage solution but as a strategic component that enhances energy security and sustainability.

Keywords: Hydrogen energy, Multi-layer energy storage, Off-grid hybrid energy system, Techno-economic optimization, HOMER Pro

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1. Introduction

The continuous growth of the global population, industrialization, and technological advancement has led to a steady increase in electricity demand worldwide. Meeting this demand predominantly through fossil fuel–based resources results in rising greenhouse gas emissions, acceleration of global climate change, and deepening environmental degradation. The significant adverse impacts of fossil fuels on the environment and human health during energy production, together with their limited reserves, have necessitated reassessing energy systems not only from an economic perspective but also in terms of environmental and social sustainability (Khan et al., 2022).

In this context, renewable energy sources have become key components of the energy transition due to their low carbon emissions, potential for local generation, and long-term sustainability. Solar and wind energy are increasingly utilized in electricity generation because of technological progress and declining investment costs. However, the intermittent and weather-dependent nature of these resources complicates the maintenance of energy supply security and makes it more difficult to preserve the balance between generation and consumption. This challenge becomes even more critical in rural and remote areas where access to the central grid is limited or economically infeasible. In such regions, access to energy is not only a technical requirement but also a decisive factor for economic development, quality of life, and social sustainability (Bhattacharyya, 2012; Kumar et al., 2023). For this reason, renewable energy–based off-grid hybrid systems stand out as a sustainable and viable solution for rural electrification (Pamuk, 2025).

The combined use of different generations and storage technologies in hybrid renewable energy systems provides a more balanced, flexible, and reliable energy production structure compared to single-source configurations. The seasonal and temporal variability of solar and wind resources indicates that these two sources exhibit a complementary generation profile. When this complementarity is supported by energy storage systems, it significantly contributes to the utilization of excess generation and to ensuring the continuity of energy supply (Jurasz et al., 2020). The general structure of an off-grid renewable energy system is illustrated in Figure 1.

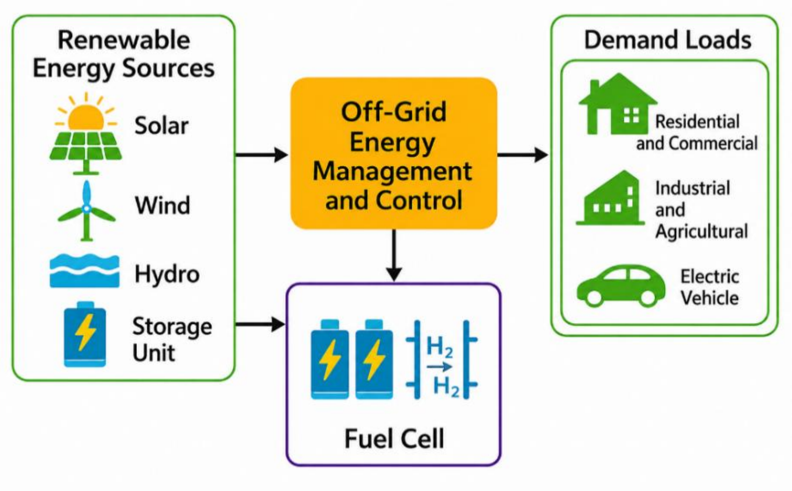

Figure 1. Off-grid renewable energy system configuration.

Energy storage technologies play a fundamental role in ensuring supply continuity and enhancing system stability in renewable energy-based power systems. Due to the inherent intermittency and variability of renewable sources, effective storage integration is essential to mitigate power fluctuations, maintain voltage and frequency stability, and improve overall system reliability. Among available storage solutions, battery energy storage systems are widely deployed for short-term balancing applications due to their high round-trip efficiency, rapid response, and technological maturity. They are particularly effective at smoothing short-duration power variations and supporting peak-load management.

However, despite these advantages, battery-based systems present important limitations, especially in off-grid applications. Their relatively limited storage duration, performance degradation over repeated charge-discharge cycles, and high replacement costs restrict their effectiveness in meeting prolonged energy deficits. In isolated systems where grid support is unavailable, these constraints may lead to capacity shortages or increased renewable energy curtailment, thereby reducing overall system efficiency.

Comparative studies in the literature examining battery and hydrogen-based storage technologies emphasize that while batteries offer superior efficiency and fast dynamic response in short-term applications, hydrogen-based systems provide distinct advantages in long-term and large-scale energy storage scenarios (Pellow et al., 2015). Hydrogen technologies, by integrating electrolyzers, storage tanks, and fuel cells, enable the conversion of surplus renewable electricity into hydrogen, which can be stored for extended periods with minimal self-discharge losses. Owing to their high energy density and long-duration storage capability, hydrogen systems are considered particularly suitable for seasonal energy management and deep decarbonization strategies. This distinction has significantly increased academic and industrial interest in hydrogen-based storage infrastructures for off-grid hybrid systems that require long-term energy security and high renewable penetration levels. In such configurations, hydrogen storage not only serves as an energy buffer but also helps improve renewable energy utilization rates and minimize curtailment losses. Hydrogen energy stands out as a strategic solution that enables excess electricity generated from renewable sources to be stored in the form of chemical energy through electrolysis and to be converted back into electrical energy by means of fuel cells when needed (Acar and Dincer, 2019; Kalinci et al., 2017). With this feature, hydrogen is considered not merely an energy storage medium but a critical component that enhances supply security and mitigates the intermittency problem in renewable energy systems.

Although numerous studies have been conducted on the optimal sizing and techno-economic analysis of hybrid renewable energy systems (Diaf et al., 2007; Ghasemi et al., 2013; Kumar et al., 2023), research addressing the impact of different storage approaches on off-grid system performance in a comparative and holistic manner remains limited. A significant portion of the existing literature focuses either on grid-connected systems or restricts the evaluation to purely economic optimization. In contrast, comparative off-grid analyses that simultaneously consider key performance indicators such as energy supply continuity, long-term utilization of excess renewable energy, and environmental performance are still scarce.

This study aims to fill this research gap by comprehensively evaluating battery and hydrogen-based storage approaches under identical conditions from technical, economic, and environmental perspectives. Islanded regions exhibit a fragile energy structure in terms of energy security due to their high dependence on external energy supply and limited local resources. The Turkish Republic of Northern Cyprus (TRNC) relies heavily on fossil fuel–based power generation yet possesses significant potential for renewable energy applications thanks to its high solar irradiation and favorable wind characteristics. The Koruçam region, selected as the case study area, provides a suitable test environment for assessing the feasibility of off-grid hybrid energy systems due to its remote location and limited infrastructure. The geographical location of the Koruçam region is presented in Figure 2.

Figure 2. Location map of the Koruçam region.

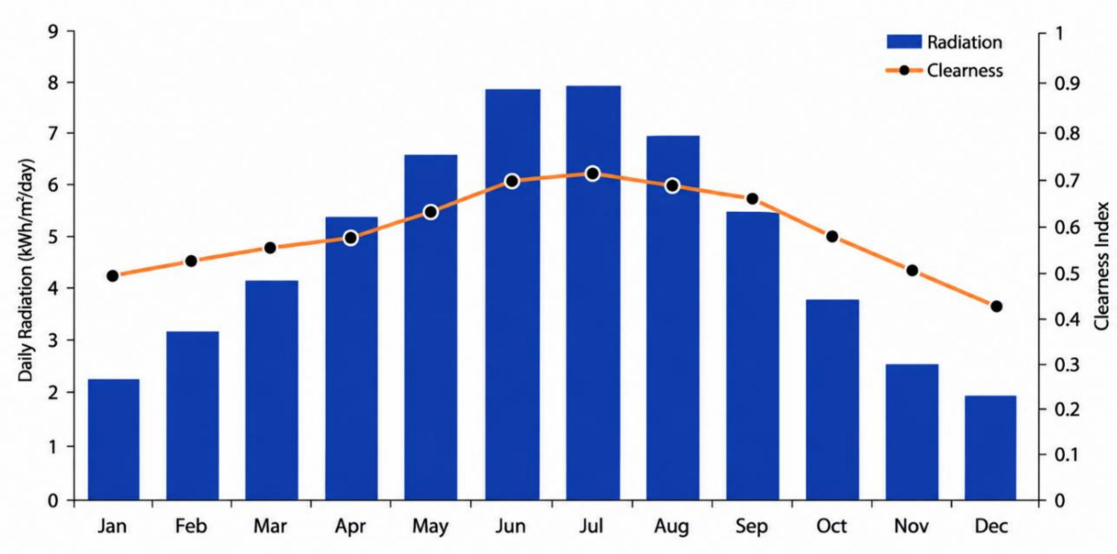

Figure 3. Monthly average solar radiation and clearness index.

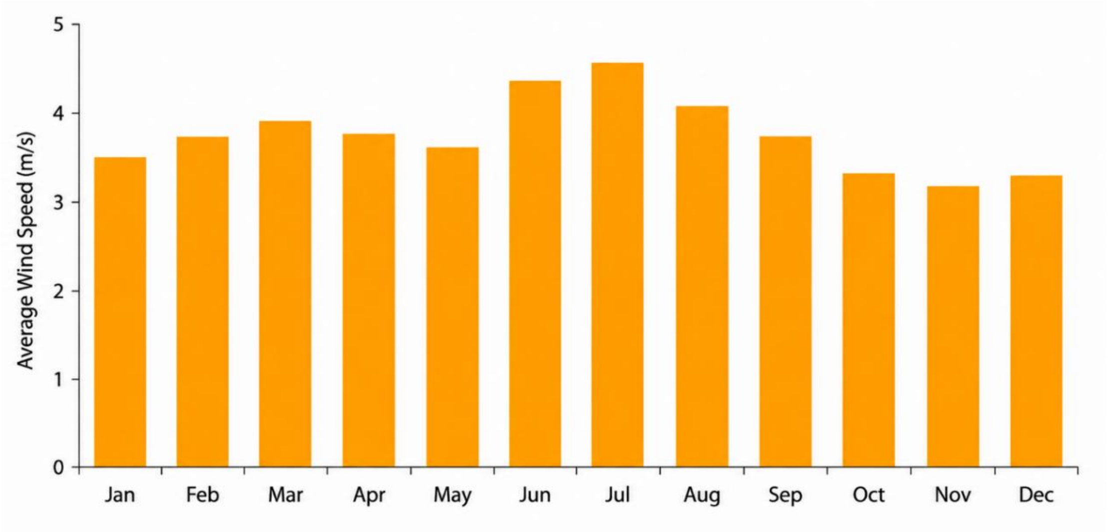

Figure 4. Monthly average wind speed.

Solar radiation, clearness index, and wind speed data for the study area were obtained from the NASA POWER database. The pronounced increase in the monthly average solar radiation during the summer months and the wind speeds remaining at levels capable of contributing to system generation throughout the year indicate that the region possesses a high potential for hybrid renewable energy systems. This potential is clearly illustrated in Figure 3, which presents the variation of the monthly average solar radiation and clearness index, and in Figure 4, which shows the monthly average wind speed values. The complementary seasonal behavior of solar and wind resources enables the provision of a continuous energy supply when supported by energy storage technologies (Jurasz et al., 2020).

The combined analysis of the technical and economic performance of hybrid energy systems requires advanced simulation and optimization techniques. HOMER Pro, which is widely preferred for this purpose, stands out as a powerful decision-support tool that enables the identification of the most suitable system configuration by analyzing different alternatives in terms of key performance indicators such as net present cost, levelized cost of energy, and renewable energy fraction (Ghasemi et al., 2013).

The main objective of this study is to comparatively assess the technical, economic, and environmental performance of a hybrid energy system consisting of photovoltaic panels, a wind turbine, battery storage, and a hybrid configuration incorporating hydrogen-based long-term energy storage for the Koruçam region of the Turkish Republic of Northern Cyprus. Within this scope, the systems were modeled and analyzed in the HOMER Pro environment using region-specific meteorological data and representative load profiles of rural settlements.

The findings are intended to reveal the impact of different storage approaches on the performance of off-grid hybrid energy systems and to contribute to the design of sustainable, reliable, and feasible energy solutions for islanded and remote areas. The results indicate that the hydrogen-based long-term energy storage infrastructure provides higher performance in terms of energy supply reliability and renewable energy utilization, whereas the battery-based system offers an economic advantage due to its lower levelized cost of energy.

2. Materials and Methods

In this study, the technical, economic, and environmental performances of off-grid hybrid renewable energy systems designed for the Koruçam region in the Turkish Republic of Northern Cyprus were comparatively analyzed using HOMER Pro software. Within the scope of the analysis, regional renewable energy resource data and a representative electrical load profile were defined as the primary input parameters, and two different system configurations incorporating alternative energy storage approaches were modeled. The system components were sized and optimized based on simulation-driven iterative calculations to determine the most feasible configuration under the defined constraints.

The output obtained from the optimization process was evaluated based on key performance indicators such as net present cost, levelized cost of energy, renewable energy fraction, and energy supply reliability. In addition, the environmental performance of the configurations was assessed through emission-related indicators provided within the simulation framework. The overall methodological flow of the modeling and optimization process followed in this study is presented in Figure 5.

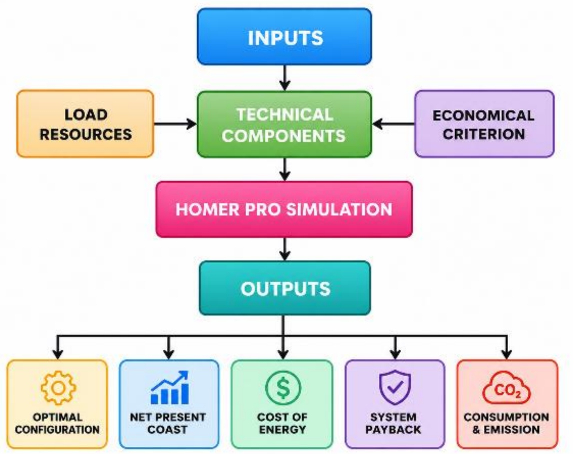

Figure 5. Flowchart of the HOMER Pro modeling and optimization process.

2.1. Description of the Study Area and Renewable Energy Dataset

The Koruçam region, selected as the study area, represents a suitable case for assessing the feasibility of off-grid energy systems due to its remote location from the central electricity grid, limited infrastructure, and significant local renewable energy potential. The monthly average solar radiation, clearness index, and wind speed data used in the system modeling were obtained from the NASA POWER database and defined as input parameters in HOMER Pro software for the calculation of hourly production values.

The solar energy potential of the region exhibits a pronounced seasonal variation throughout the year and reaches high levels, particularly during the summer months, which provides a significant advantage for photovoltaic generation. Wind speeds remaining at levels capable of contributing to system production over the entire year indicate that wind energy can be utilized as a complementary resource to support solar generation within the hybrid system structure. The temporally complementary nature of these two resources allows for the provision of a continuous energy supply when evaluated together with energy storage technologies.

2.2. Electrical Load Modeling

Since measured electricity consumption data for the study area were not available, the load profile was generated based on typical consumption patterns of rural settlements. The daily load curve was modeled by considering the increased demand during morning and evening hours, the reduced consumption at night, and the impact of cooling loads in the summer season. The representative daily electrical load profile defined in the HOMER Pro software is presented in Figure 6.

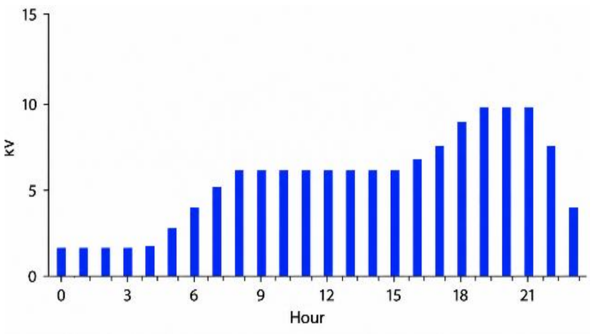

Figure 6. Sample daily electrical load profile defined in HOMER Pro software.

The generated load model was used as the primary reference input for the sizing of system components and for the comparative evaluation of the technical and economic performance of different system configurations. The constructed daily load curve was extrapolated to an annual scale to represent seasonal variations.

The average daily demand of 2,446 kWh was defined to represent the typical electricity consumption of a small rural settlement consisting of residential buildings and basic community facilities. The load profile reflects higher demand during morning and evening hours, while lower consumption levels occur during nighttime periods.

2.3. System Architecture and Scenario Definition

In this study, two different system configurations were developed to reveal the impact of alternative energy storage approaches on the performance of off-grid hybrid systems. In the first scenario, a battery-supported hydrogen-based long-term energy storage infrastructure was integrated into the system in addition to photovoltaic panels and a wind turbine. In the second scenario, the system architecture was simplified, and only a battery-based storage structure was considered. In this way, the effect of long-term energy storage capability on technical and economic performance was evaluated comparatively.

In both configurations, a hybrid structure including alternating current and direct current buses was preferred, and the energy flow between different generation and storage components was provided through a bidirectional power converter. The hybrid system configuration created in the HOMER Pro software is presented in Figure 7.

In the system operating strategy, the energy generated from renewable sources was primarily used to meet the load demand, the surplus energy was directed to battery storage and hydrogen production, and the storage units were dispatched in case of insufficient generation.

2.4. HOMER Pro Modeling and Optimization Approach

The HOMER Pro software simultaneously evaluates the defined load profile, renewable energy resource data, technical characteristics of system components, and economic parameters, simulates different system configurations, and determines the optimal solution. The simulations were performed with an hourly time step to represent the annual operating behavior.

During the optimization process, a search space including the capacity ranges for each component was defined, and all generated configurations were ranked according to their Net Present Cost (NPC) values. The levelized Cost of Energy (COE) and the Renewable Energy Fraction (REF) were used as supporting criteria for the evaluation of system performance. HOMER Pro software scanned all possible combinations within the defined search space and sorted the solutions based on the NPC. In addition to the technical characteristics of system components, key economic parameters were defined in the HOMER Pro model. The project lifetime was assumed as 25 years with a discount rate of 8%.

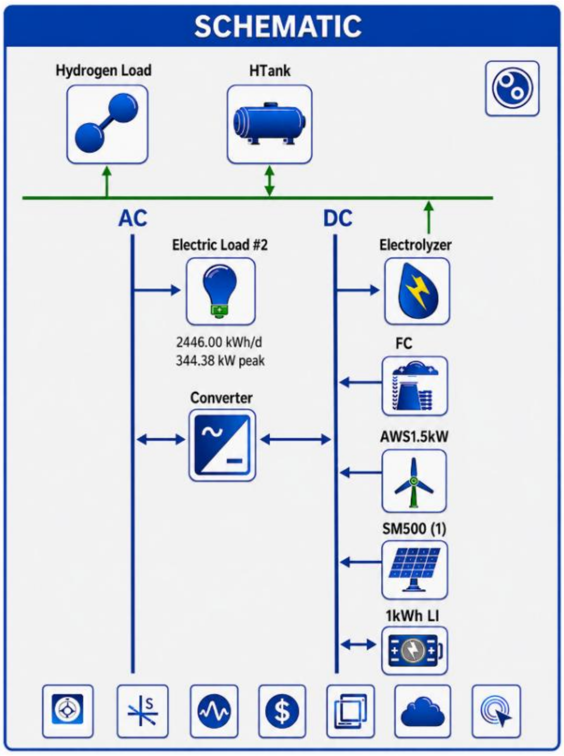

Figure 7. HOMER Pro–based hybrid system configuration.

The investment, replacement, and operation–maintenance costs of the photovoltaic panels, wind turbine, battery storage system, electrolyzer, fuel cell, and power converter were entered into the simulation environment based on values commonly reported in the literature.

2.5. Mathematical Model and Economic Performance Indicators

In the economic analysis, the project lifetime, discount rate, and the capital, replacement, and operation–maintenance costs of the system components were entered into the model through the economic inputs defined in HOMER Pro. Net Present Cost (NPC) and the levelized Cost of Energy (COE) were used as the primary decision criteria for evaluating the economic performance of the systems. The net present cost represents the total present value of all costs incurred over the project lifetime and is expressed by equation 1.

$$NPC = \sum_{t=0}^{N} \frac{C_t}{(1+i)^t} \quad (1)$$

In this equation, C_t represents the total system cost in year t, $i$is the discount rate, and Ndenotes the project lifetime. All economic calculations in the HOMER Pro simulation software are based on discounted cash flow analysis over the project lifetime. The levelized cost of energy is defined as the ratio of the total annualized cost to the total annual electrical energy production, as given in equation 2. Here, C_{annual} represents the total annualized cost, and E_{annual}denotes the total annual electrical energy production.

$$COE = \frac{C_{annual}}{E_{annual}} \quad (2)$$

The renewable energy fraction (REF) represents the ratio of electricity generated from renewable sources to the total electricity production of the system. REF, which is used to evaluate the environmental performance of the system, is defined as the ratio of the total electrical energy generated from renewable sources to the total electrical energy produced by the system and is calculated using equation 3. In this equation, E_{RES} represents the amount of energy generated from renewable sources, while E_{total} denotes the total electricity production.

$$REF = \frac{E_{RES}}{E_{total}} \times 100 \quad (3)$$

The loss of power supply probability (LPSP), which is used to determine the continuity of energy supply in off-grid systems, is defined as the ratio of the total unmet energy to the total load demand and is expressed by equation 4. In this equation, $E_{deficit}$ represents the amount of unmet energy, while E_{load} denotes the total electrical load.

$$LPSP = \frac{\sum E_{deficit}}{\sum E_{load}} \quad (4)$$

The energy production–consumption balance of the system is given by equation 5. In this equation, E_{PV}represents the energy generated by the photovoltaic panels, E_{WT} is the energy obtained from the wind turbine, E_{FC}denotes the energy supplied by the fuel cell, E_{load} represents the electrical load, and E_{loss} indicates the energy losses in the system.

$$E_{PV} + E_{WT} + E_{FC} = E_{load} + E_{loss} \quad (5)$$

The time-dependent state of charge (SOC) of the battery energy storage system is modeled by equation 6. In this equation, $SOC(t)$represents the state of charge at time t, E_{ch} is the amount of energy charged into the battery, E_{dis} denotes the energy discharged from the battery, and C_{bat} represents the nominal capacity of the battery.

$$SOC(t) = SOC(t-1) + \frac{E_{ch} - E_{dis}}{C_{bat}} \quad (6)$$

The hydrogen production process is modeled by equation 7 considering the electrolyzer efficiency η_{el}. Here, E_{excess} represents the surplus electrical energy generated in the system, while E_{H_2} denotes the energy equivalent of the produced hydrogen.

$$E_{H_2} = \eta_{el} \cdot E_{excess} \quad (7)$$

The reconversion of hydrogen into electrical energy through the fuel cell is expressed by equation 8 using the fuel cell efficiency η_{fc}.

$$E_{FC} = \eta_{fc} \cdot E_{H_2} \quad (8)$$

These equations are presented to provide a theoretical representation of the calculation methodology implemented in the HOMER Pro software.

2.6. Multi-Criteria Optimization Evaluation

All system configurations generated by the HOMER Pro software were ranked according to their net present cost (NPC) values, while the levelized cost of energy (COE), renewable energy fraction, and energy supply continuity indicators were used for the integrated assessment of technical and environmental performance.

Through this multi-criteria evaluation approach, not only the systems with the minimum cost but also the configurations that ensure high levels of renewable energy utilization and supply reliability were identified. This approach enables a more comprehensive assessment by simultaneously considering economic efficiency, energy sustainability, and system performance criteria. Accordingly, the analysis provides a balanced perspective that goes beyond purely cost-based optimization. In line with this methodological framework, the technical and economic performance results of the two different system scenarios are comparatively presented in the following section, allowing for a systematic evaluation of their relative advantages and overall feasibility.

3. Results

In this section, the simulation results of the off-grid hybrid energy system modeled in the HOMER Pro environment for the Koruçam region are presented based on two scenarios representing different energy storage approaches. In the first scenario, the system was supported by a hydrogen-based long-term energy storage infrastructure in addition to battery storage providing short-term balancing, whereas in the second scenario, the energy storage was limited to a battery-only configuration. In this way, the effects of short- and long-term storage technologies on system behavior, energy supply reliability, renewable energy penetration, and economic performance were comparatively evaluated.

3.1. Scenario 1 – PV–Wind–Hydrogen-Based Off-Grid Hybrid Microgrid

In this scenario, the system architecture was designed with a multi-layered storage approach capable of balancing the temporal variability of renewable energy generation not only on an hourly basis but also on a seasonal scale. Connecting the photovoltaic panels to the system through the DC bus enabled the electrolyzer to directly utilize surplus DC power, while the integration of the wind turbine via the AC bus ensured the simultaneous and coordinated operation of resources with different generation characteristics. The bidirectional converter positioned between the AC and DC buses acted as the main balancing component that managed the energy flow depending on the load demand and the state of the storage units. The installed capacities and rated power values of the optimal system components obtained from the HOMER Pro optimization are presented in Table 1.

Table 1. Optimum system components and capacity values for scenario 1

Component	Capacity / Value
PV array	730 kW
Wind turbine	300 kW
Electrolyzer	150 kW
Fuel cell	50 kW
Hydrogen tank	1,000 kg
Battery storage	750 kWh
Converter	267 kW
Electrical load	2,446 kWh/day

The installed capacity distribution indicates that the system was configured to avoid dependence on a single energy source. Directing the excess energy generated during periods of high photovoltaic production to the electrolyzer prevented curtailment and enabled long-term storage in the form of chemical energy. This mechanism eliminated the inability to utilize surplus generation commonly encountered in battery-based systems and became the main factor increasing the renewable energy fraction.

Within this configuration, the battery system was operated not as the primary storage unit but as a buffer that rapidly responded to short-term power imbalances. In this way, the number of battery charge–discharge cycles was reduced, deep discharge conditions were limited, and the operational lifetime of the storage components was extended. During prolonged periods of low generation, the energy stored in the hydrogen tank was reconverted into electricity through the fuel cell, ensuring an uninterrupted supply to the load demand. This energy management strategy resulted in a flexible system behavior that allowed the temporal shifting of the production–consumption balance.

The absence of capacity shortage in the simulation results demonstrates that the multi-layer storage approach can ensure energy supply continuity under off-grid operating conditions. The high renewable energy fraction indicates that the system effectively utilized excess generation and that the storage infrastructure played a decisive role in both reliability and renewable energy penetration. The considerable annual hydrogen production further shows that the system was able to establish a long-term energy reserve against seasonal variations in generation.

From an economic perspective, the hydrogen production and reconversion components increase the total initial investment cost. However, the absence of fuel cost and the fully renewable-based generation structure keep the life-cycle cost under control. This results in a predictable and sustainable economic structure in the long term despite the higher initial investment. Since no fossil fuel is used, the system exhibits a directly carbon-neutral operational characteristic. In this respect, scenario 1 not only provides a technically reliable energy supply but also demonstrates that a renewable-based local energy production model is fully compatible with sustainability targets.

3.2. Scenario 2: Hydrogen-Free PV–Wind–Battery Hybrid Configuration

In this scenario, the system architecture was simplified by removing the hydrogen production and reconversion components and was configured to rely on photovoltaic generation, a wind turbine, and battery storage. Although this structure provides a more compact configuration with a lower initial investment cost, it results in the entire energy balance being maintained by the battery system. The optimized capacity values of the system components for scenario 2 are presented in Table 2.

Table 2. Optimum system components and capacity values for scenario 2

Component	Capacity / Value
PV array	500 kW
Wind turbine	500 kW
Battery storage	1,750 kWh
Converter	227 kW
Electrical load	2,446 kWh/day
Peak load	344.38 kW

Increasing the battery capacity to 1,750 kWh was necessary to maintain energy continuity in a system without long-term storage infrastructure. However, due to the limited energy time-shifting capability of the battery-based storage structure, seasonal variations in generation could not be effectively balanced. The occurrence of capacity shortage during certain periods in the simulation results emerged as a direct consequence of this limitation.

The inability to store excess renewable generation for long durations was one of the main factors restricting system performance. The curtailment of surplus production limited renewable energy penetration and led to the underutilization of the installed capacity. This result indicates that although battery storage provides high efficiency for short-term power balancing, its flexibility in long-term energy management remains limited.

From an economic perspective, removing the hydrogen components significantly reduced the total initial investment cost and resulted in a lower levelized cost of energy. This shows that the battery-based system offers a more accessible solution from a short-term investment perspective. Nevertheless, the emergence of capacity shortage and the inability to utilize excess generation reveal that this economic advantage involves certain trade-offs in terms of technical performance.

Environmentally, the system maintains a low-emission characteristic since it is entirely based on renewable energy sources. However, the inability to store surplus renewable energy prevented the system from reaching its theoretically achievable carbon-neutral operational performance.

Overall, scenario 2 presents an economically attractive structure with a lower initial investment cost and lower levelized cost of energy; however, due to the absence of long-term storage infrastructure, it exhibits a more limited performance in terms of energy supply reliability and effective utilization of renewable energy.

3.3. Comparison of Technical Performance

To reveal the impact of hydrogen-based long-term storage and battery-only storage approaches on system performance, the scenarios were comparatively evaluated in terms of renewable energy utilization, capacity shortage, and surplus energy management indicators.

In terms of the renewable energy fraction, the hydrogen-supported system reached 84.7%, whereas this value remained at 78.2% for the battery-based configuration. This difference indicates that a larger portion of the energy generated from renewable sources could be utilized within the system due to the ability to store surplus production in the form of hydrogen. In the hydrogen-free scenario, the excess generation that could not be stored was curtailed, which limited the overall renewable energy penetration. Therefore, long-term storage infrastructure plays a decisive role not only in ensuring energy continuity but also in improving the effective utilization of renewable energy.

In terms of energy supply reliability, the most significant difference between the two scenarios emerges in the capacity shortage values. While the hydrogen-supported system fully met the load demand throughout the year without any capacity shortage, the battery-based system exhibited a capacity shortage of 5.2%. Despite increasing the battery capacity, the system was unable to ensure an uninterrupted supply during prolonged periods of low renewable generation. This outcome indicates that short-duration storage technologies have limited capability in addressing seasonal or extended energy deficits.

In contrast, the hydrogen storage infrastructure was able to preserve surplus energy over extended periods and effectively compensate for consecutive low-generation intervals. By enabling long-term temporal shifting of renewable energy, the hydrogen-supported configuration ensured a continuous power supply and significantly enhanced overall system reliability. These findings highlight the structural advantage of hydrogen-based storage in off-grid systems where energy security is a primary concern.

From the perspective of surplus renewable energy management, a structural difference exists between the scenarios. In the hydrogen-based system, excess generation was directly directed to the electrolyzer, resulting in an annual hydrogen production of 27,772 m^3. This energy was later reconverted into electricity through the fuel cell and made available for use within the system. In this way, temporal shifting of the generated energy became possible, and a long-term energy reserve capable of balancing seasonal production–consumption mismatches was established. In the battery-based system, although an annual excess electricity production of 129,782 kWh occurred, this energy could not contribute to system performance due to the lack of long-term storage. This result clearly shows that, despite its high efficiency, battery storage has limited energy time-shifting capability. In terms of the total served load, the battery-based system was able to meet 94.8% of the annual demand, whereas the hydrogen-supported system supplied the entire load without interruption. This difference demonstrates that under off-grid operating conditions, long-term storage infrastructure is not merely a storage component but a strategic reliability mechanism ensuring system continuity.

When all technical indicators are evaluated together, it is understood that the battery-based system provides adequate performance for short-term power balancing but offers limited flexibility against seasonal variations in generation. The hydrogen-supported hybrid configuration, on the other hand, enabled higher renewable energy penetration by storing excess renewable energy, eliminated the capacity shortage, and exhibited a more stable operating characteristic for off-grid systems by meeting the entire load demand without interruption. The comparison of renewable energy fraction served load, and capacity shortage values for the scenarios is presented in Figure 8.

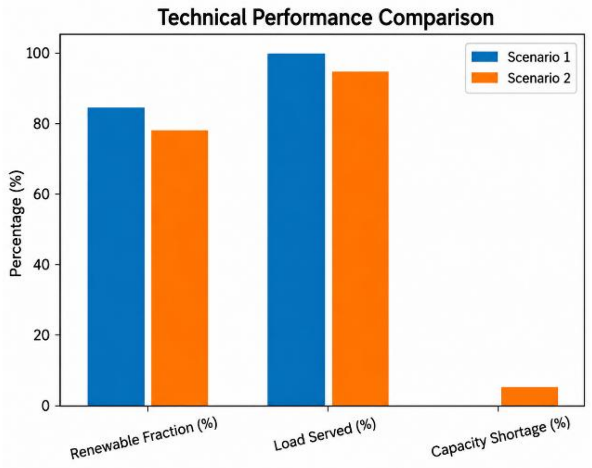

Figure 8. Comparison of technical performance indicators for scenario 1 and scenario 2.

3.4. Economic Performance Comparison of the Scenarios

In the economic comparison of the scenarios, net present cost (NPC), initial capital cost, annual operation and maintenance (O&M) cost, and levelized cost of energy (COE) were considered as the main evaluation criteria. The results indicate that the storage technology integrated into the system architecture directly determines not only the technical performance but also the life-cycle cost structure. For scenario 1, which includes hydrogen-based long-term energy storage infrastructure, the net present cost was calculated as 3.89 M$, whereas this value remained at 2.73 M$ for scenario 2 with the hydrogen-free battery-based configuration. This corresponds to an approximately 29.8% higher total cost, mainly due to the high initial investment requirements of the electrolyzer, hydrogen tank, and fuel cell components. Accordingly, the initial capital cost was obtained as 3.04 M$ for scenario 1 and 1.89 M$ for scenario 2, clearly demonstrating the decisive impact of the hydrogen infrastructure on the total investment cost. The comparison of the initial capital costs is presented in Figure 9.

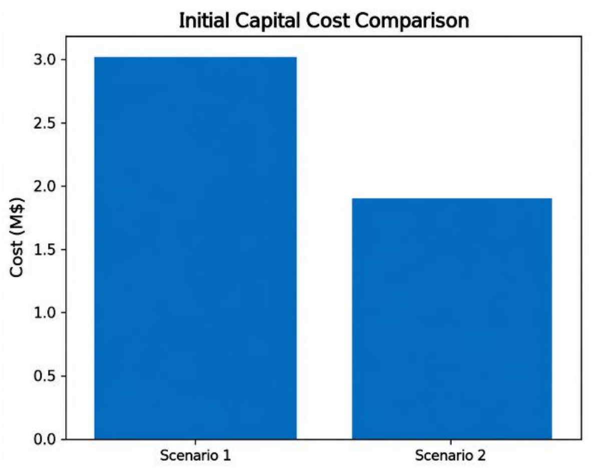

Figure 9. Initial capital cost comparison of scenario 1 and scenario 2.

The annual operation and maintenance costs were calculated as 34,625 $/year for scenario 1 and 25,992 $/year for scenario 2. This difference arises from the additional operational requirements of the hydrogen production and reconversion components and reveals the direct relationship between system complexity and operating costs. The comparison of the annual operation and maintenance costs is presented in Figure 10.

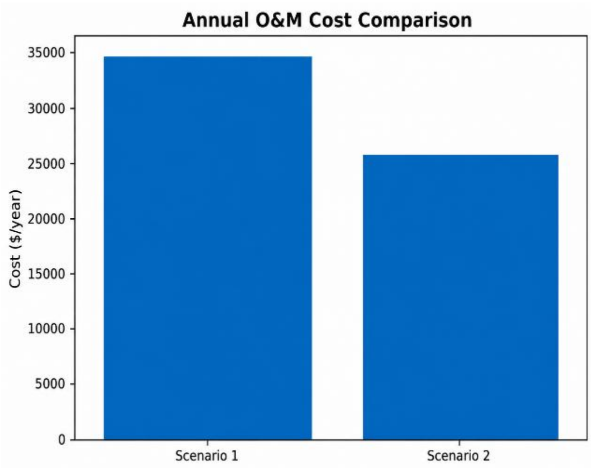

Figure 10. Annual operation and maintenance cost comparison of scenario 1 and scenario 2.

Although the inclusion of hydrogen components increased the operating costs to a certain extent, the absence of fuel cost in both systems kept the total operating expenditure at relatively low levels. This demonstrates that renewable energy-based off-grid systems provide a significant advantage in terms of long-term economic predictability compared to fossil-fuel-based alternatives.

The evaluation based on the levelized cost of energy makes the difference in the economic approaches of the two systems more apparent. The COE value calculated as 0.192 $/kWh for the battery-based scenario 2 increased to 0.275 $/kWh in the hydrogen-supported scenario 1. From a short-term investment perspective, this result indicates that the hydrogen-free system offers a lower-cost electricity generation structure. However, when this cost advantage is considered together with the technical performance indicators, a different interpretation emerges. Despite the lower NPC and COE values obtained in scenario 2, the occurrence of a 5.2% capacity shortage and the inability to utilize the annual excess energy of 129,782 kWh within the system show that economic performance should be evaluated together with energy supply reliability and effective renewable energy utilization. In scenario 1, on the other hand, the absence of capacity shortage, the possibility of storing excess energy in the form of hydrogen and reusing it when needed, and the uninterrupted supply of the load throughout the year stand out as factors that directly increase the economic value of the system in terms of long-term operational reliability, despite the higher investment cost.

These results clearly reveal that an assessment based solely on the levelized cost of energy is not sufficient for off-grid systems. The energy continuity provided by long-term storage infrastructure, the prevention of interruption-related indirect costs, and the more effective utilization of renewable generation contribute to a more sustainable economic structure over the life cycle of the hydrogen-supported system. The comparison of the net present cost and levelized cost of energy values for scenario 1 and scenario 2 is presented in Figure 11.

A comprehensive comparison of the technical, economic, and environmental performance indicators of scenario 1 and scenario 2 is presented in Table 3.

3.5. Determination of the Optimal System Configuration

In determining the optimal configuration of the hybrid microgrid system, the evaluation was not limited to a single economic parameter such as the levelized cost of energy (COE) or the net present cost (NPC). Instead, system performance was assessed comprehensively within a multi-criteria framework that incorporated technical reliability, renewable energy utilization efficiency, capacity shortage levels, and surplus energy management. This holistic approach clearly demonstrates that, particularly in off-grid energy systems, economic indicators alone are insufficient as decision-making criteria. Reliability of supply and effective resource utilization play equally critical roles in ensuring long-term system viability.

An examination of the life-cycle cost curve obtained from the HOMER Pro optimization results reveals that the system incorporating hydrogen-based long-term storage infrastructure presents a higher initial capital investment but offers a more predictable and stable cost structure over the project lifetime. The cumulative cost variation illustrated in Figure 12 shows that, despite the capital-intensive nature of the early investment phase, the absence of fuel expenses and the ability to maintain an uninterrupted renewable energy supply contribute to balancing the overall economic performance during the operational period. Moreover, the reduction of capacity shortages and improved renewable energy penetration minimizes indirect costs associated with supply interruptions and energy curtailment. From a life-cycle perspective, these factors collectively indicate that systems with higher upfront investment costs may provide a more sustainable and resilient economic structure in the long term. Consequently, evaluating hybrid microgrid configurations through an integrated performance lens allows for a more realistic and strategically sound assessment of optimal system design.

Although the battery-based system provides a short-term economic advantage with lower NPC (2.73 M$) and lower COE (0.192 $/kWh), the 5.2% capacity shortage and the inability to utilize the annual excess energy of 129,782 kWh within the system constitute a critical limitation in terms of energy supply continuity. In contrast, the absence of capacity shortage in the hydrogen-supported system, the possibility of storing surplus renewable generation in the form of hydrogen and reusing it when needed, and the uninterrupted supply of the load throughout the year significantly enhanced system reliability. The renewable energy fraction reaching 84.7% further indicates the superior performance of this configuration in terms of effective energy utilization.

These technical advantages provided by the long-term storage infrastructure directly contribute to economic value by eliminating interruption-related indirect costs, increasing energy supply reliability, and enabling a more predictable system operation. Therefore, the selection of the optimal system was not based solely on the configuration with the lowest COE, but on a combined assessment of energy continuity and effective renewable energy utilization over the entire life cycle.

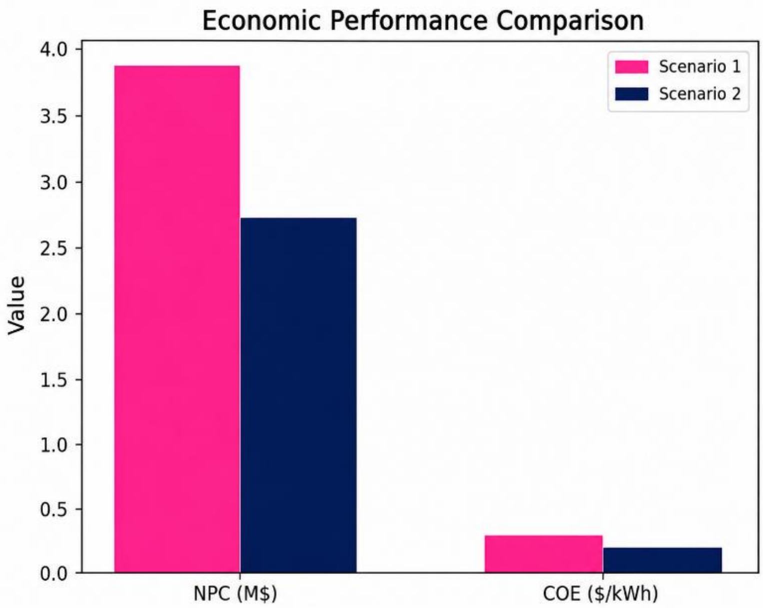

Figure 11. Economic performance comparison of the two scenarios based on NPC and COE.

Table 3. Overall technical, economic and environmental performance comparison of the proposed scenarios

Parameter	Scenario 1PV–WT–Battery–Hydrogen	Scenario 2PV–WT–Battery
Installed PV capacity	730 kW	500 kW
Installed wind capacity	300 kW	500 kW
Battery capacity	750 kWh	1,750 kWh
Electrolyzer capacity	150 kW	–
Fuel cell capacity	50 kW	–
Hydrogen storage	1,000 kg	–
Converter capacity	267 kW	227 kW
Average electrical load	2,446 kWh/day	2,446 kWh/day
Peak load	344.38 kW	344.38 kW
Renewable energy fraction	84.7 %	78.2 %
Capacity shortage	0 %	5.2 %
Served load	100 %	94.8 %
Excess electricity	Utilized for H_2 production	129,782 kWh/year (unused)
Annual hydrogen production	27,772 m^3	–
Net present cost (NPC)	3.89 M$	2.73 M$
Initial capital cost	3.04 M$	1.89 M$
Annual OandM cost	34,625 $/year	25,992 $/year
Cost of energy (COE)	0.275 $/kWh	0.192 $/kWh
Fuel cost	0	0
Direct emissions	0	0
Long-term energy storage	Yes	No
Energy supply reliability	Very high	Limited

Within this framework, scenario 1, which includes hydrogen-based long-term storage infrastructure, was identified as the optimal system configuration from a technical and operational perspective, as it provides zero capacity shortage, higher renewable energy penetration, effective utilization of surplus energy, and uninterrupted energy supply despite its higher initial investment cost. This result demonstrates that, for off-grid systems, energy continuity is a more critical design criterion than economic optimization alone. Consequently, scenario 1 represents a more appropriate solution not only in technical terms but also in terms of long-term economic sustainability. These findings indicate that for islanded and off-grid settlements, long-term energy storage infrastructure is not merely a technical design preference but a strategic necessity for ensuring energy supply reliability and long-term economic sustainability.

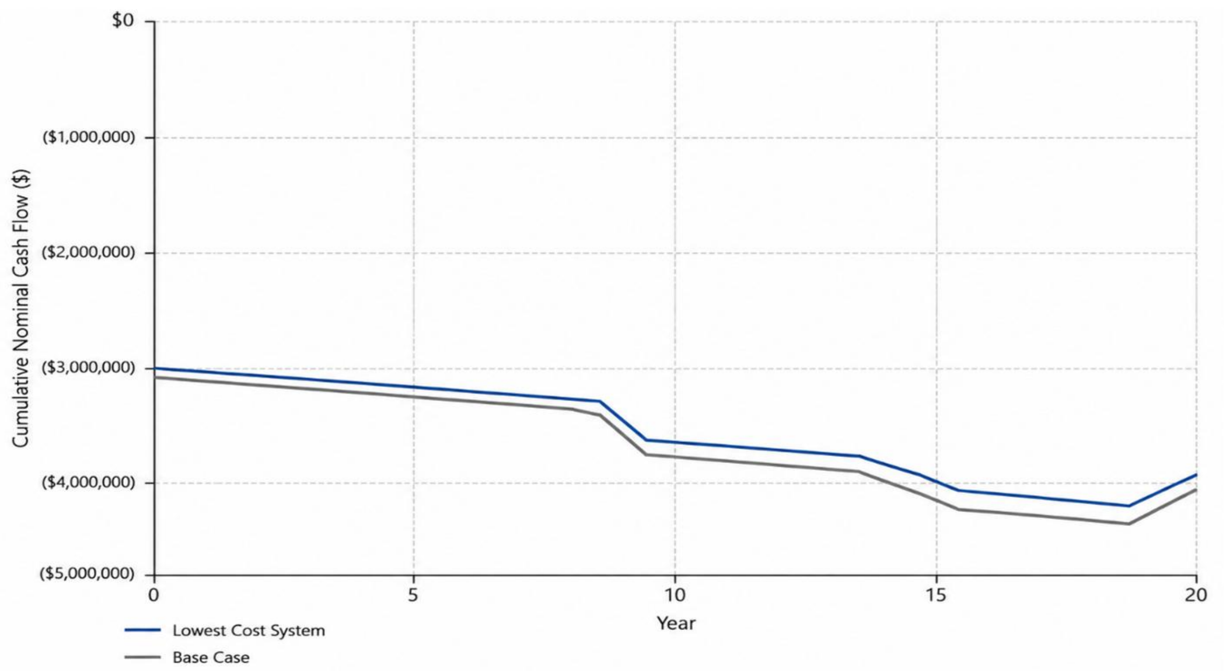

Figure 12. Cumulative net present cost comparison of the optimized system and the base case over the project lifetime.

3.6. Interpretation of the Results

When the results obtained in this study are evaluated together with the literature investigating the effects of different storage technologies on the technical and economic performance of off-grid hybrid energy systems, several important implications emerge. The increase in renewable energy utilization and the elimination of capacity shortage achieved by the hydrogen-based long-term storage infrastructure are consistent with studies emphasizing the temporal impact of energy storage technologies on system behavior. Hybrid storage structures have been shown to enhance system flexibility by simultaneously balancing short- and long-term energy dynamics, and the multi-layer storage performance obtained in this study confirms this approach (Bocklisch, 2015). The occurrence of capacity shortage and the inability to utilize excess renewable generation in the battery-only configuration indicate that, despite their high efficiency, batteries have limited energy time-shifting capability. This finding is in line with studies reporting that batteries are effective for short-term power fluctuation mitigation but remain insufficient for managing seasonal variations in generation (Khalid and Savkin, 2010). In contrast, the ability of the hydrogen storage infrastructure to preserve surplus energy for long durations and make it reusable overlaps with studies demonstrating that power-to-gas-based storage systems provide a strategic solution, particularly in systems with high renewable energy penetration (Gahleitner, 2013).

The higher renewable energy fraction obtained in the hydrogen-supported system shows that storage technologies are decisive not only for energy continuity but also for the effective utilization of renewable energy. It has been emphasized that integrating different storage technologies into operational strategies can improve system performance, and the energy management approach adopted in this study clearly reveals the impact of such strategies on an off-grid system (Lund et al., 2009).

From an economic perspective, the high initial investment cost of hydrogen production and reconversion components is consistent with the literature on the cost structure of energy storage technologies. It has been reported that although long-term storage technologies have high capital costs, their contribution to system reliability and energy continuity directly affects the life-cycle cost (Zakeri and Syri, 2015). In this study, the elimination of capacity shortage and the effective utilization of surplus energy despite the higher NPC value support this life-cycle perspective.

The contribution of hydrogen production and reconversion to system performance is also consistent with comprehensive assessments demonstrating that hydrogen can be used as a versatile energy carrier in energy systems (Nikolaidis and Poullikkas, 2017). The operation of the hydrogen storage infrastructure in this study not only as a storage component but also as a seasonal energy reserve confirms the strategic role of hydrogen in renewable-based systems.

Overall, the findings indicate that the hybrid storage approach provides superior system behavior not only in terms of technical performance but also in terms of long-term economic sustainability. This result shows a high level of agreement with the literature reporting that energy systems integrating multiple storage technologies offer a strong solution for future off-grid applications with high renewable energy penetration.

In a large portion of the existing studies, hydrogen systems are mostly evaluated within grid-connected structures, or the analyses are limited to economic optimization criteria. In this study, however, a multi-criteria and holistic evaluation was carried out for an off-grid hybrid microgrid by considering energy continuity, effective renewable energy utilization, surplus energy management, and life-cycle cost structure. Within this framework, hydrogen was modeled not only as an alternative storage component but as a seasonal energy balancing mechanism that directly determines system reliability.

The obtained results clearly demonstrate that the optimal system configuration cannot be determined solely based on minimum levelized cost of energy (COE) or net present cost (NPC) values. The decisive role of long-term storage infrastructure in achieving zero capacity shortage and uninterrupted energy supply under off-grid operating conditions has been quantitatively revealed. In this respect, the study presents a holistic decision-making approach for the design of renewable energy-based off-grid hybrid systems and provides an original contribution to the literature by numerically demonstrating the technical and economic impact of multi-layer energy storage integration under real load and resource data.

3.7. Environmental Performance Assessment of the Scenarios

Since both scenarios were designed to operate entirely based on renewable energy sources, no direct carbon emissions are produced during the operational phase. This indicates that the systems provide an environmentally sustainable energy production structure compared to fossil-fuel-based alternatives. However, the type of storage technology used directly affects the effective utilization of renewable energy within the system and therefore determines the indirect environmental performance.

In scenario 1, which includes hydrogen-based long-term storage infrastructure, the entire renewable generation could be utilized within the system by storing the surplus production in the form of hydrogen through the electrolyzer. This approach not only ensured the continuity of energy supply but also increased the renewable energy fraction and strengthened the carbon-neutral operational characteristic of the system. The ability to establish a long-term energy reserve positively affected the environmental performance by eliminating the need for external energy sources, especially during low-generation periods.

In battery-based scenario 2, the inability to store excess renewable generation for long durations resulted in 129,782 kWh of energy remaining unused annually. This caused the system to operate below its theoretically achievable renewable energy utilization level and limited the efficiency of resource use. Therefore, although no direct emissions occur, the incomplete utilization of renewable generation represents a relative environmental disadvantage.

Overall, scenario 1 exhibits superior environmental performance due to the effective utilization and reuse of surplus renewable energy and the elimination of capacity shortage. This result demonstrates that long-term energy storage infrastructure is a critical component not only from technical and economic perspectives but also for the effective use of renewable energy resources and sustainable energy production. It should be noted that the environmental assessment in this study focuses only on operational-phase emissions. Life-cycle emissions associated with the manufacturing and disposal of system components were not included in the scope of this analysis.

4. Discussion

This section provides a broader interpretation of the results by focusing on the implications of the findings for off-grid hybrid energy system design, while the previous section primarily compared the obtained results with existing literature. The findings of this study clearly demonstrate the decisive role of the storage technology used in off-grid hybrid energy systems on overall system behavior. The complete elimination of capacity shortage and the increase in the renewable energy fraction achieved by the hydrogen-based long-term storage infrastructure are consistent with studies showing that multi-layer storage structures enhance system flexibility (Bocklisch, 2015). In contrast, although the battery-based system provided adequate performance in balancing short-term power fluctuations, its inability to manage seasonal variations in generation confirms the literature indicating the limited energy time-shifting capability of batteries (Khalid and Savkin, 2010).

The capability of the hydrogen storage infrastructure to preserve surplus renewable energy for long periods and make it reusable agrees with studies emphasizing that power-to-gas-based systems provide a strategic solution in configurations with high renewable energy penetration (Gahleitner, 2013). This approach not only improves energy continuity but also enables more effective utilization of renewable generation within the system. It has been highlighted in the literature that system performance can be significantly enhanced when storage technologies are evaluated together with appropriate operational strategies (Lund et al., 2009), and the energy management approach implemented in this study provides a quantitative demonstration of this effect in an off-grid system.

From an economic perspective, the high initial investment cost associated with hydrogen production and reconversion components is consistent with studies on the cost structure of energy storage technologies (Zakeri and Syri, 2015). However, the elimination of capacity shortage and the possibility of reusing surplus energy emerge as the main factors that increase the economic value of the system from a life-cycle perspective. This finding shows that the optimal configuration in off-grid energy systems cannot be determined solely based on minimum COE or NPC values and that energy supply reliability should be considered as a primary design criterion in the decision-making process.

The operation of hydrogen as a component forming a seasonal energy reserve within the system is also consistent with comprehensive assessments demonstrating its role as a versatile energy carrier in energy systems (Nikolaidis and Poullikkas, 2017). In this respect, hydrogen appears not only as an alternative storage technology but also as a strategic balancing mechanism that ensures continuity in renewable energy-based off-grid systems. The obtained results indicate that for islanded and isolated settlements, long-term storage infrastructure is a critical design parameter not only in terms of technical performance but also for energy security and economic sustainability. This outcome reveals that the design approach for off-grid systems with high renewable energy penetration is evolving from short-term cost minimization toward long-term operational reliability. Future studies considering different load profiles, variable hydrogen equipment costs, and grid-connected operating scenarios will further contribute to the development of decision-making processes for hybrid system design.

5. Conclusion

This study models an off-grid hybrid energy system for the Koruçam region using HOMER Pro and comparatively evaluates the effects of battery-based short-term storage and hydrogen-supported long-term storage on overall system performance. The findings clearly demonstrate that energy storage technology should not be considered merely as an energy balancing component, but rather as a fundamental design parameter that directly determines technical reliability, renewable energy utilization efficiency, and life-cycle cost structure.

The hydrogen-based system configuration eliminated capacity shortages, achieved a renewable energy penetration level of 84.7%, and enabled surplus generation to be stored in hydrogen form for subsequent use. In contrast, although the battery-based system offered lower initial capital investment and a lower levelized cost of energy, it exhibited a 5.2% capacity shortage and limited capability for long-term energy storage, resulting in constrained performance in terms of supply continuity. These results highlight the structural limitations of short-duration storage technologies in systems with high renewable penetration and seasonal variability.

From an economic perspective, while the hydrogen infrastructure required a higher upfront investment, it provided an uninterrupted energy supply, enabled effective utilization of excess renewable generation, and maintained a predictable operational structure over the project lifetime. When evaluated from a life-cycle standpoint, these advantages translated into more sustainable and resilient economic performance. This outcome clearly indicates that optimal configuration in off-grid systems cannot be determined solely based on minimum COE or NPC values; as such indicators may overlook long-term reliability and strategic energy security considerations.

The multi-criteria technical and economic evaluation identified the hydrogen-based long-term storage configuration as the optimal system alternative due to its zero-capacity shortage, higher renewable penetration, and uninterrupted energy supply capability. Beyond numerical performance indicators, the results underline the importance of integrating long-duration storage solutions into the planning framework of isolated and island-type energy systems.

By quantitatively demonstrating the decisive role of long-term energy storage infrastructure under real load and renewable resource data, this study provides a meaningful contribution to the existing literature. The findings suggest that energy continuity in off-grid settlements should not be approached purely as an economic optimization problem; rather, long-term storage infrastructure should be recognized as a strategic planning component that supports energy security, supply reliability, and sustainable development objectives. In this regard, the study offers a technically grounded and decision-oriented roadmap for the design of future energy systems characterized by high renewable energy penetration.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	N.D.	N.P.
C	50	50
D	50	50
S	50	50
DCP	50	50
DAI	50	50
L	50	50
W	50	50
CR	50	50
SR	50	50
PM	50	50
FA	50	50

C= concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because there was no study on animals or humans.

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