Techno-Economic Optimization of a Grid-Connected Hybrid Photovoltaic–Wind System in Failaka Island, Kuwait

Ali Fard
College of Engineering and Technology, American University of the Middle East, Kuwait
10083624@aum.edu.kw

Abdulmohsen Al-Qallaf
College of Engineering and Technology, American University of the Middle East, Kuwait
10083287@aum.edu.kw

Nasser Al-Roomi
College of Engineering and Technology, American University of the Middle East, Kuwait
57396@aum.edu.kw

Khaled Msaieed
College of Engineering and Technology, American University of the Middle East, Kuwait
10083403@aum.edu.kw

Saleh Mahmoud
College of Engineering and Technology, American University of the Middle East, Kuwait
Saleh.mahmoud@aum.edu.kw

Turki AlQemlas
College of Engineering and Technology, American University of the Middle East, Kuwait
Turki.al-qemlas@aum.edu.kw (corresponding author)

Received: 15 January 2026 | Revised: 8 February 2026 | Accepted: 14 February 2026

Licensed under a CC-BY 4.0 license | Copyright (c) by the authors | *DOI: https://doi.org/10.48084/etasr.17564*

ABSTRACT

Kuwait's national electricity grid is increasingly contending with summer peak demand and stress on the infrastructure caused by population growth and extensive air conditioning use. As part of the transition toward a sustainable power system, this study examines the techno-economic feasibility of introducing a grid-connected hybrid Photovoltaic (PV)-wind energy system for Failaka Island, located 20 km from Kuwait's coast. Using the HOMER Pro optimization platform, the study analyzes optimal system configuration, Levelized Cost Of Energy (LCOE), Net Present Cost (NPC), and renewable energy fraction, using validated solar and wind resource data. The results indicate that Failaka Island has an annual average solar irradiation of 5.6 kWh/m^2/day and wind speeds of 6.0 m/s at a 100 m hub height, with both resources peaking during the summer months. The optimal configuration comprises 208 kW of PV capacity, one 1.5 MW wind turbine, a 44-kW power converter, a 1 MWh lithium-ion battery with zero annual throughput under the optimal grid-connected configuration, and a 1 MW grid interconnection. The system achieves a renewable energy fraction of 65.7%, an LCOE of 0.148 \$/kWh, and an NPC of \$9,560,000. Annual electricity production is dominated by wind generation of 3,127,902 kWh/yr and PV generation of 343,746 kWh/yr, while grid purchases and sales are 1,714,414 and 1,349,232 kWh/yr, respectively. These findings show that grid-connected hybrid renewable systems can substantially enhance clean energy penetration and significantly reduce dependence on grid imports. Moreover, a scalable model is provided for Kuwait's island electrification strategy aligned with Vision 2035 objectives, highlighting the potential of hybrid systems to mitigate grid stress and reduce dependence on fossil fuels.

Keywords-hybrid renewable energy systems; photovoltaic-wind integration; HOMER Pro optimization; island electrification; techno-economic analysis; grid-connected systems; energy storage

I. INTRODUCTION

Global energy systems are undergoing a rapid transition toward renewable and distributed generation technologies, driven by climate change mitigation, energy security concerns, and the depletion of fossil fuels [1, 2]. Islands and remote coastal areas represent some of the most challenging energy environments, often relying on costly and unreliable fossil fuel imports and having limited access to large-scale infrastructure [3, 4]. These vulnerabilities are particularly pronounced in arid regions, where extreme temperatures lead to substantial cooling-related electricity demand and pronounced seasonal load variations [5].

Kuwait's power sector faces similar challenges and is characterized by high summer peak demand, low reserve margins, and high dependence on conventional thermal generation. According to the Ministry of Electricity and Water (MEW), summer peak demand is around 17 GW, or 95% of the total installed power, placing a great strain on transmission networks and submarine cable systems [6]. The combination of rising demand and aging infrastructure underscores the need for decentralized, resilient energy solutions. Hybrid Renewable Energy Systems (HRES) with solar PV and wind technologies are significant and economical solutions for such environments [7, 8].

Failaka Island was selected as the case study for reasons beyond its proximity to Kuwait City. First, it is a strategic priority in Kuwait's national development plans, with expected growth in residential, commercial, and tourism activities that will increase electricity demand and diversify load characteristics. Second, despite the existing submarine-cable linkage, the island remains sensitive to supply constraints and operational vulnerabilities, which make resilient local generation highly relevant. Third, Failaka presents a technically favorable resource context: strong solar irradiation and seasonally robust coastal winds, particularly during summer peak-demand periods, support complementary hybrid PV–wind operation. Finally, the island's scale and projected growth make it a suitable pilot for transferable hybrid renewable planning across other Kuwaiti islands and coastal communities [9].

Kuwait's renewable energy potential is significant, with global horizontal irradiation exceeding 2,000.00 kWh/m^2 per year and coastal wind speeds of 5.5-6.5 m/s [10, 11]. Failaka Island benefits from strong solar radiation and favorable summer wind conditions driven by the northwesterly Shamal winds. These complementary resource profiles create ideal conditions for hybrid PV–wind configurations that can provide nearly continuous renewable energy coverage.

Globally and regionally, techno-economic assessments using tools such as HOMER Pro have demonstrated the feasibility of hybrid renewable systems in island contexts. Authors in [7, 8] established methodological frameworks for hybrid optimization and sensitivity analysis. Regional studies confirmed the viability of PV–wind systems in Gulf climates, achieving levelized costs of 0.18–0.22 $/kWh under coastal conditions [12, 13]. Kuwaiti investigations validated strong wind potential at 100 m hub height across coastal and island zones, particularly on Failaka Island [14, 15]. Despite these advances, few studies have focused specifically on grid-connected hybrid systems for Kuwaiti islands. Existing literature has primarily addressed off-grid microgrids or single-technology analyses. Furthermore, the techno-economic implications of Kuwait's current electricity tariff structure and grid capacity limitations have not been adequately assessed. The current study fills these gaps through a detailed case study of Failaka Island, employing validated meteorological data, realistic community load modeling, and comprehensive economic optimization using HOMER Pro.

The solar and wind energy potential of Failaka Island are evaluated using validated meteorological data. Realistic load profiles are developed to reflect local community demand. Hybrid PV–wind configurations are then optimized for grid-connected operation using HOMER Pro. Techno-economic feasibility is analyzed through key indicators such as NPC, LCOE, and IRR. Finally, the findings provide policy insights to support Kuwait's Vision 2035 and grid modernization.

Table I summarizes some of the key recent studies on HRES in the Gulf and the surrounding regions. It highlights each study's focus, methodological limitations, and the specific contribution of the present work, which applies validated 100 m hub-height wind data and HOMER-based optimization for Failaka Island under grid-connected operation.

TABLE I. COMPARISON OF SELECTED REGIONAL HYBRID RENEWABLE ENERGY STUDIES AND CONTRIBUTIONS OF THIS WORK

Study	System type	Focus	Key limitation	This study's contribution
[13]	PV–Wind (Saudi Arabia)	Off-grid coastal system	No grid integration, limited seasonal analysis	Grid-connected optimization for Failaka Island with validated Gulf data
[16]	PV–Wind–Diesel–Battery (Saudi Arabia)	Sensitivity study for Saudi sites	Diesel backup increases emissions	100% renewable grid-connected configuration, no fossil backup
[17]	PV–Wind (Tunisia)	Desalination case	Single-site, low Gulf relevance	Application to Kuwait's island electrification context
[18]	Wind assessment (Kuwait)	Wind mapping only	No techno-economic system design	Integrated PV–wind techno-economic optimization using HOMER Pro
[19]	PV–Wind–Fuel Cell (Generic)	Multi-source optimization	Generic data, no site validation	Use of real meteorological data at 100 m hub height for Failaka Island

II. SITE DESCRIPTION AND RESOURCE ASSESSMENT

A. Geographic and Climatic Context

Kuwait lies in the northeastern Arabian Peninsula (28.5°–30.1° N, 46.5°–48.5° E) and is characterized by an arid desert climate with extremely hot summers and mild winters. Summer daytime temperatures regularly exceed 45 °C, while winter temperatures range between 8 °C and 18 °C [9]. Annual precipitation is low, averaging 100–150 mm and concentrated in the winter months. The region experiences high solar irradiation throughout the year and moderate to strong northwesterly Shamal winds that intensify during summer [20].

Failaka Island, situated approximately 20 km east of Kuwait City, is among Kuwait's most historically and strategically significant offshore islands, as depicted in Figure 1. The island covers roughly 43 km² with a flat topography and an average elevation of about 10 m above sea level. Its proximity to the mainland, combined with open coastal exposure, creates favourable conditions for both solar and wind power generation. The Kuwaiti government's development plans envision a mixed-use community in Failaka, including residential, commercial, and tourism facilities [9]. The island's electricity is supplied primarily through diesel generators and a limited submarine cable connection, resulting in high operational costs and reliability challenge.

Fig. 1. Geographic location of Failaka Island in the Arabian Gulf, showing proximity to Kuwait City and the Kuwaiti mainland. The inset map illustrates the regional context within the Gulf.

B. Solar Resource Assessment

Solar resource evaluation was conducted using the NASA Surface Meteorology and Solar Energy (SSE) database, which was validated against ground measurements from the Kuwait Institute for Scientific Research (KISR) [20, 21]. Long-term data (2000–2021) indicate that Failaka receives monthly average daily solar radiation ranging from 3.1 kWh/m²/day in December to 7.9 kWh/m²/day in June, with an annual mean of 5.6 kWh/m²/day. The clearness index ranges from 0.58 to 0.71, confirming consistently clear atmospheric conditions, typical of arid climates.

Peak solar radiation coincides with summer cooling demand, providing excellent temporal alignment between generation and load. As illustrated in Figure 2, Kuwait's coastal belt, including Failaka Island, demonstrates among the highest PV potentials in the region, with daily yields exceeding 4.6 kWh/kWp. The monthly trend of irradiance and clearness index derived from HOMER Pro simulations is presented in Figure 3, highlighting high summer irradiance stability.

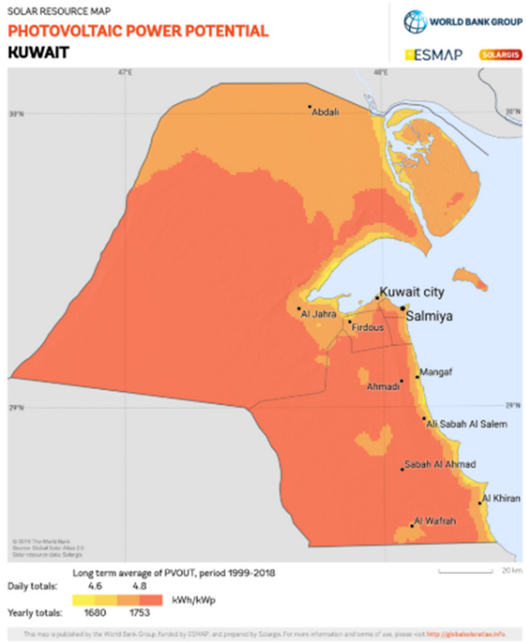

Fig. 2. Solar resource map of Kuwait showing long-term PV power potential (World Bank/ESMAP 2019). A surrounding circle indicates high solar zones near Failaka Island.

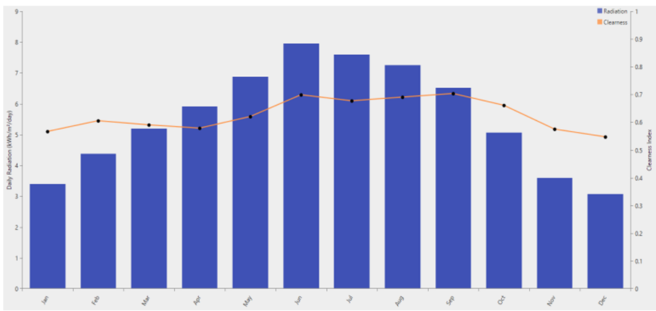

Fig. 3. Monthly average solar radiation and clearness index for Failaka Island derived from HOMER Pro, demonstrating strong summer irradiance and stable atmospheric conditions.

C. Wind Resource Assessment

Wind resource data were obtained from KISR meteorological stations and validated using regional studies of Kuwaiti coastal and offshore sites [14, 15, 19]. Observed 10 m wind speed data were extrapolated to 100 m hub height using [22]:

$$v_2 = v_1 \times \left(\frac{h_2}{h_1}\right)^{\alpha} \quad (1)$$

where v_1 and v_2 represent wind speeds at reference and hub heights h_1 and h_2, respectively, and α is the surface roughness exponent (0.14 for coastal terrain).

At 100 m hub height, monthly average wind speeds for Failaka range from 5.0 m/s in October to 7.7 m/s in June, with an annual average of 6.0 m/s. The wind regime follows a Weibull distribution with the shape parameter k=2.1 and the scale parameter c=6.8 m/s, signifying consistent and predictable wind conditions suitable for modern medium-speed turbines.

As illustrated in Figure 4, summer months (June–August) experience the highest wind speeds (7.4–7.7 m/s) due to intensified Shamal winds, coinciding with the period of maximum solar irradiation. This complementary seasonal pattern ensures reliable hybrid generation throughout the year.

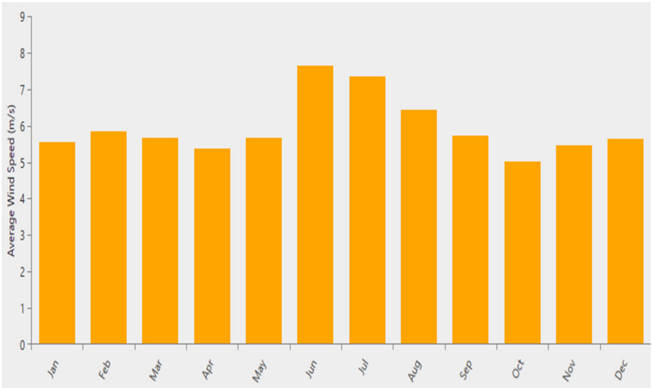

Fig. 4. Average monthly wind speed at 100 m hub height for Failaka Island, demonstrating strong summer peaks associated with Shamal wind patterns.

According to the International Electrotechnical Commission (IEC 61400-1) classification [23], Failaka's wind regime corresponds to IEC Class III–IV, confirming its suitability for standard 1.5 MW turbines, designed for moderate wind conditions.

D. Load Profile Development

The electrical load profile for Failaka Island was constructed to reflect community-based energy consumption across the residential, commercial, and public service sectors [12]. Residential demand dominates, accounting for roughly 60–70% of total energy use in summer, mainly due to cooling systems. Commercial and public service loads include retail, hospitality, water pumping, and street lighting, while community facilities such as mosques, schools, and clinics add moderate daily variation.

The resulting profile exhibits an average demand of 400–600 kW with pronounced daily peaks of 1.4–1.6 MW during summer afternoons (14:00–18:00). Minimum nighttime loads (03:00–06:00) drop to 100–300 kW, producing a load factor of 0.35–0.40. Monthly energy consumption peaks during June–August, exceeding winter demand by 150–200 %, consistent with Kuwait's cooling-dominated consumption pattern.

Figure 5 shows the monthly variation of Failaka's scaled load as modeled in HOMER Pro. The pronounced seasonal and diurnal variations underscore the need for a hybrid system design that leverages complementary solar and wind resources to ensure a stable energy supply.

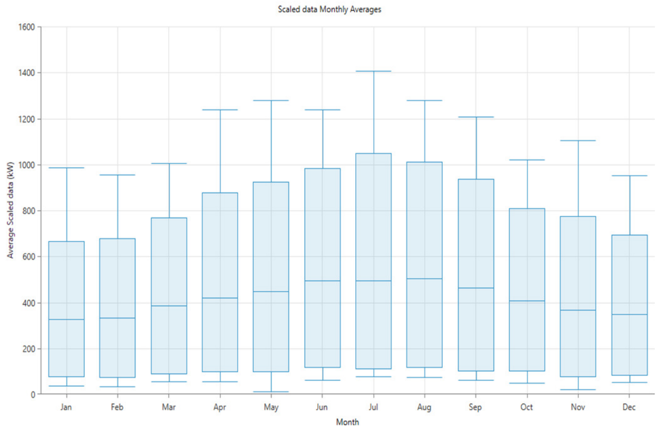

Fig. 5. Monthly variation of scaled electrical load demand for Failaka Island obtained from HOMER Pro, showing pronounced summer peaks due to air-conditioning demand.

To ensure input reliability, solar and wind resource datasets from NASA SSE were validated against KISR records over the common available period. Validation was performed in three steps. First, monthly mean values of irradiance and wind speed were compared to verify consistency in magnitude. Second, seasonal trend agreement was checked to confirm that both datasets reproduced the same summer–winter resource pattern and peak-month behavior. Third, annual averages were compared to ensure that long-term resource levels remained within acceptable engineering deviation for feasibility modeling. Following this consistency check, NASA SSE was used as the continuous time-series source for HOMER Pro, while KISR was used as a regional ground-reference benchmark. This combined approach improves confidence in the representativeness of the modeled resource inputs for Failaka Island.

III. METHODOLOGY

A. Overview of Optimization Framework

The hybrid renewable energy system for Failaka Island was modeled and optimized using HOMER Pro (Hybrid Optimization of Multiple Energy Resources), a comprehensive simulation platform developed by HOMER Energy LLC. HOMER Pro performs hourly simulations over an annual cycle to determine the least-cost configuration of generation, storage, and grid components that reliably meet a system's electrical demand [22, 24]. The optimization process evaluates each configuration's NPC and LCOE under defined technical and economic constraints, thereby identifying the most cost-effective design. The simulation framework integrates renewable energy resources, storage technologies, and grid interactions, ensuring a realistic operational dispatch strategy for isolated or semi-isolated grids [25].

B. System Components and Technical Parameters

The hybrid system modeled for Failaka Island comprises four primary components: PV panels, wind turbines, battery storage, and a bidirectional converter connected to the existing national grid. Each component's characteristics and economic parameters were defined according to the HOMER Pro settings.

The PV subsystem consists of a generic flat-plate PV array representative of commercially available crystalline silicon modules designed for hot and arid conditions. The model assumes that the capital cost is 1,600.00 $/kW, the replacement cost is 1,600,00 $/kW and the annual operation and maintenance costs are 20 $/kW. The PV panels have a 25-year lifetime and a derating factor of 75%, accounting for system losses due to dust accumulation, high ambient temperature, and inverter inefficiencies. The PV modules were configured on the DC bus and interfaced with the converter to enable bidirectional energy exchange with the grid. These parameters are consistent with cost benchmarks reported for large-scale installations in the Gulf region [26].

The wind energy system was modeled using a generic 1.5 MW horizontal-axis wind turbine, suitable for the moderate wind regime of Failaka Island. The average wind speed at 100 m hub height is approximately 6.0 m/s, peaking in the summer months under the Shamal wind regime [27]. Each turbine unit was assigned a capital cost of $ 3,300,000, a replacement cost of $ 2,800,000, and an annual O&M cost of $ 140,000.00. The turbine's expected lifetime is 18 years, with a hub height of 100 m. The selected turbine configuration and cost inputs are consistent with commercial-scale turbines used in desert and coastal environments across the GCC.

Battery storage was incorporated into the system to mitigate power intermittency and balance short-term fluctuations in renewable output. A 1 MWh lithium-ion battery bank was modeled, with parameters derived directly from HOMER Pro. The capital and replacement costs were set at $ 700,000.00 per unit, with an annual O&M cost of $ 10,000.00 and an operational lifetime of 15 years. The battery round-trip efficiency was set to 90%, with minimum state of charge limits consistent with HOMER defaults. Under the optimal solution, the battery has zero annual throughput due to the availability of the grid for balancing.

A bidirectional converter was implemented to regulate energy transfer between the DC and AC buses, thereby enabling efficient interaction among the PV array, battery, and the grid. The converter was modeled with a capital and replacement cost of 300 $/kW, an O&M cost of 3 $/kW/year, an inverter efficiency of 95 %, a rectifier efficiency of 90 %, and a lifetime of 15 years. These characteristics ensure minimal conversion losses and long-term operational stability within the hybrid architecture.

Failaka Island's hybrid system remains connected to Kuwait's mainland grid via a submarine cable. The grid connection was represented in HOMER using a simple tariff model, with an electricity purchase price of 0.131 $/kWh, a sellback rate of 0.030 $/kWh. The grid serves as both a backup supply and a sink for surplus renewable generation, reflecting the national electricity tariff structure maintained by the Ministry of Electricity and Water [6].

C. Simulation Parameters and Optimization Settings

The optimization problem was defined to minimize the system's NPC while ensuring zero unmet load. Component capacities were allowed to vary within predefined ranges during the optimization process. The PV capacity varied from 0 to 500 kW, while the number of wind turbines ranged from 0 to 3 1.5 MW units. The battery capacity ranged from 0 to 2 MWh, and the converter size was continuously optimized between 0 and 1,000 kW. The grid connection was set to 1.0 MW, reflecting the technical capacity of the existing submarine link. The optimal configuration obtained from HOMER included 208 kW PV, a 1.5 MW wind turbine, 1 MWh of storage, and a 44 kW converter, achieving a renewable fraction of 65.7% with no unmet load.

A Cycle-Charging (CC) dispatch strategy was used in HOMER Pro, in which renewable generation and the grid meet the load while excess generation is exported to the grid under the defined tariff and sellback structure. The model simulated hourly operation over one year using site-specific solar radiation, wind speed, and electrical load data.

Under the modeled tariff structure and CC dispatch, HOMER prioritizes grid transactions over battery cycling when this minimizes total NPC; therefore, the selected battery may exhibit negligible annual throughput in the optimal grid-connected case.

D. Economic Analysis

The system's economic feasibility was evaluated using the NPC and the LCOE, the two principal indicators generated by HOMER Pro. The NPC aggregates all capital, replacement, O&M, and grid transaction costs over the project lifetime, discounted at an annual rate of 5 %. The LCOE is calculated as the ratio of the total NPC to the lifetime energy served. A 25-year project horizon was assumed, consistent with PV module lifespan and regional energy planning practices [28].

The NPC and LCOE were computed according to:

$$NPC = \sum_{t=1}^{N} \frac{C_{cap,t}+C_{rep,t}+C_{O\&M,t}-R_{sell,t}}{(1+d)^t} \quad (2)$$

$$\mathrm{LCOE} = \frac{\mathrm{NPC}}{\sum_{t=1}^{N} \mathrm{E_{served,t}}/(1+d)^t} \quad (3)$$

where $C_{cap,t}$ represents the initial capital investment, $C_{rep,t}$ is the replacement cost, $C_{O\&M,t}$ denotes the annual operation and maintenance expenditures, $R_{sell,t}$ represents revenues from grid sales, $E_{served,t}$ is the annual energy supplied to the load, d is the discount rate, and N is the project lifetime.

E. Model Validation

The validity of the modeling approach was verified through comparison with recent hybrid energy optimization studies for arid and coastal regions [29]. The cost assumptions, technical parameters, and component lifetimes applied in the model are consistent with empirical data reported for similar Gulf and North African contexts. As all parameter values were derived directly from HOMER Pro inputs, the model is fully transparent and reproducible, ensuring the reliability of the simulation results. The validation was intended to establish dataset consistency for feasibility modeling rather than to perform formal bias-correction of the NASA SSE time series.

The HOMER Pro framework in this study is applied to techno-economic optimization (component sizing, annual dispatch, and lifecycle cost evaluation) rather than dynamic grid-stability simulation. Therefore, transient phenomena such as short-term frequency excursions, voltage stability margins, fault ride-through behavior, and detailed converter control dynamics are not explicitly resolved in the present model.

IV. RESULTS

A. *Optimal System Configuration*

The hybrid renewable energy system for Failaka Island was optimized using the HOMER Pro simulation framework to minimize the total NPC while maintaining 100% load reliability. The optimal configuration consists of 208 kW of PV capacity, a 1.5 MW wind turbine, 1 MWh of lithium-ion battery storage, a 44 kW bidirectional converter, and an existing grid connection of 1.0 MW. The grid operates in a bidirectional mode, importing electricity during renewable generation deficits and exporting surplus power during periods of high renewable output. The selected battery size remains in optimal configuration but exhibits negligible utilization due to the grid providing the primary balancing service under the applied tariff structure. This behavior is driven by tariff-based economic dispatch, in which grid import/export provides lower-cost balancing than charge–discharge cycling.

Although the bidirectional converter capacity is limited to 44 kW, this does not constrain system operation because the wind turbine and grid are directly connected to the AC bus and supply most of the load. The converter primarily facilitates limited PV integration and DC-side balancing, while the battery remains largely inactive under grid-connected operation

B. *Economic Performance*

The system's NPC is estimated at $ 9,560,000 , with an LCOE of 0.148 $/kWh, positioning the project as one of the most cost-effective renewable configurations reported for similar island or coastal contexts in the Gulf region. The initial capital cost is approximately $ 4,350,000, while annual operating and maintenance expenses total $ 403,117.00. These values reflect the combined effects of declining global prices for renewable technologies and Kuwait's strong solar and wind resource base. Under the applied tariff structure and net metering settings, HOMER reports the above economic indicators as the basis for comparing candidate configurations.

C. *Energy Generation and Grid Interaction*

The annual energy balance confirms effective utilization of renewable resources with grid interaction. The PV annual energy production is 343,746.00 kWh/yr and the wind annual energy production is 3,128.00 MWh/yr, resulting in total renewable generation of 3,472.00 MWh/yr. The annual grid electricity purchased is 1,714 MWh/yr, while the annual electricity sold to the grid is 1,349,00 MWh/yr. The resulting renewable energy fraction reported by HOMER is 65.7%, with zero unmet load, demonstrating that the majority of the island's load is supplied by local renewable generation, with the grid providing limited supplementary power. The excess generation also represents a potential revenue stream, as surplus electricity exported to the grid earns compensation under Kuwait's net metering regulations [6].

D. *Monthly Performance and Resource Complementarity*

The temporal analysis reveals strong seasonal complementarities between solar and wind resources. During summer months (June–August), the Shamal wind intensifies, increasing wind generation and coinciding with high solar irradiance and peak cooling demand. Wind generation peaks during summer months, consistent with intensified Shamal winds, while PV output also increases due to higher irradiance. This seasonal complementarity supports stable bidirectional grid interaction under the modeled tariff, with periods of export during high renewable output and import during renewable deficits. In contrast, winter months (December–February) exhibit reduced wind and solar output, yet energy supply remains sufficient due to the moderate load profile. These results confirm the effectiveness of resource complementarity in Kuwait's coastal climate, mitigating the need for large storage systems and supporting stable grid interaction.

E. *Summary of System Performance*

Table II summarizes the optimal hybrid system configuration and performance indicators for Failaka Island.

TABLE II. . OPTIMAL HYBRID SYSTEM CONFIGURATION AND PERFORMANCE FOR FAILAKA ISLAND

Parameter	Value
PV capacity	208 kW
Wind turbine capacity	1 × 1.5 MW
Battery storage	1 MWh Li-ion
Converter capacity	44 kW
Grid connection	1.0 MW (nominal)
Net Present Cost (NPC)	$9.560,000
LCOE	0.148$/kWh
Initial capital cost	$4,350,000
Annual operating cost	$403,117
PV energy production	343,746 kWh/yr
Wind energy production	3,127,902 kWh/yr
Grid energy purchased	1,714,414 kWh/yr
Grid energy sold	1,349,232 kWh/yr
Renewable energy fraction	65.7%
Unmet load	0%

V. DISCUSSION

A. *Economic and Technical Assessment*

The results confirm that grid-connected hybrid renewable systems can reliably deliver electricity to Failaka Island under Kuwait's climatic and regulatory conditions. The optimized configuration achieves a renewable energy fraction of 65.7% with zero unmet load, while enabling bidirectional grid interaction to manage periods of renewable surplus and deficit. The LCOE of 0.148 $/kWh remains higher than the subsidized purchase tariff of 0.131 $/kWh, indicating that the principal value of the hybrid system under current pricing is increased clean energy penetration and reduced grid dependency rather than immediate cost parity. These findings are consistent with regional techno-economic studies [13, 16], which reported LCOE values between 0.18–0.21 $/kWh for comparable hybrid systems in Saudi Arabia.

The battery remains effectively unused (zero annual throughput) in the optimal grid-connected configuration, under the assumed tariff and dispatch settings, indicating that the grid provides the primary balancing flexibility. This reduces both the capital cost and long-term maintenance burden while maintaining system reliability.

B. Resource Complementarity and Reliability

The combination of solar and wind energy in Kuwait's coastal environment provides a more stable generation profile than single-source systems. The summer wind maximum associated with the Shamal wind regime coincides with peak solar radiation and cooling demand, supporting hybrid operation with reduced variability. Authors in [15, 18] confirm that Kuwait's coastal regions exhibit mean wind speeds of 6.0–6.2 m/s annually, with summer peaks of 7.4–8.0 m/s, supporting high wind turbine capacity factors. This seasonal synergy minimizes dependency on storage and ensures high renewable penetration without compromising supply reliability.

C. Comparison with Regional Studies

A comparative assessment with regional hybrid system studies highlights Failaka Island's competitive performance in clean energy penetration under grid-connected operation. As shown in Table III, the system achieves an LCOE of 0.148 $/kWh with a renewable fraction of 65.7%, demonstrating that grid-connected hybrid PV–wind systems can increase renewable penetration substantially while maintaining reliability in Gulf coastal climates.

TABLE III. COMPARISON OF FAILAKA ISLAND RESULTS WITH REGIONAL HYBRID RENEWABLE STUDIES

Study	**System type**	**LCOE ($/kWh)**	**Renewable fraction (%)**	**Key findings**
Current study	PV–Wind–Grid	0.148	65.7	Community load; 1 MWh battery included but zero annual throughput (grid provides balancing)
[19]	PV–Wind–Fuel Cell–Grid	0.165	95.0	Fuel cell backup
[13]	PV–Wind–Grid	0.210	88.0	Western coastal area
[17]	PV–Wind–Grid	0.180	92.0	Desalination application
[30]	PV–Wind–Hydrogen	0.250	100	Hydrogen production
[16]	PV–Wind–Diesel–Battery	0.180	85.0	Diesel backup included

To improve visual interpretation of the regional benchmark, Figure 6 presents a comparative bar chart of LCOE and renewable fraction values corresponding to Table III.

The LCOE of 0.148 $/kWh for Failaka, as also illustrated in Figure 6, is significantly lower than the regional average of 0.18–0.22 $/kWh, primarily due to excellent wind resource quality, grid support, and optimized sizing ratios that balance capital and operational costs. While some of the off-grid configurations achieve higher renewable fractions, their reliance on expensive storage and higher curtailment levels limits cost competitiveness.

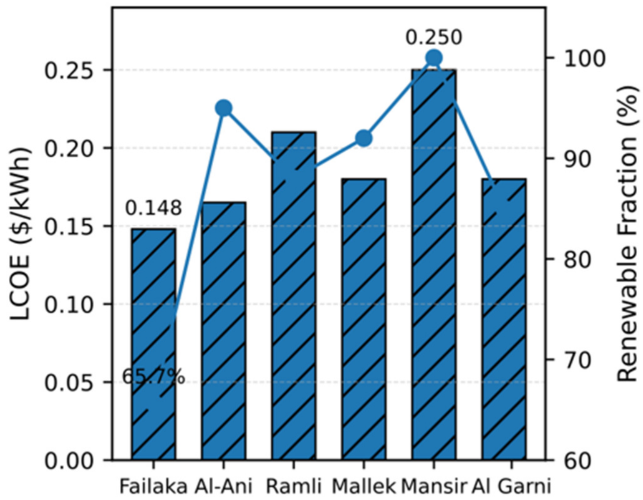

Fig. 6. Comparative LCOE and renewable fraction for Failaka Island and selected regional hybrid renewable studies [13, 16, 17, 19, 30].

Although the optimized system demonstrates favorable techno-economic performance under grid-connected operation, higher renewable penetration levels may require dedicated control strategies to preserve network stability. In practical deployment, advanced inverter functions, coordinated voltage/frequency control, and reserve-management strategies should be assessed using dynamic power-system tools. This represents an important next step beyond the annual energy-balance and cost-focused scope of the current HOMER-based analysis

D. Environmental and Policy Implications

From an environmental perspective, the system increases the share of clean electricity serving Failaka Island. It reduces reliance on grid imports, thereby contributing to reductions in emissions, proportional to the avoided conventional electricity consumption. Over a 25-year operational horizon, the total avoided CO_2 emissions were calculated using:

$$E_{CO_2,\text{avoided}} = E_{\text{grid,displaced}} \times EF_{\text{grid}} \times N \quad (4)$$

where $E_{\text{grid,displaced}}$ is the annual electrical load served directly by on-site renewable generation, excluding exported energy, EF_{grid} is Kuwait's average grid emission factor of 0.70 kg CO_2/kWh [28], complying with International Energy Agency (IEA) regional data [2], and N is the project lifetime (25 years). Substituting the study values yields a total reduction of approximately 43,000.00 tons of CO_2-equivalent emissions. If exported renewable electricity is credited at the grid marginal emission factor, the total avoided emissions increase to approximately 61,000.00 tons CO_2. In addition to carbon dioxide, proportional decreases in nitrogen oxides (NO_x) and sulfur oxides (SO_x) are achieved through the displacement of fossil-fuel-fired grid generation. These environmental benefits demonstrate the significant contribution of hybrid renewable systems to Kuwait's Vision 2035 decarbonization goals and broader grid-emission mitigation strategies.

From a policy perspective, the results emphasize that under Kuwait's low subsidized electricity tariffs, the economic case for renewables may require policy mechanisms that recognize the value of clean energy and grid support, such as improved compensation for exports, tariff reform, or incentives for renewable penetration.

E. Sensitivity Analysis of Grid Sellback Tariff

A sensitivity analysis was conducted to evaluate the influence of the grid sellback price on system economics. The sellback tariff varied between 0.03 $/kWh (base case), 0.05 $/kWh, and 0.08 $/kWh, while all other technical and economic parameters were held constant. Because the optimized configuration exports a substantial amount of electricity to the grid (1,349,232 kWh/yr in the base case), increasing the sellback tariff improves project economics by increasing export revenue and reducing the NPC. The magnitude of improvement depends on the tariff level and export volume; therefore, the sellback policy is a key economic driver for grid-connected hybrid systems in Kuwait.

These findings demonstrate that the sellback policy is a key economic driver for grid-connected HRES in Kuwait. Tariff reform or enhanced compensation mechanisms for exported renewable electricity could significantly improve project viability and strengthen the role of hybrid systems in national decarbonization strategies.

An additional consideration is the potential effect of climate change on long-term renewable resource availability. The present study uses validated historical solar and wind datasets to establish a baseline techno-economic design; therefore, projected climate-driven changes were not explicitly modeled. Over multi-decadal horizons, variations in ambient temperature, aerosol/dust loading, and wind regime characteristics may alter PV output, turbine capacity factors, and seasonal complementarity. Accordingly, future planning for Failaka Island should incorporate climate-informed resource scenarios (e.g., low/medium/high resource pathways) and associated sensitivity analyses to quantify uncertainty in LCOE, renewable fraction, and grid-interaction behavior.

VI. CONCLUSION

This paper presented a techno-economic optimization of a grid-connected hybrid Photovoltaic (PV)–wind energy system for Failaka Island, Kuwait, using HOMER Pro. In direct response to the first objective, the resource assessment confirmed strong renewable potential, with an annual average solar irradiation of 5.6 kWh/m²/day and an average wind speed of 6.0 m/s at a 100 m hub height, including favorable summer peaks. In response to the second objective, a realistic community-based load profile was developed, capturing pronounced seasonal and diurnal variability driven by cooling demand.

Addressing the third objective, the HOMER optimization identified an optimal configuration consisting of 208 kW PV, a 1.5 MW wind turbine, 1 MWh lithium-ion battery, a 44 kW converter, and a nominal 1 MW grid interconnection. For the fourth objective, techno-economic analysis showed an NPC of $ 9,560,000 and a Levelized Cost Of Energy (LCOE) of 0.148 $/kWh, with a renewable fraction of 65.7% and zero unmet load. The battery remained in the optimal design but exhibited negligible annual throughput under tariff-driven grid-connected dispatch, where grid import/export provided the primary balancing service.

For the fifth objective, the results provide policy-relevant evidence that hybrid island systems can increase clean-energy penetration and reduce dependence on conventional grid supply under Kuwait's current conditions. Although the LCOE remains above the subsidized retail tariff, the system offers strategic value for decarbonization, peak-demand mitigation, and long-term grid resilience in line with Kuwait Vision 2035.

Future work should extend the framework to other Kuwaiti islands, integrate climate-projection-based resource scenarios, and combine techno-economic sizing with dynamic grid-stability analysis to evaluate advanced control strategies at higher renewable penetration levels.

REFERENCES

[1] *Climate Change 2023: Synthesis Report*, 1st ed., IPCC., Geneva., Switzerland, 2023.

[2] *World Energy Outlook 2023*, 1st ed., IEA Publications., Paris., France, 2023.

[3] A. J. Handique, R. A. M. Peer, and J. Haas, "Understanding the Challenges for Modelling Islands' Energy Systems and How to Solve Them," *Current Sustainable/Renewable Energy Reports*, vol. 11, no. 4, pp. 95–104, Sept. 2024, https://doi.org/10.1007/s40518-024-00243-8.

[4] E. Michalena and J. M. Hills, "Renewable energy issues and implementation of European energy policy: The missing generation?," *Energy Policy*, vol. 45, pp. 201–216, Jun. 2012, https://doi.org/10.1016/j.enpol.2012.02.021.

[5] M. Almazroui, M. Nazrul Islam, H. Athar, P. D. Jones, and M. A. Rahman, "Recent climate change in the Arabian Peninsula: annual rainfall and temperature analysis of Saudi Arabia for 1978–2009," *International Journal of Climatology*, vol. 32, no. 6, pp. 953–966, May 2012, https://doi.org/10.1002/joc.3446.

[6] *Electricity Tariff Structure*, 1st ed., Ministry of Electricity and Water, Kuwait City, Kuwait, 2023.

[7] S. Bahramara, M. P. Moghaddam, and M. R. Haghifam, "Optimal planning of hybrid renewable energy systems using HOMER: A review," *Renewable and Sustainable Energy Reviews*, vol. 62, pp. 609–620, Sept. 2016, https://doi.org/10.1016/j.rser.2016.05.039.

[8] T. Ma, H. Yang, and L. Lu, "A feasibility study of a stand-alone hybrid solar–wind–battery system for a remote island," *Applied Energy*, vol. 121, pp. 149–158, May 2014, https://doi.org/10.1016/j.apenergy.2014.01.090.

[9] *Failaka Island Development Master Plan*, 1st ed., Kuwait Municipality, Kuwait City, Kuwait, 2023.

[10] W. E. Alnaser and N. W. Alnaser, "The status of renewable energy in the GCC countries," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 6, pp. 3074–3098, Aug. 2011, https://doi.org/10.1016/j.rser.2011.03.021.

[11] M. M. Salah, A. G. Abo-khalil, and R. P. Praveen, "Wind speed characteristics and energy potential for selected sites in Saudi Arabia," *Journal of King Saud University - Engineering Sciences*, vol. 33, no. 2, pp. 119–128, Feb. 2021, https://doi.org/10.1016/j.jksues.2019.12.006.

[12] A. H. Al-Badi, A. Malik, and A. Gastli, "Assessment of renewable energy resources potential in Oman and identification of barrier to their significant utilization," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 9, pp. 2734–2739, Dec. 2009, https://doi.org/10.1016/j.rser.2009.06.010.

[13] M. A. M. Ramli, A. Hiendro, and Y. A. Al-Turki, "Techno-economic energy analysis of wind/solar hybrid system: Case study for western coastal area of Saudi Arabia," *Renewable Energy*, vol. 91, pp. 374–385, Jun. 2016, https://doi.org/10.1016/j.renene.2016.01.071.

[14] K. Al-Salem and W. Al-Nassar, "Assessment of wind energy potential at Kuwaiti Islands by statistical analysis of wind speed data," *E3S Web of Conferences*, vol. 51, Apr. 2018, Art. no. 01001, https://doi.org/10.1051/e3sconf/20185101001.

[15] A. H. Hasan *et al.*, "Wind resource assessment and site selection of offshore wind farms in the state of Kuwait," *Energy Sources, Part B: Economics, Planning, and Policy*, vol. 20, no. 1, Dec. 2025, Art. no. 2507683, https://doi.org/10.1080/15567249.2025.2507683.

[16] H. Z. Al Garni, A. Abubakar Mas'ud, M. A. Baseer, and M. A. M. Ramli, "Techno-economic optimization and sensitivity analysis of a PV/Wind/diesel/battery system in Saudi Arabia using a combined dispatch strategy," *Sustainable Energy Technologies and Assessments*, vol. 53, Oct. 2022 , Art. no. 102730, https://doi.org/10.1016/j.seta.2022.102730.

[17] M. Mallek, M. A. Elleuch, J. Euchi, and Y. Jerbi, "Optimum design of on-grid PV/wind hybrid system for desalination plant: A case study in Sfax, Tunisia," *Desalination*, vol. 576, May 2024, Art. no. 117358, https://doi.org/10.1016/j.desal.2024.117358.

[18] M. A. Alkhalidi, S. Kh. Al-Dabbous, S. Neelamani, and H. A. Aldashti, "Wind energy potential at coastal and offshore locations in the state of Kuwait," *Renewable Energy*, vol. 135, pp. 529–539, May 2019, https://doi.org/10.1016/j.renene.2018.12.039.

[19] M. A. J. Al-Ani, M. A. Zdiri, F. Ben Salem, and N. Derbel, "Optimized Grid-Connected Hybrid Renewable Energy Power Generation: A Comprehensive Analysis of Photovoltaic, Wind, and Fuel Cell Systems," *Engineering, Technology & Applied Science Research*, vol. 14, no. 3, pp. 13929–13936, Jun. 2024, https://doi.org/10.48084/etasr.6936.

[20] NASA Langley Research Center, *NASA Surface Meteorology and Solar Energy Database*, 1st ed. Hampton, VA, USA, 2023.

[21] *Kuwait Institute for Scientific Research, Kuwait Solar Radiation Atlas. Kuwait City, Kuwait: KISR Publications, 2020.*

[22] *HOMER Pro Version 3.14 User Manual*, 1st ed., HOMER Energy LLC, Boulder, CO, USA, 2023.

[23] *IEC 61400-1: Wind Energy Generation Systems – Part 1: Design Requirements*, 1st ed., International Electrotechnical Commission, Geneva., Switzerland, 2019.

[24] P. Nema, R. K. Nema, and S. Rangnekar, "A current and future state of art development of hybrid energy system using wind and PV-solar: A review," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 8, pp. 2096–2103, Oct. 2009, https://doi.org/10.1016/j.rser.2008.10.006.

[25] S. Sinha and S. S. Chandel, "Review of software tools for hybrid renewable energy systems," *Renewable and Sustainable Energy Reviews*, vol. 32, pp. 192–205, Apr. 2014, https://doi.org/10.1016/j.rser.2014.01.035.

[26] *Renewable Power Generation Costs in 2023*, 1st ed., IRENA, Abu Dhabi., UAE, 2024.

[27] *Kuwait Wind Resource Data*, 1st ed., Global Wind Atlas, 2023.

[28] *Kuwait Energy Outlook 2023*, 1st ed., KISR, Kuwait City, Kuwait, 2023.

[29] S. M. Shaahid and M. A. Elhadidy, "Technical and economic assessment of grid-independent hybrid photovoltaic–diesel–battery power systems for commercial loads in desert environments," *Renewable and Sustainable Energy Reviews*, vol. 11, no. 8, pp. 1794–1810, Oct. 2007, https://doi.org/10.1016/j.rser.2006.03.001.

[30] I. B. Mansir, P. C. Okonkwo, and N. Farouk, "Techno-economic optimization of a photovoltaic-wind energy-based hydrogen production system: A case study of different cities of Saudi Arabia," *Energy & Environment*, Apr. 2024, Art. no. 0958305X241248373, https://doi.org/10.1177/0958305X241248373.