White Rose Research Online

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk
Universities of Leeds, Sheffield and York

Deposited via The University of Sheffield.

White Rose Research Online URL for this paper:
https://eprints.whiterose.ac.uk/id/eprint/247182/

Version: Published Version

Article:
Sawafi, A.A., Rashdi, A.H.A., Ismaili, Y.A. et al. (2026) Techno-economic assessment of large-scale renewable energy systems: a case study in the Gulf Cooperation Council. Energy Science & Engineering. ISSN: 2050-0505

https://doi.org/10.1002/ese3.70682

Reuse
This article is distributed under the terms of the Creative Commons Attribution (CC BY) licence. This licence allows you to distribute, remix, tweak, and build upon the work, even commercially, as long as you credit the authors for the original work. More information and the full terms of the licence here: https://creativecommons.org/licenses/

Takedown
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

UNIVERSITY OF LEEDS
University of Sheffield
UNIVERSITY of York

Check for updates

Energy Science & Engineering

WILEY

MODELLING AND ANALYSIS OPEN ACCESS

Techno-Economic Assessment of Large-Scale Renewable Energy Systems: A Case Study in the Gulf Cooperation Council

Ammar Al Sawafi | Al Hussain Al Rashdi | Yahya Al Ismaili | Kevin Hughes | Lin Ma | Derek Ingham | Mohammed Pourkashanian | Yang Zhang | Bill Nimmo

School of Mechanical, Aerospace and Civil Engineering, The University of Sheffield, Sheffield, UK

Correspondence: Ammar Al Sawafi (aralsawafi1@sheffield.ac.uk)

Received: 20 July 2026 | **Revised:** 14 September 2026 | **Accepted:** 9 October 2026

Keywords: GCC | levelised cost of energy | photovoltaic | renewable energy | techno-economic assessment | wind energy

ABSTRACT

This study assesses the techno-economic and environmental performance of large-scale hybrid renewable energy systems in the Gulf Cooperation Council (GCC) region. A 3 GW hybrid solar-wind plant comprising 1.5 GW of bifacial PV capacity and 1.5 GW of wind capacity was evaluated across five GCC sites: KSA, Oman, Kuwait, Qatar, and the UAE. Technical simulations used Meteonorm 8.2 meteorological data, PVsyst for bifacial PV modelling, and HOMER Pro for wind-energy simulation and techno-economic analysis over a 25-year project lifetime. The assessment used a 5% discount rate and a 2% inflation rate. KSA achieved the highest annual renewable electricity generation and electricity exported to the grid, at 9594.7 and 9434.1 GWh/year, respectively, followed by Oman at 9287.7 and 9128.5 GWh/year. Grid-delivered levelised cost of energy (LCOE) ranged from \$0.0262/kWh in KSA to \$0.0396/kWh in the UAE, with Oman, Kuwait, and Qatar at \$0.0271/kWh, \$0.0352/kWh, and \$0.0371/kWh, respectively. Reported NPC ranged from \$4805.3 million to \$9271.1 million, with a payback period of 4.03–6.28 years. Annual avoided CO2 emissions ranged from 2.29 to 5.21 Mt/yr, corresponding to 55.4—126.8 Mt over 25 years. Overall, KSA and Oman demonstrated the strongest technical and cost performance, highlighting the importance of site-specific renewable resource conditions for large-scale hybrid PV-wind deployment across the GCC.

1 | Introduction: Global Energy Demand and Climate Change

The global average surface temperature has risen by about 1.2°C since pre-industrial times. In 2023, energy-related CO_2 emissions reached a record 37 Gt, predominantly from industrial energy use [1].

The energy crisis, characterised by increasing demand and reliance on finite fossil fuels, is a global concern with significant environmental, economic, and social implications. Burning fossil fuels releases greenhouse gases, accelerating climate change and environmental degradation. A shift towards renewable energy sources, such as solar, wind, and hydro, is essential for the area. These sources provide cleaner, more sustainable alternatives that can substantially mitigate climate change and air pollution. As the world moves towards a more sustainable, clean, and reliable future, renewable energy plays a crucial role in this transition. The detrimental effects of the fossil fuel era on our planet are increasingly acknowledged. While tensions in energy markets have eased recently, they remain precarious. Consequently, emerging renewable energy opportunities are paving the way for a brighter future. Yet,

Abbreviations: CRF, capital recovery factor; GCC, gulf cooperation council; Gt, gigaton; LCOE, levelised cost of energy; NPC, net present cost; STC, standard test conditions.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2026 The Author(s). *Energy Science & Engineering* published by Society of Chemical Industry and John Wiley & Sons Ltd.

several uncertainties could hinder this transition. (Figure 1) One of the most significant challenges facing the world is the risk to affordability and security during this shift. A new clean energy economy is gaining significant attention and promises to transform the energy sector. Figure 2 showcases the vast potential for clean energy investment.

From 2015 to 2024, investments in renewable power and supporting clean technologies have increased steadily, while investments in fossil fuels have remained relatively stable or declined. Notably, energy efficiency and grid infrastructure are gaining more financial attention, reflecting global efforts to modernise energy systems. This trend underscores the global momentum toward a low-carbon future and a diversified energy portfolio.

2 | Renewable Energy in the Gulf Area

The primary factors driving renewable energy adoption in the Gulf region include economic, strategic, and environmental incentives. The region's abundant solar and wind resources, coupled with strong policy frameworks and infrastructure development, facilitate rapid innovation and deployment, particularly in emerging fields such as green hydrogen [3]. Importantly, the dramatic decrease in the cost of solar photovoltaic (PV) technology – now below 2 US cents per kilowatt-hour – makes renewables the most cost-effective option for new power generation, even outperforming the region's abundant natural gas resources. Second, the Gulf states are strategically using renewable energy to diversify their economies, reduce reliance on hydrocarbons, and create new employment opportunities, especially given the increasing volatility of oil revenues and intensifying global climate obligations [4]. Furthermore, ambitious national targets and government strategies – such as the UAE's goal of 44% renewable energy by 2050 and KSA's 50% by 2030 – are supported by significant public investments and unprecedented renewable energy auctions that attract international capital [3]. In conclusion, the need to address rising domestic energy demand, facilitate oil and gas exports, and mitigate the environmental impacts of power generation further strengthens the transition to renewable energy in the Gulf region [5].

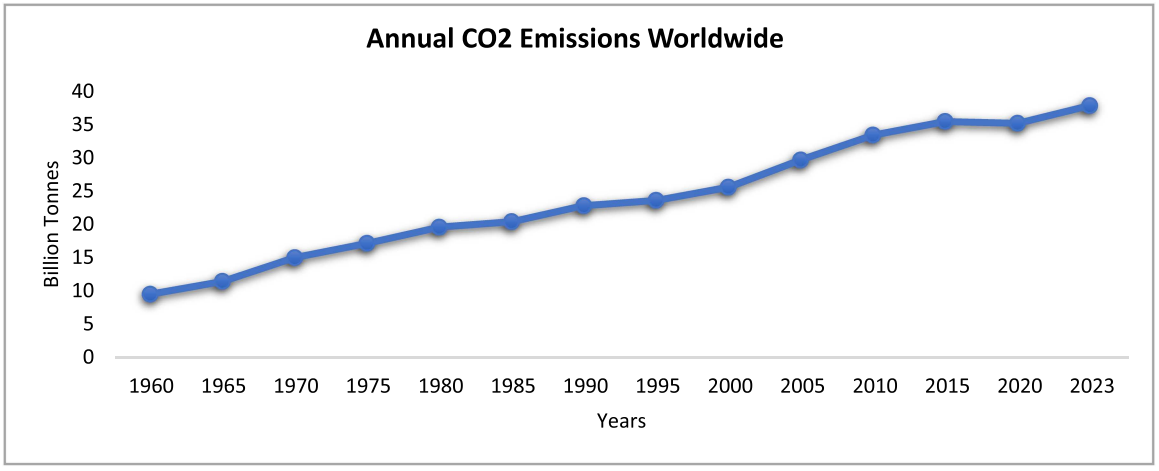


FIGURE 1 | The global trajectory of CO_2 emissions from 1990 to 2023 [1].

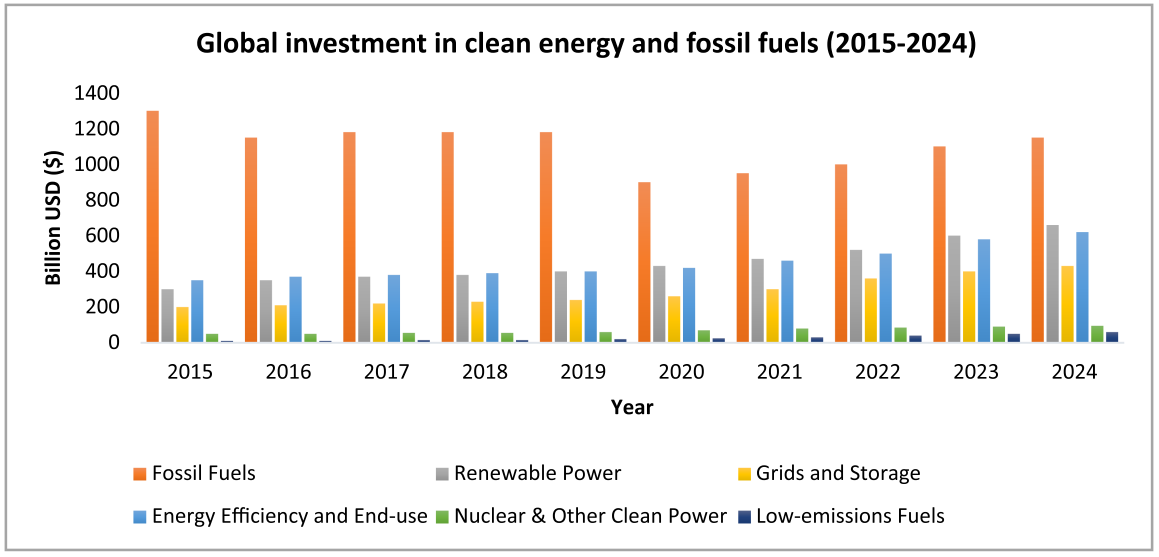


FIGURE 2 | The global energy investment in both fossil fuels and clean energy [2].

20500505, 0, Downloaded from https://scijournals.onlinelibrary.wiley.com/doi/10.1002/ese3.70682 by NICE, National Institute for Health and Care Excellence, Wiley Online Library on [28/10/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

The Gulf countries possess immense potential for renewable energy production, driven by some of the world's highest solar irradiance levels and vast tracts of available land, especially for solar and wind projects. In recent years, renewable electricity generation in the GCC surged by over 70% in 2023 alone, with regional capacity expected to expand to up to 18 times its current level by 2025 as governments invest heavily and set ambitious national targets. Projections indicate that the GCC will generate over 12 billion kWh of electricity from renewables in 2025, with solar PV leading growth due to its cost-effectiveness and suitability for the region's climate [6]. Recent research on bifacial solar cells shows significant progress in their efficiency, design flexibility, and commercial potential. Bifacial panels, which collect sunlight on both the front and rear surfaces, can generate 5%–30% or more additional energy than traditional monofacial panels, especially in environments with high ground reflectivity such as snow, sand, or white gravel [7]. This rapid expansion is supported by falling technology costs, strong policy frameworks, and the strategic imperative to diversify energy sources and reduce greenhouse gas emissions, positioning the Gulf as a rising global leader in renewable energy deployment [8].

Figure 3 illustrates the renewable energy generation capacity across the GCC countries in 2022, highlighting the different levels of renewable energy deployment within the region. The variation in installed capacity reflects the differences in national renewable energy strategies, available resources, investment priorities, and the maturity of renewable energy projects. Although all GCC countries have substantial solar potential, renewable energy capacity development remains uneven across the region. This variation provides an important basis for assessing how differences in renewable resource availability translate into differences in the technical and economic performance of large-scale hybrid renewable energy systems. In particular, combining solar and wind resources may improve energy utilisation and reduce the dependence on a single variable renewable source. Therefore, the regional differences illustrated in Figure 3 support the need for a consistent techno-economic comparison of large-scale hybrid PV-wind systems across multiple GCC locations.

The studies summarised in Table 1 demonstrate the growing application of hybrid renewable energy systems across the GCC and neighbouring regions, with previous research generally focusing on smaller-scale or location-specific PV-wind configurations. In comparison, the present study extends this research by evaluating a common 3 GW hybrid configuration comprising 1.5 GW of bifacial PV and 1.5 GW of wind capacity across five GCC locations. While several studies in Table 1 employ HOMER Pro for techno-economic assessment, the present model combines Meteonorm 8.2, PVsyst, and HOMER Pro to provide a more integrated assessment of renewable generation and economic performance. LCOE values reported in previous studies vary considerably because they consider smaller systems, different configurations, storage components, or local electricity loads, whereas the present model evaluates utility-scale, grid-connected generation under a consistent system configuration.

Despite the growing deployment of renewable energy across the GCC, consistent comparative assessments of large-scale hybrid PV-wind systems under a common system configuration remain limited. Previous studies have generally focused on individual countries, small-scale systems, or different hybrid configurations, making direct comparison of technical, economic, and environmental performance across GCC locations difficult. In particular, a systematic assessment of common gigawatt-scale PV-wind configurations is needed, using consistent technical and economic assumptions across multiple GCC locations. Such an assessment can clarify how site-specific solar and wind resources influence electricity generation, grid electricity export, economic performance, and environmental benefits.

Therefore, this study evaluates the techno-economic and environmental performance of a 3 GW hybrid renewable energy

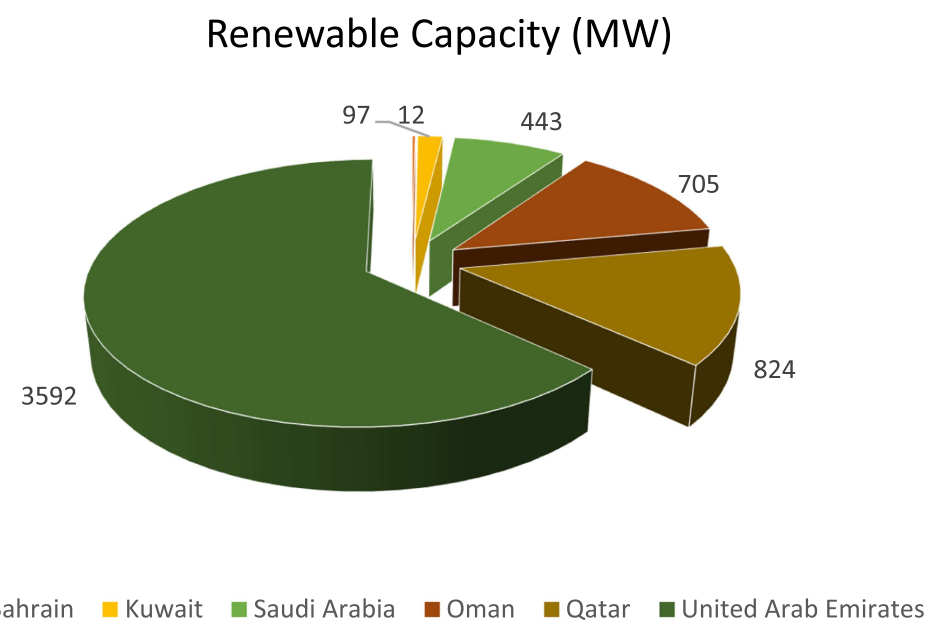


FIGURE 3 | Renewable energy generation capacity by country in 2022 [3].

20500505, 0, Downloaded from https://scijournals.onlinelibrary.wiley.com/doi/10.1002/ese3.70682 by NICE, National Institute for Health and Care Excellence, Wiley Online Library on [28/10/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 1 | Previous studies conducted for hybrid renewable energy generation across the Gulf region.

2021	Optimal selection and management of hybrid renewable energy system (PV, wind, battery, diesel)	Neom City, KSA	HOMER simulation, optimisation	Sized for city-scale load	$0.11–$0.15/kWh [9]
2024	Techno-economic analysis of hybrid renewable energy systems using DMOA (PV, wind, battery, diesel)	KSA	Dwarf Mongoose Optimisation Algorithm, simulation	System sized for building cooling loads	$0.199/kWh [10]
2024	Feasible and sustainable standalone hybrid renewable energy system (PV, wind, battery)	GCC nations (focus on Saudi Arabia, UAE, Oman)	Hybrid system modelling, LCOE calculation	Not specified (system-scale hybrid)	$0.13–$0.20/kWh (hybrid systems) [11]
2025	Green hydrogen production from hybrid solar-wind systems	Oman	HOMER Pro simulation	84 kW PV, 9 kW wind, 16 kW fuel cell	$0.1449/kWh [12]
2022	Techno-economic analysis of hybrid energy system for remote cluster electrification (wind/DG/FC/battery)	Al-Shumaisi, KSA	HOMER Pro simulation, sensitivity analysis	Commercial load	$0.271/kWh [13]
2023	Cost-effectiveness of solar electricity in Gulf capitals (with comparative LCOE)	Kuwait, Qatar	HOMER Pro simulation, technical and economic analysis	Grid-connected PV, city-scale	Kuwait: $0.22/kWh; Qatar: $0.18/kWh [14]
2023	Comparison between 5 different hybrid system configurations & the effect on the economics	KSA	HOMER Pro simulation	PV/Wind/DG/Electrolyser/Batt	$0.0582/kWh [15]
2023	Evaluate the feasibility of different configurations for on & off grid system.	Jordan	HOMER Pro simulation	PV/Wind/DG/Batt	$0.024/kWh [16]
2019	Techno-economic feasibility of hybrid wind/PV/diesel/battery for rural electrification	Persian Gulf Coast, Iran (adjacent to Iraq/Kuwait)	HOMER Pro simulation, cost optimisation	Sized for rural village load	$0.15–$0.22/kWh [17]
2024	Techno-economic and environmental analysis of hybrid energy systems for remote areas: A sustainable case study in Bangladesh	Kunder Char, Bangladesh	HOMER Pro simulation, comparison between 6 different configurations	Small community 139.88 kW	$0.0436-$0.266/kWh [18]
2026	Energy management and techno-economic-environmental analysis of hybrid renewable energy based isolated microgrid with various energy storage technologies	Kanur, Maharashtra, India	African Vultures Optimisation Algorithm (AVOA) was compared with Crayfish Optimisation Algorithm (COA) and Sine Cosine Algorithm (SCA)	245.59 MW for the optimal PV–WT–$NaNiCl_2$-BES configuration. Alternative configurations achieved 261.27 MW (PHS), 510.93 MW (HES), and 452.00 MW	$0.1050/kWh for PV–WT–$NaNiCl_2$-BES. Other storage options: $0.4094/kWh (PHS), $0.2824/kWh (HES), and $0.1429/kWh (TES) [19]
2025	Hybrid renewable energy systems design and techno-economic analysis for isolated rural microgrid using HOMER	India	HOMER Pro simulation	273.34 MWh/year	$0.146/kWh [20]

20500505, 0, Downloaded from https://scijournals.onlinelibrary.wiley.com/doi/10.1002/ese3.70682 by NICE, National Institute for Health and Care Excellence, Wiley Online Library on [28/10/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

system comprising 1.5 GW of bifacial PV and approximately 1.5 GW of wind capacity across five GCC locations: KSA, Oman, Kuwait, Qatar, and the UAE. This study uses Meteonorm 8.2 meteorological data, PVsyst, and HOMER Pro to evaluate renewable electricity generation and economic performance over a 25-year project lifetime. The analysis compares renewable electricity generation, grid electricity export, conversion losses, net present cost (NPC), payback period, grid-delivered levelised cost of energy (LCOE), and avoided CO_2 emissions. The study aims to identify how site-specific renewable resource conditions influence the technical, economic, and environmental performance of a common large-scale hybrid PV-wind configuration across the GCC region.

The main contributions of this study are:

- A rigorous techno-economic comparison of a 3 GW hybrid solar–wind system across five GCC locations under consistent design and financial assumptions.
- An integrated PVsyst–HOMER Pro modelling framework enabling realistic evaluation of large-scale hybrid renewable systems.
- Clear quantification of how regional climate conditions impact energy output, system performance, and LCOE.
- Identification of the most viable GCC locations for large-scale deployment based on key techno-economic indicators, offering actionable insights for policymakers and investors.

The remainder of this paper is organised as follows. Section 2 describes the methodology, including the site selection criteria, renewable resource assessment, photovoltaic and wind energy system modelling, and the techno-economic analysis framework. Section 3 presents and discusses the technical and economic results, including energy production, financial performance, and levelised cost of energy (LCOE) comparisons across the selected GCC locations. Finally, Section 4 summarises the study's main findings and presents key conclusions and recommendations for future large-scale deployment of renewable energy in the GCC region.

3 | Methodology

This study analyses the Levelised Cost of Energy (LCOE) for hybrid renewable systems comprising 1.5 GW of solar photovoltaic capacity and 1.5 GW of wind capacity across five sites in the Gulf Cooperation Council (GCC) region. Site selection is based on the availability and potential of regional renewable resources. Solar and wind resource data were obtained using Meteonorm 8.2 (TMY), with PV performance simulated in PVsyst, while wind generation and techno-economic analysis were conducted in HOMER Pro. HOMER Pro runs hourly energy-balance calculations throughout a modelled year to evaluate the technical feasibility and energy flows of the hybrid system components. Its optimisation algorithm then simulates thousands of resource and hardware combinations to identify the design that yields the lowest lifetime net present cost. Each system was sized using standardised configurations and financial parameters, such as inflation, the discount rate, and inverter costs, applied over a 25-year project life. We compared the resulting LCOE across locations and benchmarked it against global figures.

3.1 | System Design Configuration

Figure 4 illustrates the overall configuration of the hybrid renewable energy system evaluated in this study. The system consists of a 1.5 GW bifacial photovoltaic plant and a 1.5 GW wind farm operating in parallel to form a 3 GW hybrid renewable power plant. Solar resource assessment and PV performance modelling were carried out using PVsyst, while wind energy simulation and techno-economic optimisation were performed using HOMER Pro. The combined electrical output is supplied to the grid, and the overall system performance is evaluated using key technical and economic indicators, including annual energy production, net present cost (NPC), levelised cost of energy (LCOE), and payback period.

3.2 | Site Selection and Resource Data

To conduct a fair techno-economic study of hybrid renewable systems across the GCC region, a standard capacity of 1.5 GW of bifacial PV and 1.5 GW of wind plants is assigned for each site. The five selected sites are Al Duqm (Oman), Al Muwaylih (KSA), Masdar City (UAE), Umm Qarn (Qatar), and Al Murayatibah (Kuwait), selected for their potential for renewable energy and clean energy initiatives. The monthly climate data, including wind speed, global horizontal irradiance, cloudiness index, and temperature, were sourced from a typical meteorological year using the 8.2 Meteonorm database. Meteonorm data includes a long-term climate profile for each site, serving as the basis for estimating the energy yield and seasonal performance of renewable plants. The spatially selected site is shown in Figure 5, while Figure 6 illustrates monthly variations of wind speed (a) and solar irradiance (b) for the selected sites.

The renewable resource analysis reveals that Oman exhibits a distinct seasonal wind profile, with average wind speeds exceeding 7 m/s in July. Like KSA, it has strong wind potential, with speeds exceeding 6 m/s during the summer months. Kuwait also exhibits a moderate wind profile, with peaks exceeding 5.4 m/s in June. In contrast, the UAE and Qatar show steady, lower wind speeds over the years, ranging from 3 to 4.5 m/s.

In terms of solar irradiance, all selected sites exhibit high solar potential year-round. KSA and Oman recorded peak levels above 7.5 kWh/m^2/day during the summer period. The sky clarity index remains above 0.6 across the region, with a small exception in Qatar and Kuwait, where the averages are 0.575 and 0.6, respectively, indicating greater sky attenuation. Table 2 summarises key site characteristics, including geographic coordinates and annual renewable resource metrics.

3.3 | PV System Modelling

Each selected site hosts a 1.5 GW bifacial PV plant simulated using PVsyst, incorporating Meteonorm meteorological data. The system features a monocrystalline bifacial Longi Solar

20500505, 0, Downloaded from https://scijournals.onlinelibrary.wiley.com/doi/10.1002/ese3.70682 by NICE, National Institute for Health and Care Excellence, Wiley Online Library on [28/01/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

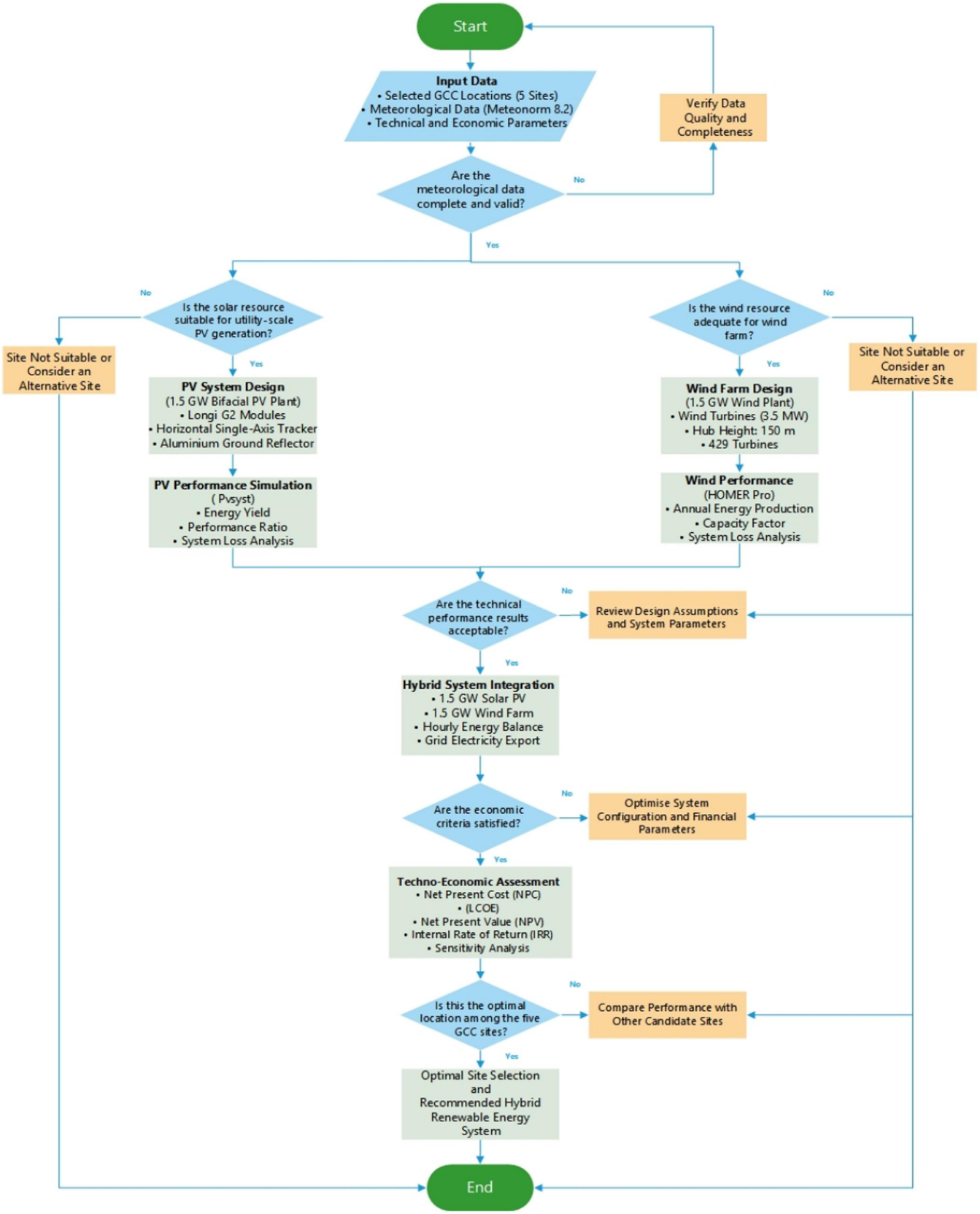


FIGURE 4 | Decision-based workflow adopted for the design, simulation, and techno-economic assessment of the proposed system across the five GCC study locations.

20500505, 0, Downloaded from https://scijournals.onlinelibrary.wiley.com/doi/10.1002/ese3.70682 by NICE, National Institute for Health and Care Excellence, Wiley Online Library on [28/10/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

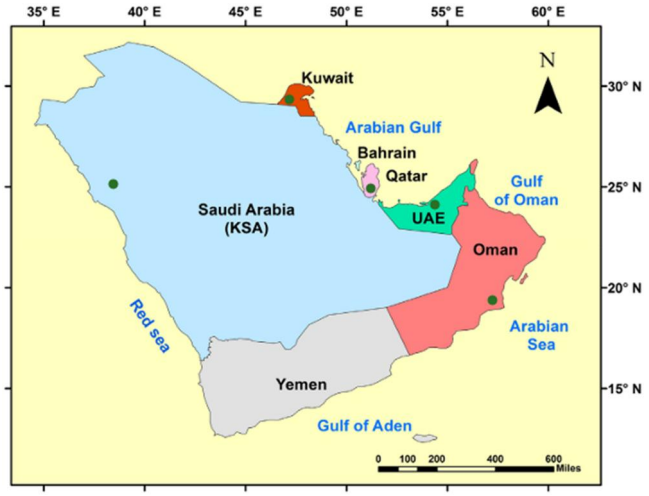


FIGURE 5 | Geographical locations of the five selected GCC study sites [21].

module (LR5-72HBD-550M G2) mounted on horizontal-axis trackers in an unlimited shed configuration. The pitch between the PV/tracking structures is 6.6 m, with a structure width of 3.04 m, resulting in a roof ground coverage ratio (GCR) of 46.1% and a height of 2.10 m above ground. An aluminium ground albedo was selected for its higher reflectivity, which enhances PV rear-side gain and mitigates efficiency losses from high module temperatures.

The module energy output is computed using a standard temperature-adjusted PV performance model in PVsyst with hourly irradiance and temperature input [22]:

$$P_{pv} = \mathrm{Pr}_{pv} \times \frac{G}{G_{stc}} \times [1 - \beta(T_G - T_{stc})] \quad (1)$$

where is P_{pv} is the instantaneous power output (W), Pr_{pv} is the rated module power (550 W), G is incident plane-of-array

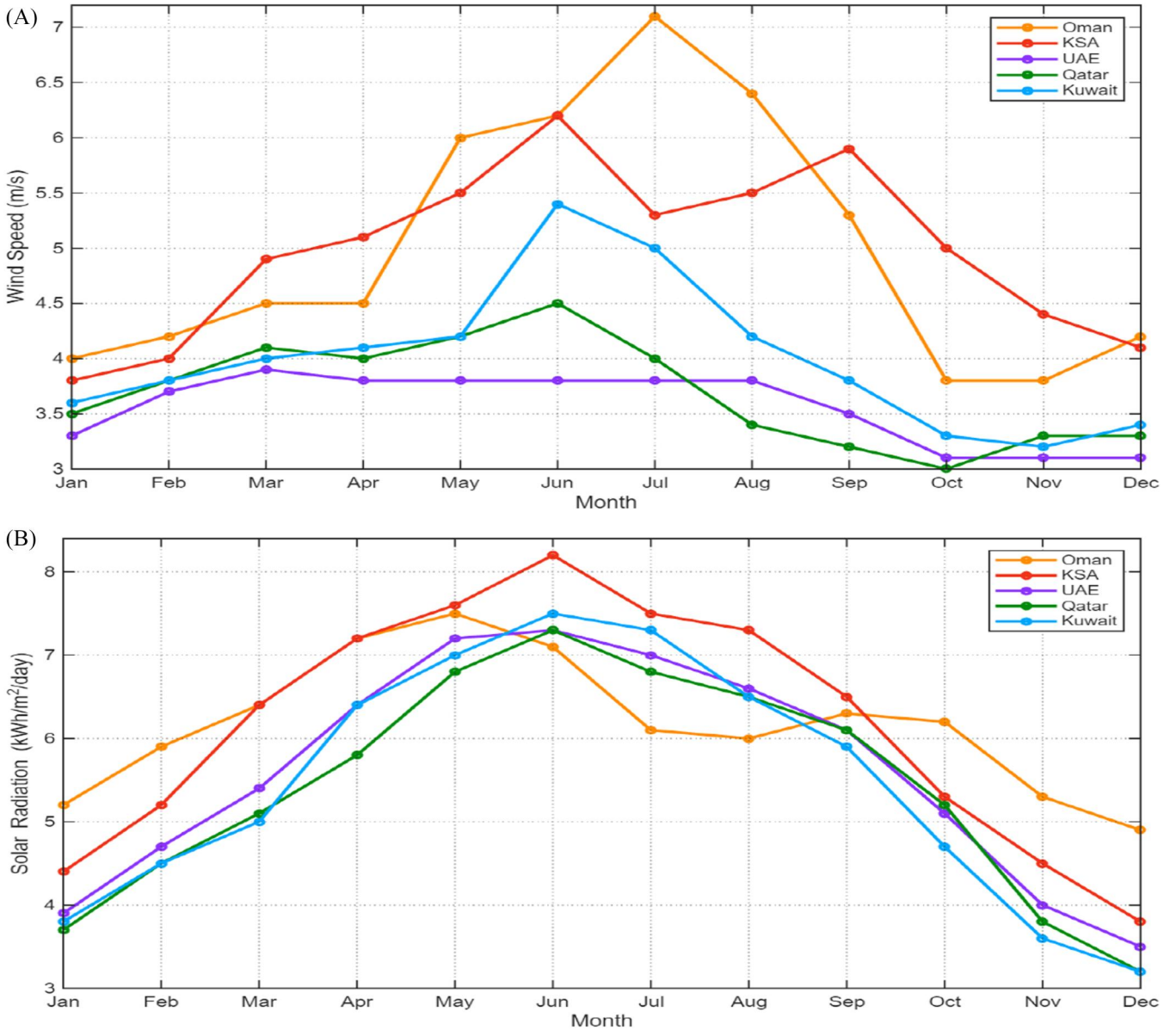


FIGURE 6 | Average monthly (A) wind speed (m/s) and (B) solar irradiance (kWh/m^2/day) for the five selected GCC study sites.

20500505, 0, Downloaded from https://scijournals.onlinelibrary.wiley.com/doi/10.1002/ese3.70682 by NICE, National Institute for Health and Care Excellence, Wiley Online Library on [28/10/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 2 | Site characteristics for the chosen locations.

Country	Location	Latitude (°N)	Longitude (°E)	Average Temp	Annual GHI (kWh/m^2/day)	Avg. wind speed (m/s)	Clearness Index
Oman	Al Duqm	19.36	57.50	26.9	6.09	5.1	0.638
KSA	Al Muwaylih	27.98	36.08	26.4	6.15	5	0.6417
UAE	Masdar City	24.43	54.61	28.4	5.58	3.6	0.613
Qatar	Umm Qarn	25.28	51.08	28.3	5.46	3.8	0.579
Kuwait	Al Muraytibah	29.28	47.18	26.8	5.47	4	0.600

TABLE 3 | The PV module key characteristics [23].

Parameter	Value
Rated Power (PSTC)	550
Module Efficiency (STC)	23.10
Open Circuit Voltage (Voc)	49.80
Voltage at Max Power (Vmpp)	41.95
Current at Max Power (Impp)	13.12
Temperature Coefficient (Pmax)	−0.33
Bifaciality Factor	70%

irradiance (W/m^2), *Gstc* is the reference irradiance at STC (1000 W/m^2), β is the temperature coefficient, T_C is the module cell temperature (°C), T_{Stc} is the reference temperature at standard test conditions (STC), which is 25°C. Table 3 summarises the main characteristics of the selected PV.

Unlike monofacial panels, bifacial modules generate power from both front and rear surfaces. The 550 W rating applies only to the front side of the device. However, Rear-side gain is dynamically calculated based on the bifaciality factor, which is 70% for the selected module, indicating the rear side can generate up to 70% of the front-side output under equivalent irradiance conditions. The actual rear-side contribution depends on several factors, including surface albedo, module height, pitch, and system geometry. Ground reflectivity and the view factor between the module and the ground also influence this rear contribution.

4 | Rear-Side Irradiance Modelling

Bifacial PV performance is modelled by assuming irradiance on both the front and rear sides. The total irradiance on the PV is used [24]:

$$G_{Total} = G_{front} + G_{rear} \times \text{bifaciality factor}, \quad (2)$$

where the rear-side irradiance is estimated using the following equation [24]:

$$G_{rear} = \alpha.\,\text{VF}.\,G_{ground}, \quad (3)$$

where α is the ground albedo (0.85 for aluminium), VF is the view factor below the rear side of the PV; the larger the pitch, the higher the view factor, and G_{ground} is the ground-reflected irradiance. Aluminium albedo was selected for the plant because of its high reflectivity ($\alpha = 0.85$), which significantly enhances the rear side and increases bifacial gain to levels comparable to typical desert surfaces, such as sand ($\alpha = 0.3$) and concrete ($\alpha = 0.35$). Thus, aluminium nearly triples the amount of reflected irradiance. The use of aluminium is especially justified in this large-scale utility setting, where long-term durability, consistent optical properties, and high energy yield are priorities, as the GCC region experiences high temperatures that reduce PV production efficiency. The system comprises 5218 Caterpillar BDP-250 inverters, providing a total AC power output of 1304.16 MW. All selected plant sites are set to a 1.15 DC/AC ratio, which was assumed for this plant, aligning with best practice for utility-scale installations to optimise inverter performance without excessive power clipping [25]. All critical losses were considered in the PVsyst simulation to ensure a realistic 25-year long-term performance projection. Those losses include optical, electrical and degrading effects summarised in Table 4.

4.1 | Wind Energy System Modelling

Wind plant systems were modelled using HOMER Pro, which provides hourly, detailed simulations based on location-specific wind profiles and selected onshore wind turbine characteristics. The selected configuration is 1.5 GW at each site, comprising Enercon wind turbines (E-138 EP3) rated at 3.5 MW each, with a height of 150 m, and a total of 429 turbines per site.

4.2 | Wind Speed Adjustment to Hub Height

Since wind speed in Meteonorm meteorological data is typically measured at low altitudes (10–15 m), vertical measurements are required to estimate wind speed at a selected height of 150 m above the wind turbine hub. In HOMER Pro, the height is adjusted using a logarithmic profile model, an empirical method that also accounts for the influence of vertical wind shear by surface roughness [27]:

$$U_{hub} = U_{anem} \times \frac{\ln(z_{hub}/z_0)}{\ln(z_{anem}/z_0)}, \quad (4)$$

where U_{hub} The wind speed at hub height (150 m) is denoted as Uanem, the measured wind speed at anemometer height, and z0 is the surface roughness length (typically 0.03–0.1 m) for desert conditions. This logarithmic adjustment is essential in

20500505, 0, Downloaded from https://scijournals.onlinelibrary.wiley.com/doi/10.1002/ese3.70682 by NICE, National Institute for Health and Care Excellence, Wiley Online Library on [28/10/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 4 | The main losses considered for the PV module calculations [26].

Loss component	Value	Description
Soiling loss	5.00%	Based on site-specific desert dust conditions
Light-induced degradation	2.00%	As per the manufacturer's specifications
Module mismatch	2.00%	Evaluated at Maximum Power Point (MPP)
String mismatch	0.15%	PVsyst default value
DC wiring loss	0.84%	Global array resistance modelled at STC
Incidence angle modifier	Variable	~0.851 at 75°, based on empirical profile
Module quality loss	~ 0.75%	PVsyst standard assumption
Thermal loss (Uc)	29 $W/m^2 \cdot K$	Constant for irradiance-based cell heating model
Annual degradation rate	0.55%/year	Applied uniformly from year 2 to year 25

TABLE 5 | The main specifications for the selected wind turbine [29].

Specification	Details
Rated Power	3.5 MW
Rotor Diameter	138.25 m
Hub Height	81-160 m
Swept Area	15,011 m^2
Cut-out wind speed	28 m/s
Cut-in wind speed	2.5 m/s
Design service life	25 years

desert and semi-arid environments, where terrain is generally flat yet highly sensitive to surface friction. The corrected hub-height wind speed was used as input for HOMER Pro to simulate hourly turbine performance.

4.3 | Power Output

Once hub-height speed is computed, the manufacturer's power curve estimates turbine output, which indicates the relationship between wind speed and electrical power under standard density conditions ($\rho 0 = 1.225\ kg/m^3$). However, air density varies with altitude and temperature; therefore, HOMER Pro applies a factor correlation to adjust the rated output for actual conditions [28]:

$$P_{actual} = P_{STP} . \left(\frac{\rho}{\rho_0} \right), \tag{5}$$

where P_{actual} is the real-time power output, P_{STP} is the power derived from the turbine's power curve at standard conditions, and ρ is the air density at the site, calculated hourly based on temperature and altitude. This correction ensures a more accurate estimation of wind energy production over time, especially in locations with substantial elevation differences. The Enercon E-138 EP3 was selected for its high efficiency, direct-drive technology, and suitability for moderate wind conditions in the GCC. Table 5 lists the key specifications.

4.4 | Techno-Economic Analysis

A techno-economic analysis evaluated the long-term performance and cost of the hybrid renewable plant modelled at five GCC locations. The study focused on two core financial metrics: net present cost (NPC) and levelised cost of energy (LCOE) for a 25-year lifetime with a fixed discount rate of 5% and an inflation rate of 2%. The replacement cost is assumed to be fixed across all locations based on the specified component lifetimes and replacement assumptions. Net present cost (NPC) refers to the total lifetime cost of a plant, discounted to its present value, including capital investment, replacement, and operation and maintenance. HOMER Pro calculates NPC using the following formula [30]:

$$\text{NPC} = \sum_{t=1}^{N} \frac{C_t}{(1 + r)^t}, \tag{6}$$

where C_t is the net cash outflow in year t, r is the real discount rate, and N is the project lifetime (25 years). The capital cost includes all wind turbines, PV modules, inverters, and supporting components.

HOMER Pro analysed and scheduled replacement costs based on component lifetimes: wind turbines (25 years), PV (25 years), and inverters (15 years). Operation and maintenance costs were defined analytically and increased with inflation.

Levelised cost of energy (LCOE) was calculated to evaluate the cost of electricity delivered to the grid by the hybrid system over the 25-year project lifetime. In this study, LCOE is calculated as a conventional cost-based indicator, using the annualised system cost divided by the annual electricity sold to the grid. Therefore, electricity-sale revenue is not included in the LCOE calculation, and only electricity delivered to the grid is considered in the denominator. The grid-delivered LCOE is expressed as [31]:

$$LCOE_{grid} = \frac{C_{annualised}}{E_{grid}}, \tag{7}$$

where $C_{annualised}$ is the total annualised system cost ($/year) and E_{grid} is the annual electricity sold to the grid (kWh/year). The annualised system cost is calculated as [31]:

20500505, 0, Downloaded from https://scijournals.onlinelibrary.wiley.com/doi/10.1002/ese3.70682 by NICE, National Institute for Health and Care Excellence, Wiley Online Library on [28/10/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 6 | Various plant component costs.

Component	Lifetime (yrs)	Capital Cost ($ M)	O&M ($ M)	Notes
PV Modules	25	$1280.821	$340.215	Longi LR5-72HBD-550M G2 [33]
Wind Turbines	25	$1544.581	$705.955	Enercon E−138 EP3, 3.5 MW each [34]
Inverters	15	$47.755	$18.291	Caterpillar BDP-250 inverters [25, 35]

TABLE 7 | National grid CO_2 emission factors for the five GCC countries.

Country	Grid CO_2 emission factor (gCO_2eq/kWh)
KSA	543
Oman	490
Kuwait	559
Qatar	489
UAE	359

$$C_{annualised} = C_{Capex} \times CRF + C_{O\&M,annual} + C_{replacement,annual} - C_{salvage,annual}, \quad (8)$$

where C_{Capex} is the initial capital cost, $C_{O\&M,annual}$ is the annual operation and maintenance cost, $C_{replacement,annual}$ is the annual replacement cost, and $C_{salvage,annual}$ is the annual salvage-value credit. The capital recovery factor (CRF) is calculated by [31]:

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1}, \quad (9)$$

where i is the discount rate, 5%, and N is the project lifetime, 25 years, resulting is a CRF of 0.07095. The total O&M cost over the 25-years is $1064.3 million, corresponding to an average annual O&M cost of $42.572 million/year. The replacement cost of $26.8 million is assumed to occur in year 15, while the salvage value of $6.7 million is received at the end of year 25 [32]. Table 6 summarises the plant component costs.

For the grid-connected configuration, HOMER Pro distinguishes electricity sold to the grid from excess electricity. Only electricity explicitly exported to the grid is assigned a financial revenue, whereas excess electricity that cannot be utilised within the modelled system is treated as unutilised generation and does not generate revenue.

4.5 | Environmental Assessment

To quantify the environmental benefit of CO_2 emissions displacement, emissions are evaluated using the renewable energy output produced and the emission factor for each country. The avoided emissions are obtained by multiplying the annual electricity generated by the national grid CO_2 emission factor of displaced generation [36]:

$$E_y = E_{wind,1} + E_{PV,1}(1-d)^{y-1}, \quad (10)$$

$$CO_{2,\text{lifetime}} = EF_{\text{grid}} \sum_{y=1}^{25} [E_{wind,1} + E_{PV,1}(1-d)^{y-1}], \quad (11)$$

where E_y is the annual electricity generation in year y (kWh), $E_{wind,1}$ is the first-year wind electricity generation (kWh), $E_{PV,1}$ is the first-year PV electricity generation (kWh), d is the annual degradation rate (0.0055), and EF_{grid} is the grid emission factor ($kgCO_2/kWh$), and N is the 25-year project lifetime; the resulting emissions are expressed in $kgCO_2$ and reported in Mt ($1\ Mt = 10^9\ kg$). The lifecycle emission factor for each country is expressed in gCO_2eq/kWh and converted to $kgCO_2/kWh$ in the calculation, as illustrated in Table 7. To quantify the environmental benefits of the proposed system, avoided CO_2 emissions were estimated by multiplying the annual renewable electricity generated by the national grid CO_2 emission factor. To account for the assumed PV degradation rate of 0.55%/year, PV electricity generation was adjusted progressively over the 25-year project lifetime, while wind generation was maintained at its annual value, as no wind degradation rate was assumed. Lifetime avoided CO_2 emissions were calculated by summing the annual avoided emissions over the 25-year project lifetime.

5 | Results and Discussions

Although all sites share a similar geographical topology, each country faces distinct climate effects, reflected in variations in wind and solar power output at each location. All the countries included in the study have a vision for a green hydrogen economy; thus, this study helps assess this transition in terms of the techno-economics of energy production. The sites were selected based on existing or planned plants, considering infrastructure availability, transportation, and proximity to load centres. The renewable plant simulated in this study is designed to support the conventional grid when required with clean, sustainable energy.

5.1 | Energy Production Analysis

To better understand the seasonal dynamics and performance of the proposed hybrid systems, this section presents the monthly electricity production profiles. Figure 7 illustrates the monthly electricity production of the wind, solar photovoltaic (PV), and combined hybrid systems for the five selected GCC locations.

Figure 7 presents the monthly wind, PV, and total hybrid electricity production potential for KSA, Oman, Kuwait, Qatar, and the UAE. The upper panel (a) shows that wind generation changes substantially throughout the year because of seasonal variations in wind speed. Oman exhibits a pronounced summer

20500505, 0, Downloaded from https://scijournals.onlinelibrary.wiley.com/doi/10.1002/ese3.70682 by NICE, National Institute for Health and Care Excellence, Wiley Online Library on [28/01/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

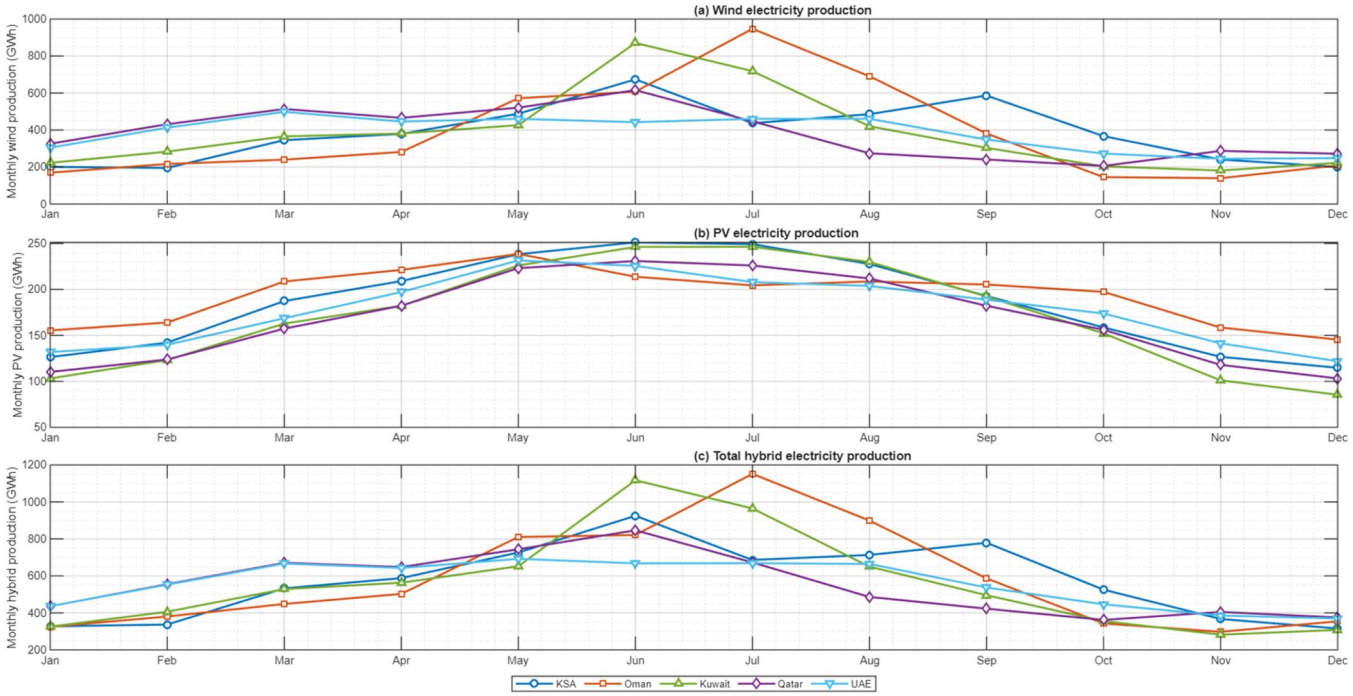


FIGURE 7 | Monthly electricity production of wind, solar PV, and total hybrid systems across the five GCC locations, showing seasonal variability in renewable energy generation.

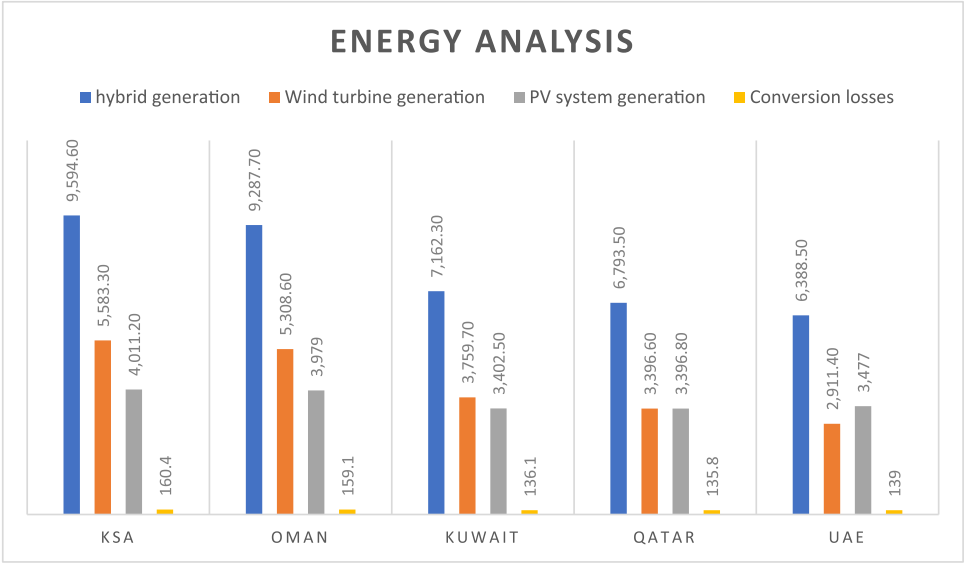


FIGURE 8 | The total electrical energy output for all five locations.

wind production peak, particularly from May to August, reflecting its relatively strong seasonal wind resource. KSA also maintains comparatively high wind production across most months, with peak output in late spring and early summer. Kuwait, Qatar, and the UAE show lower or more moderate wind production patterns, although each country has distinct monthly variations. The middle panel (b) indicates that PV electricity production generally increases from winter to summer as solar irradiance rises. PV generation reaches its highest value mainly between May and August, when daily GHI is greatest across the GCC countries. Oman and KSA show strong PV production because of their high monthly solar irradiation, especially during summer. Kuwait also achieves high PV output in June and July, despite its comparatively lower wind resource. The lower panel (c) combines the wind and PV contributions and demonstrates the complementary role of the two renewable technologies. Total hybrid electricity production is highest in months when both solar irradiance and wind speed are favourable, while production is lower during periods of weaker resources. Overall, the figure shows that combining wind and PV systems can reduce seasonal variability and provide a more stable monthly renewable electricity supply than either technology operating alone. Figure 8 shows the energy production for each system in each country.

20500505, 0, Downloaded from https://scijournals.onlinelibrary.wiley.com/doi/10.1002/ese3.70682 by NICE, National Institute for Health and Care Excellence, Wiley Online Library on [28/01/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

KSA's energy production is 9594.6 GWh/year, the highest in the Gulf region, supplied by wind and solar PV systems. Wind turbine energy production is 5583.3 GWh/year, accounting for 58.2% of total production, with a capacity factor of 42.5%. The PV system's energy output is 4011.2 GWh/year, representing 41.8% of total production and a capacity factor of 30.5%. The conversion losses are 160.4 GWh/year.

Oman's total energy production is 9287.7 GWh/year, the second-highest in the region. The wind turbine system produces 5,308.6 GWh/year, accounting for 57.2% of total production, with a capacity factor of 40.4%. The PV system produces 3,979 GWh/year, accounting for 42.8% of total production, with a capacity factor of 30.3%. The conversion losses are 159.1 GWh/year.

Kuwait ranks third, with total energy production of 7,162.3 GWh/year, of which 3759.7 GWh/year is produced by wind turbine systems, representing 52.5% of total output. The solar bifacial PV system accounts for 47.5% of the total, at 3402.5 GWh/year. The capacity factors for the wind turbine and PV systems are 28.6% and 25.9%, respectively. The conversion losses are 136.1 GWh/year.

Next comes Qatar, with a total energy production of 6793.5 GWh/year, split between wind turbine production of 3396.6 GWh/year and PV system output of 3396.8 GWh/year, contributing 50% and 50%, respectively. The wind capacity factor is 25.8%, and the PV system is 25.9%. The conversion losses are 135.8 GWh/year.

Fifth is the UAE, with total energy production of 6388.5 GWh/year. Wind turbines contribute 2911.4 GWh/year, accounting for 45.6% of the total output, while solar systems produce 3477 GWh/year, representing 54.4% of the total energy produced. The wind turbine system achieves a capacity factor of 22.2%, while the solar PV system achieves 26.5%. The conversion losses are 139 GWh/year. The difference in annual energy production is primarily attributed to spatial variation in solar irradiance and wind resources. In particular, stronger wind resources at the KSA and Oman sites result in higher wind capacity factors and, consequently, greater annual hybrid electricity production.

5.2 | Technical Performance Analysis

This section examines how effectively installed capacity is utilised, expressed as system-level technical indicators summarised in Table 8. To ensure consistency, capacity-factor comparisons are based on nameplate capacity.

The wind resource varies markedly across the sites (CF 42.5-22.2%), shifting the generation mix from wind-dominant in KSA (58.3%) to PV-dominant in the UAE (54.4%). This is mainly because PV output varies less across regions (26.5%–30.5%) than wind output; therefore, variation in hybrid capacity factor across sites is strongly influenced by the wind resource, which falls from 42.5% to 22.2% across sites. Results indicate that pairing a wind source with a stable solar baseline sustains the system capacity factor at 26.5%–30.5% across all sites.

The site results reveal two technical regimes: KSA and Oman, with strong wind energy production achieving energy density above 3000 GWh/yr per installed GW, whereas Kuwait, Qatar, and the UAE are constrained by weaker wind energy output of around 2129.5–2387.4 GWh/yr per GW despite comparable solar resources. This analysis confirms that, for hybrid RE in the GCC, wind energy is the significant factor relative to solar resources in terms of technical utilisation.

5.3 | Economic Analysis

All five plants share the same initial capital cost and component configuration assumptions. The capital, O&M, replacement, and salvage costs are therefore identical across the five locations. Differences in economic performance primarily arise from site-specific renewable electricity generation, electricity exported to the grid, electricity-sale revenue, NPC and payback period. The five locations vary in the amount of energy sold to the grid, and the selling price is set at \$0.08/kWh to support the conventional grid power, green energy hubs, and industrial areas [37]. In HOMER Pro, electricity exported to the grid is distinguished from excess electricity and plant losses. For example, KSA generated 9594.7 GWh/year of clean electricity, of which 9434.1 GWh/year was sold to the grid. Only electricity explicitly exported to the grid was assigned revenue at the export tariff. Therefore, KSA's annual grid-sale revenue was calculated from 9434.1 GWh/year at a rate of \$0.08/kWh, resulting in \$754.7 million/year [38]. The excess electricity was treated as unutilised energy and was not included in the electricity sale revenue. The energy losses mainly result from power-conversion losses. As in all locations, Table 9 shows grid export, electricity losses, and the losses fraction.

Table 9 further indicates that Oman sold 9128.5 GWh/year to the grid, with a loss fraction of 1.71%, and generated annual revenue of \$730.2 million/year. Next, Kuwait sold 7026.2 GWh/year to the grid, with a loss fraction of 1.90%. Annual revenue is \$562 million/year. Then, Qatar sold 6,657.6 GWh/year to the grid, with a loss fraction of 2%. The revenue is \$532.6 million/year. Finally, the UAE injected 6249.4 GWh/year into the grid, with a fractional loss of 2.18%. The total revenue is \$499.9 million/year. Figure 9 summarises selling-to-grid revenue.

TABLE 8 | System-level technical performance indicators of the 3 GW hybrid plants across the five GCC locations.

Country	Wind CF (%)	PV CF (%)	Hybrid CF (%)	Energy density (GWh/yr per GW)	Wind: PV split (%)
KSA	42.5	30.5	36.5	3,198.2	58.3:41.7
Oman	40.4	30.3	35.3	3,095.9	57.2:42.8
Kuwait	28.6	25.9	27.3	2,387.4	52.5:47.5
Qatar	25.8	25.9	25.9	2,264.5	50:50
UAE	22.2	26.5	24.3	2,129.5	45.6:54.4

20500505, 0, Downloaded from https://scijournals.onlinelibrary.wiley.com/doi/10.1002/ese3.70682 by NICE, National Institute for Health and Care Excellence, Wiley Online Library on [28/10/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Figure 9 indicates that KSA has the highest income, totalling $754.7 million/year. Second is Oman, at $730.2 million/year. Kuwait ranks next, at $562 million/year. Fourth is Qatar, at $532.6 million/year. Finally, the UAE has total selling revenue of $499.9 million. The same 3 GW system configuration and cost assumptions were used at all five locations; initial capital cost, O&M cost, replacement cost, and salvage cost are identical. Differences in economic performance therefore result mainly from site-specific electricity generation, grid sales revenue, NPC, and payback period. Higher renewable output increases lifetime revenue and shortens the payback period. Figure 10 shows the NPC analysis.

TABLE 9 | Annual grid export, electricity losses, and losses fraction.

Country	Electricity sold to grid (GWh/year)	Electricity losses (GWh/year)	Losses fraction (%)
KSA	9434.1	160.4	1.68
Oman	9128.5	159.1	1.71
Kuwait	7026.2	136.1	1.90
Qatar	6657.6	135.8	2.00
UAE	6249.4	139.0	2.18

The NPC analysis shows substantial differences in the lifetime economic performance of the five locations. KSA and Oman achieve higher electricity generation and grid electricity exports, resulting in higher electricity-sale revenues, whereas Kuwait, Qatar, and the UAE exhibit progressively lower revenues. HOMER Pro represents electricity sales as a negative cash flow rather than a conventional cost-only lifecycle metric. Therefore, interpret the NPC values alongside electricity export, revenue, payback period, and grid-delivered LCOE rather than as standalone measures of project cost. Table 10 summarises the economic analysis.

The payback period varies across the five locations, ranging from 4.03 years in KSA to 6.28 years in the UAE. The shorter payback periods in KSA and Oman mainly reflect higher annual electricity generation and grid sales, which increase revenues. Capital, O&M, replacement, and salvage costs are identical across the five locations because the same system configuration and cost assumptions apply.

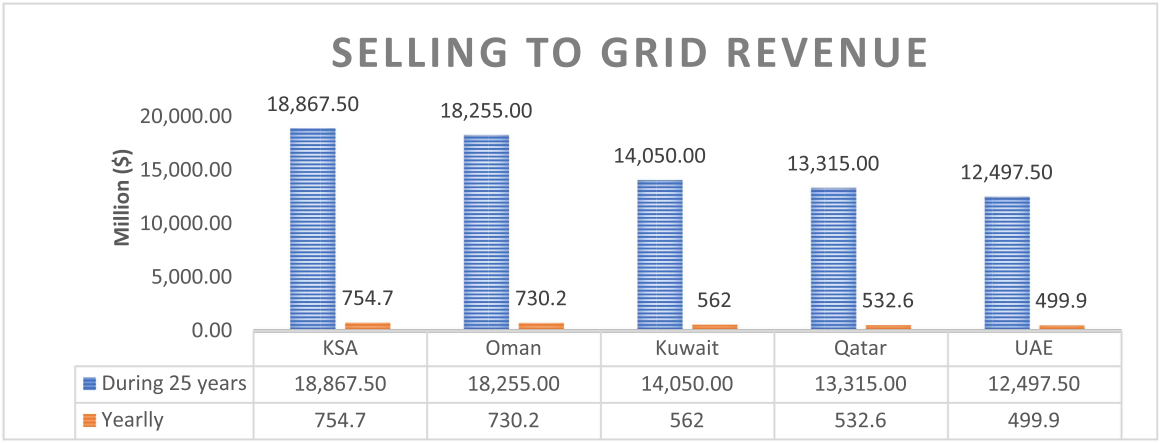


FIGURE 9 | The total income obtained from selling electricity to the grid.

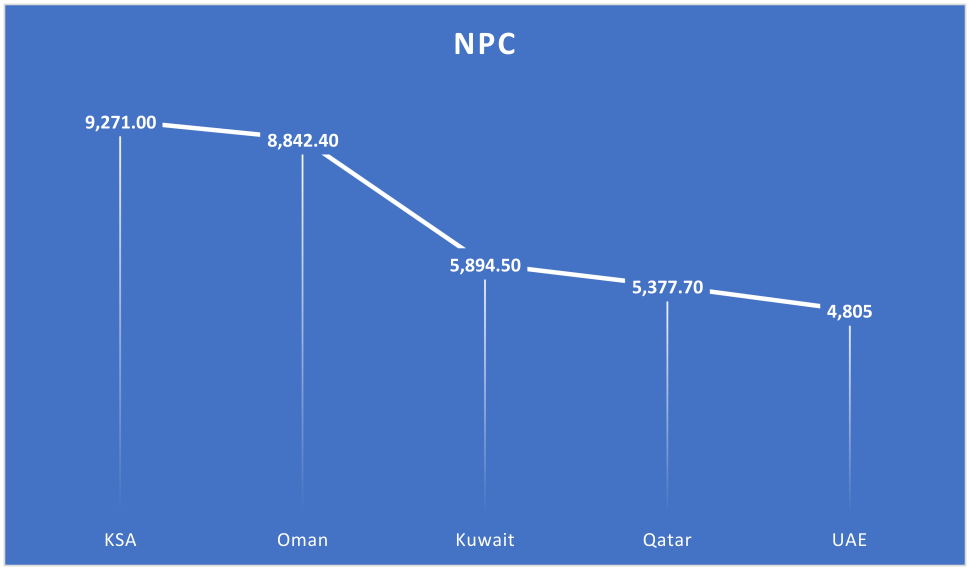


FIGURE 10 | NPC variation among five GCC countries.

20500505, 0, Downloaded from https://scijournals.onlinelibrary.wiley.com/doi/10.1002/ese3.70682 by NICE, National Institute for Health and Care Excellence, Wiley Online Library on [28/10/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 10 | Economic analysis summary.

Country	NPC ($M)	Capital Cost ($M)	O&M Cost ($M)	Replacement cost ($M)	Salvage cost ($M)	Revenue ($M/25 yr)	Payback period (yr)
KSA	9271	2873.1	1064.3	26.8	6.7	18,867.5	4.03
Oman	8842.4	2873.1	1064.3	26.8	6.7	18,255	4.18
Kuwait	5894.5	2873.1	1064.3	26.8	6.7	14,050	5.53
Qatar	5377.7	2873.1	1064.3	26.8	6.7	13,315	5.86
UAE	4805.3	2873.1	1064.3	26.8	6.7	12,497.5	6.28

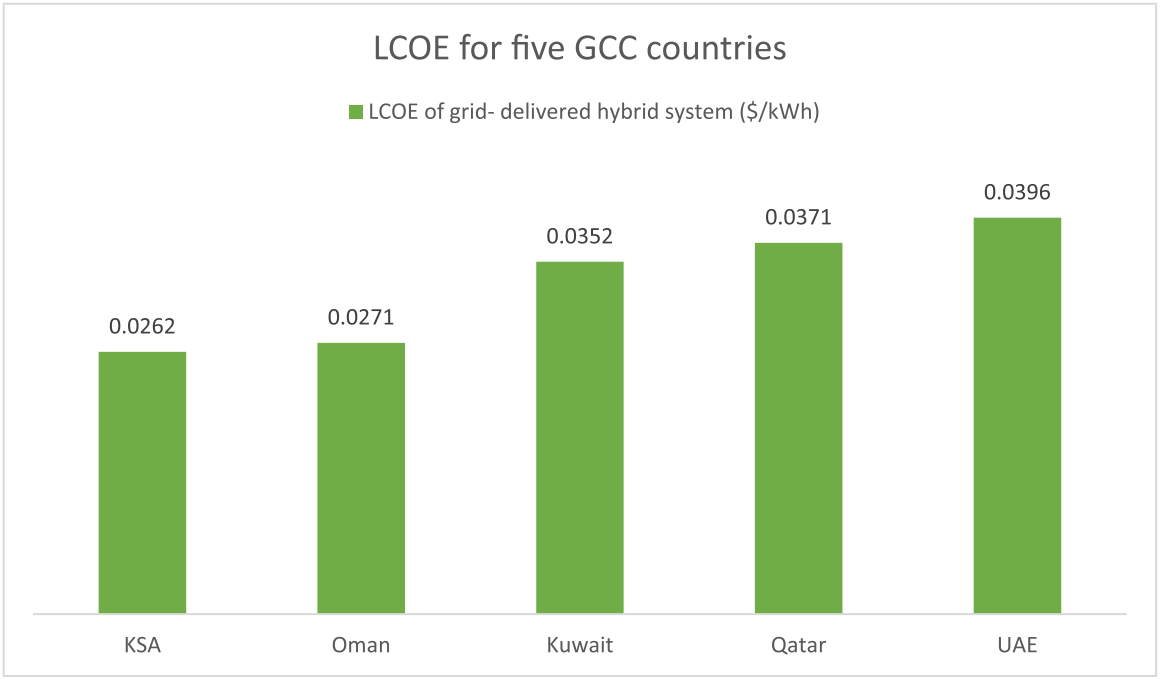


FIGURE 11 | Grid-delivered levelised cost of energy for the five GCC countries.

5.4 | Levelised Cost of Energy (LCOE)

Figure 11 below presents the calculated grid-delivered levelised cost of energy LCOE for the five investigated GCC locations. The LCOE was calculated using the cost-based approach described in section 2.9:

Figure 11 shows clear differences in the LCOE among the five GCC locations. KSA achieves the lowest LCOE at $0.0262/kWh, followed by Oman at $0.0271/kWh. Kuwait, Qatar, and the UAE exhibit higher values of $0.0352/kWh, $0.0371/kWh, and $0.0396/kWh, respectively. The lower LCOE in KSA and Oman is mainly due to higher annual electricity generation and greater electricity delivered to the grid, which increases the energy output over which the annualised system cost is distributed. In contrast, the UAE exhibits the highest LCOE because of its lower renewable electricity generation and grid electricity export.

Overall, the results indicate that KSA and Oman provide the most favourable cost performance among the investigated locations, while the UAE has the highest cost per unit of electricity delivered to the grid. The variation highlights the importance of selecting locations with complementary and favourable renewable resource conditions when developing a large-scale hybrid renewable energy system. The result also demonstrates that improving renewable resource utilisation can reduce the cost of electricity delivered to the grid without changing the installed system configuration.

5.5 | Sensitivity Analysis of the NPC

To evaluate the sensitivity of the economic performance of the proposed hybrid renewable energy system to key financial assumptions, a comprehensive sensitivity analysis was performed by varying the inflation rate (2%, 4%, and 6%), discount rate (3%, 5%, and 7%) and electricity selling price ($0.03, $0.08, $0.13/kWh), while maintaining the same technical configuration, installed capacities, and renewable resource conditions for all five GCC countries, The base case was defined using an inflation rate of 2%, a discount rate of 5%, and electricity selling price of $0.08/kWh. These three financial parameters produced 27 financial scenarios for each country, allowing evaluation of the individual and combined effects of the economic assumptions on the system's net present cost (NPC). Figures 12–14 illustrate the sensitivity of the economic performance to variations in the discount rate, inflation rate, and electricity selling price.

20500505, 0, Downloaded from https://scijournals.onlinelibrary.wiley.com/doi/10.1002/ese3.70682 by NICE, National Institute for Health and Care Excellence, Wiley Online Library on [28/10/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

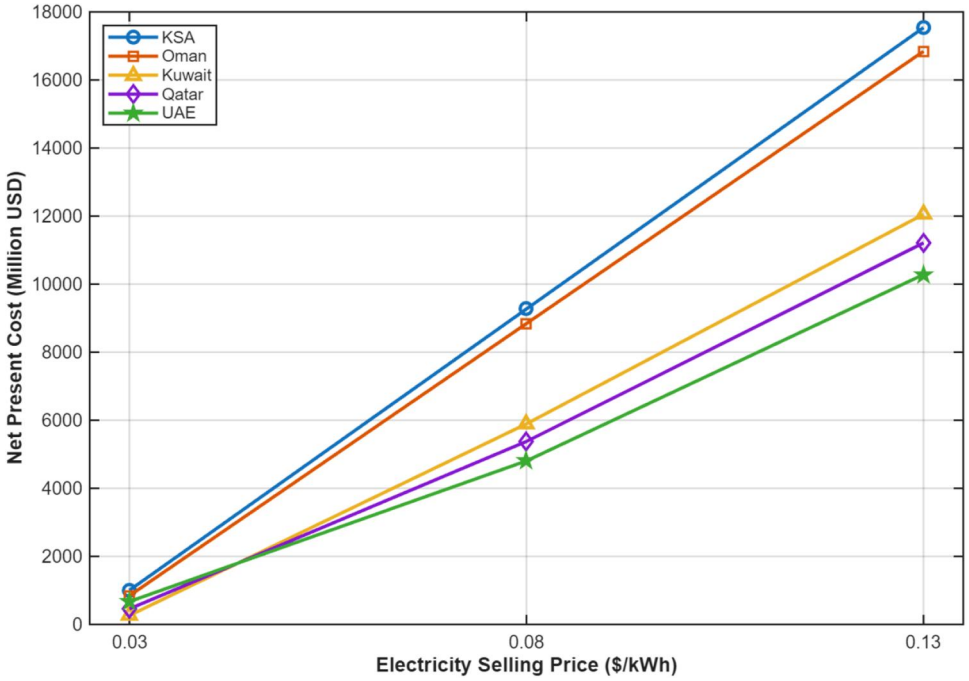


FIGURE 12 | Sensitivity of NPC to electricity selling price.

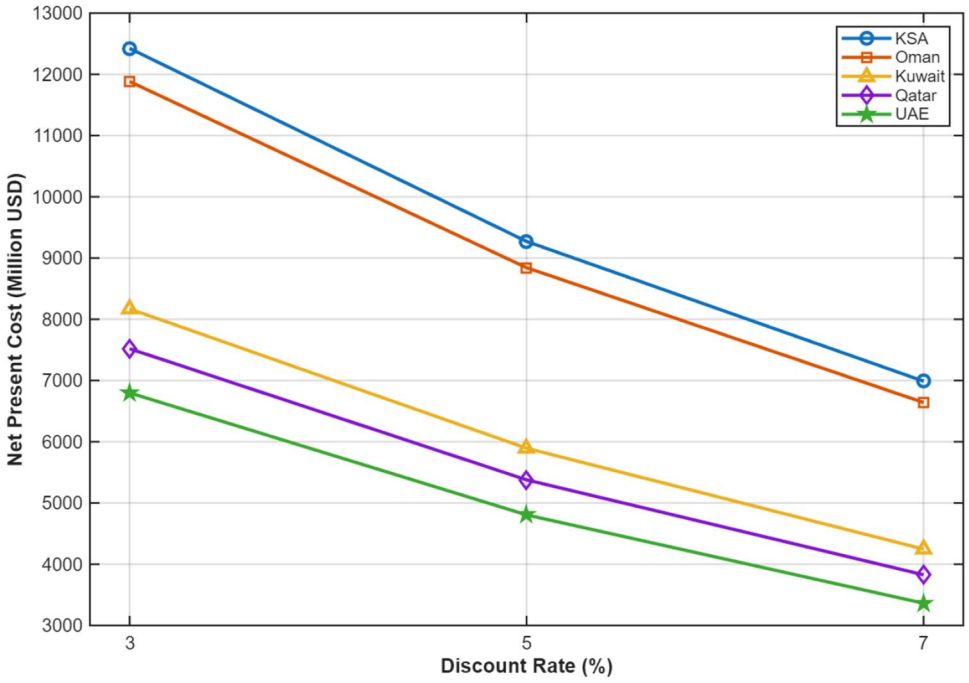


FIGURE 13 | Sensitivity of NPC to the discount rate.

Figure 12 shows a strong increase in NPC as the electricity selling price rises from \$0.03 to \$0.13/kWh across all five GCC countries. KSA and Oman exhibit the largest increase in NPC, while the UAE shows the smallest change over the investigated price range. Overall, the results highlight the strong influence of electricity selling price on the hybrid renewable system's economic performance. Figure 13 explains the sensitivity of NPC to the discount rate.

Figure 13 shows that NPC decreases as the discount rate rises from 3% to 7% across all five GCC countries. KSA has the highest NPC, decreasing from \$12,423.3 million to \$6988.9 million, while the UAE has the lowest, decreasing from \$6789.4 million to \$3362.4 million. This behaviour reflects the reduced present value of the future cash flow at higher discount rates. Despite these changes, the country ranking remains unchanged. Figure 14 shows the NPC sensitivity to the inflation rate.

Figure 14 shows that NPC increase consistently as the inflation rate rises from 2% to 6% across all five GCC countries. KSA exhibits the highest NPC, increasing from \$9271 million to \$16,767.8 million, while the UAE shows the lowest values,

20500505, 0, Downloaded from https://scijournals.onlinelibrary.wiley.com/doi/10.1002/ese3.70682 by NICE, National Institute for Health and Care Excellence, Wiley Online Library on [28/10/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

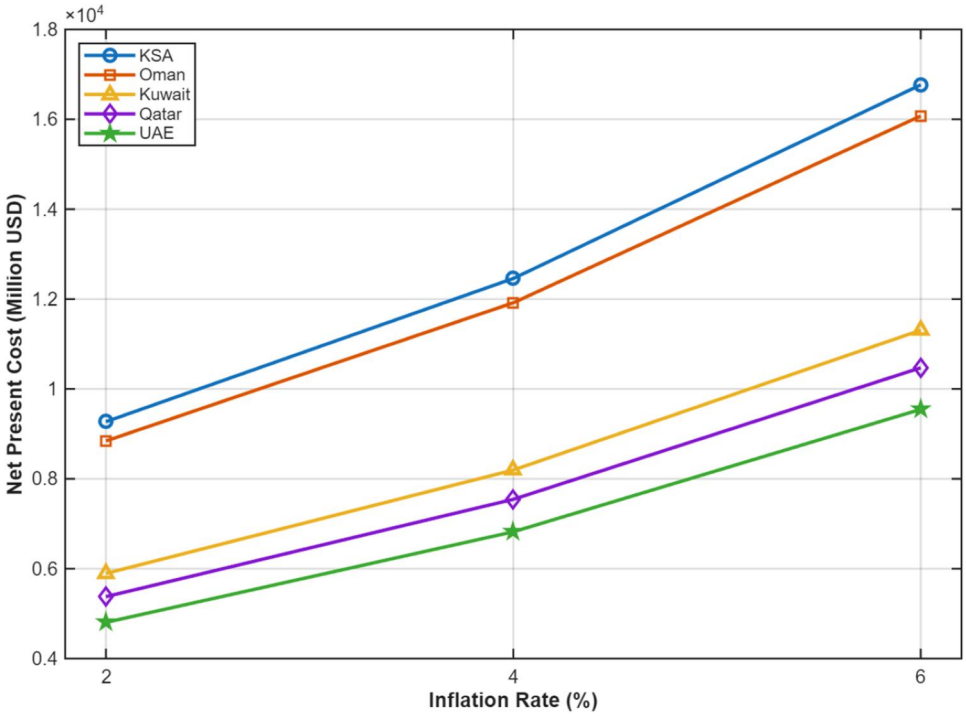


FIGURE 14 | Sensitivity of NPC to the inflation rate.

increasing from $4805.3 million to $9546.1 million. The results indicate that inflation substantially affects the long-term economic performance of hybrid renewable energy systems.

Overall, the sensitivity analysis shows that electricity selling price and inflation strongly affect NPC, while a higher discount rate reduces NPC. KSA and Oman maintain the strongest economic performance across the investigated scenarios.

5.6 | Sensitivity Analysis of the LCOE

A sensitivity analysis evaluated the influence of the discount rate and inflation rate on the LCOE. The discount rate was varied between 3%, 5%, and 7%, while the inflation rate was varied between 2%, 4%, and 6%. The remaining technical configuration, installed capacities, renewable resource conditions, and electricity sold to the grid were maintained at their respective values. The base case corresponds to a discount rate of 5% and an inflation rate of 2%. Figure 15 presents the combined sensitivity analysis of LCOE for the five locations.

Figure 15 presents the combined sensitivity analysis of the discount rate and inflation rate on the LCOE. Increasing the discount rate increases the LCOE across all five GCC countries because the annualised capital cost increases with the capital recovery factor. At a fixed 2% inflation rate, increasing the discount rate from 3% to 7% increases the LCOE from $0.0222 to 0.0335/kWh to $0.0306 to 0.0463/kWh across the five locations. Increasing the inflation rate also increases the LCOE because the assumed inflation increases the future O&M cost burden over the project lifetime. At the base discount rate of 5%, increasing inflation from 2% to 6% increases the LCOE from $0.0262 to 0.0396/kWh to $0.0287 to 0.0433/kWh. KSA and Oman maintain the lowest LCOE across the investigated scenarios, whereas the UAE consistently exhibits the highest LCOE. The country ranking therefore remains unchanged, indicating that the comparative advantage of the higher-yielding location is robust to the financial assumptions investigated.

5.7 | Environmental Analysis

Applying Equation (10) and Equation (11) with the grid emission factor in Table 7, the annual and lifetime avoided CO_2 emissions were evaluated for each hybrid plant in five countries as presented in Table 11.

The hybrid renewable plants mitigated between 2.29 Mt/yr (UAE) and 5.21 Mt/yr (KSA) of CO_2, equivalent to 55–126 Mt over the plants' lifetimes. The result reflects the product of two important factors, annual generation and grid carbon intensity, rather than generation alone. This is why Kuwait, despite generating less than Oman, mitigates a comparable amount (4.00 vs. 4.55 Mt/yr), since most of its grid is carbon-intensive (559 gCO_2eq/kWh). In contrast, the UAE mitigates the least because of lower power generation and a national grid already partially decarbonised by nuclear plants, resulting in less CO_2 displacement per unit of electricity. The analysis confirms that, alongside economic competitiveness, the renewable energy system delivers substantial decarbonisation, aligning with the national net-zero commitments of the GCC.

6 | Conclusion

This study presents a techno-economic and environmental assessment of a 3 GW hybrid renewable energy system comprising 1.5 GW of bifacial photovoltaic (PV) capacity and

20500505, 0, Downloaded from https://scijournals.onlinelibrary.wiley.com/doi/10.1002/ese3.70682 by NICE, National Institute for Health and Care Excellence, Wiley Online Library on [28/10/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

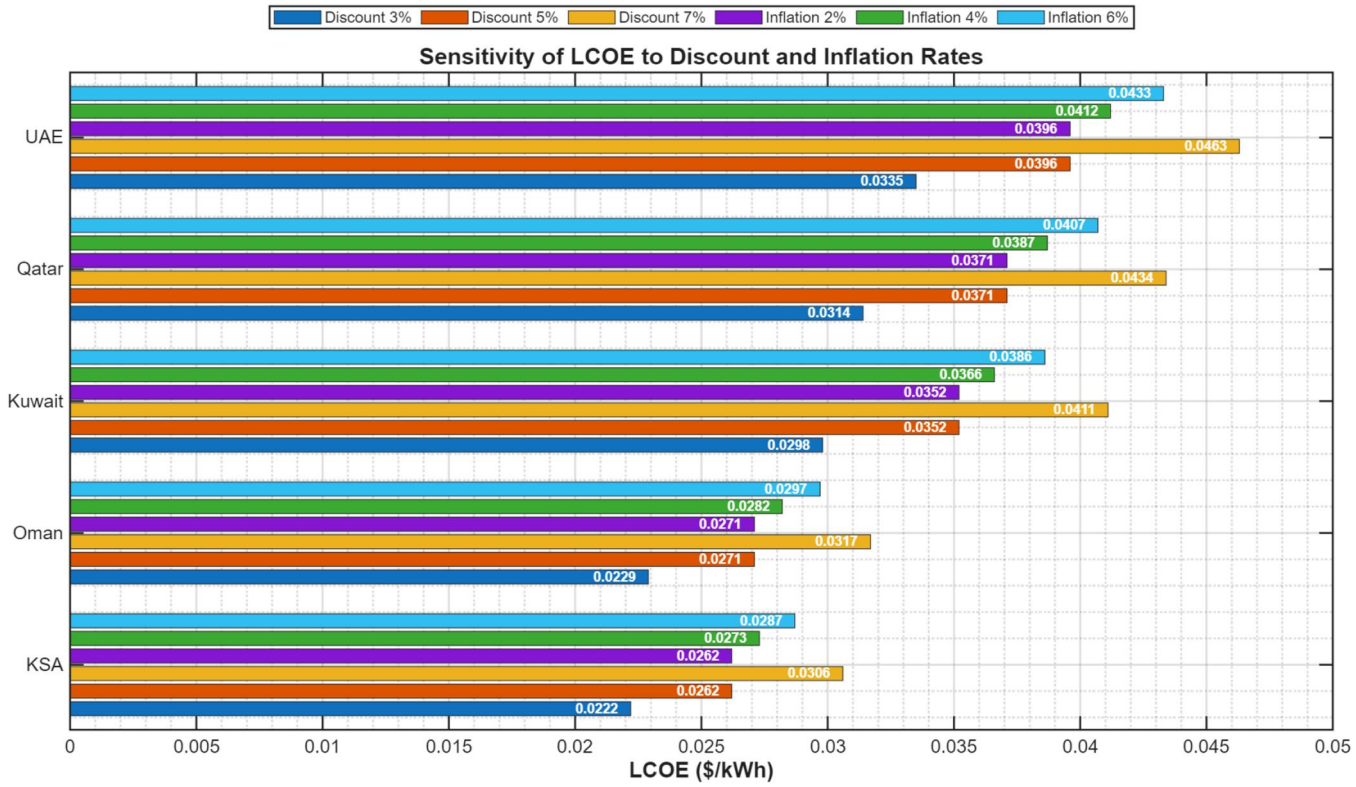


FIGURE 15 | Sensitivity analysis of LCOE to discount and inflation rates.

TABLE 11 | Annual and lifetime avoided CO_2 emissions for the five GCC hybrid plants.

Country	Annual generation (GWh/yr)	Annual avoided CO_2 (Mt/yr)	Lifetime avoided CO_2 — 25 yr (Mt)
KSA	9595	5.21	126.8
Oman	9287	4.55	110.7
Kuwait	7162	4.00	97.1
Qatar	6793	3.32	80.4
UAE	6388	2.29	55.4

1.5 GW of wind capacity across five locations: KSA, Oman, Kuwait, Qatar, and the UAE. The results show that site-specific renewable resource conditions strongly influence the hybrid system's performance. KSA achieved the highest annual renewable electricity generation of 9594.7 GWh/year, followed by Oman at 9287.7 GWh/year, while the UAE recorded the lowest generation at 6388.5 GWh/year. The corresponding electricity delivered to the grid was 9434.1 GWh/year, 9128.5 GWh/year, 7026.2 GWh/year, 6657.6 GWh/year, and 6,249.4 GWh/year for KSA, Oman, Kuwait, Qatar, and the UAE, respectively.

The economic results indicate that KSA and Oman provide the most favourable performance among the investigated locations. Grid-delivered LCOE ranged from \$0.0262/kWh in KSA to \$0.0396/kWh in the UAE, with Oman, Kuwait, and Qatar at \$0.0271/kWh, \$0.0352/kWh, and \$0.0371/kWh, respectively. The lower LCOE values in KSA and Oman mainly reflect higher renewable electricity generation and greater electricity delivered to the grid. The sensitivity analysis showed that increasing the discount rate or inflation rate increases the LCOE, while the ranking of the five locations remained unchanged, demonstrating that the relative cost advantages of KSA and Oman are robust to the investigated financial assumptions.

The environmental assessment showed substantial potential to reduce grid-related CO_2 emissions. Annual avoided emissions ranged from 2.29 Mt/yr in the UAE to 5.21 Mt/yr in KSA, corresponding to approximately 55.4 - 126.8 Mt over the 25-year project lifetime. These results demonstrate that the environmental benefits depend on both renewable electricity generation and national grid carbon intensity. Overall, KSA provides the strongest combination of renewable electricity generation, electricity delivered to the grid, and cost performance, followed by Oman. The findings highlight the importance of site-specific renewable resource assessment when planning large-scale hybrid PV-wind systems across the GCC. Future work should consider energy storage, grid constraints, transmission requirements, electricity curtailment, and more detailed component degradation and operational assumptions to further improve the assessment of large-scale renewable energy deployment in the region.

Author Contributions

Ammar Al Sawafi: software, writing – original draft, project administration. **Al Hussain Al Rashdi:** methodology, software, formal analysis, writing – review and editing. **Yahya Al Ismaili:** formal analysis, project administration, visualisation, writing – review and editing. **Kevin Hughes:**

20500505, 0, Downloaded from https://scijournals.onlinelibrary.wiley.com/doi/10.1002/ese3.70682 by NICE, National Institute for Health and Care Excellence, Wiley Online Library on [28/10/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

supervision. **Lin Ma:** supervision. **Derek Ingham:** supervision, writing – review and editing, project administration. **Mohammed Pourkashanian:** supervision. **Yang Zhang:** supervision. **Bill Nimmo:** supervision.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. Hannah Ritchie and Max Roser. (2020) [Online Resource] (archived on August 10, "CO_2 emissions" 2020: Published online at OurWorldinData.org. Retrieved from: 'https://archive.ourworldindata.org/20260810-163104/co2-emissions.html'.

2. IEA, World Energy Outlook. 2023. 2023, IEA: Paris.

3. IRENA., *Renewable Energy Market Analysis: GCC 2019* (International Renewable Energy Agency, 2019).

4. A. Sanfilippo, M. Vermeersch, and V. B. Benito, "Energy Transition Strategies in the Gulf Cooperation Council Countries," *Energy Strategy Reviews* 55 (2024): 101512.

5. IRENA. Renewable Energy Markets: GCC 2023. 2023: Abu Dhabi, 2023.

6. F. R. Alharbi and D. Csala, "Gulf Cooperation Council Countries' Climate Change Mitigation Challenges and Exploration of Solar and Wind Energy Resource Potential," *Applied Sciences* 11, no. 6 (2021): 2648.

7. X. Sun, M. R. Khan, C. Deline, and M. A. Alam, "Optimization and Performance of Bifacial Solar Modules: A Global Perspective," *Applied Energy* 212 (2018): 1601–1610.

8. J. Krupa, R. Poudineh, and L. D. D. Harvey, "Renewable Electricity Finance in the Resource-Rich Countries of the Middle East and North Africa: A Case Study on the Gulf Cooperation Council," *Energy* 166 (2019): 1047–1062.

9. E. T. S. Tareq Salameh, M. A. Abdelkareem, A. G. Olabi, and H. Rezk, "Optimal Selection and Management of Hybrid Renewable Energy System: Neom City as a Case Study," *Energy Conversion and Management* 244 (2021): 114434. https://doi.org/10.1016/j.enconman.2021.114434.

10. S. Al Dawsari, F. Anayi, and M. Packianather, "Techno-Economic Analysis of Hybrid Renewable Energy Systems for Cost Reduction and Reliability Improvement Using Dwarf Mongoose Optimization Algorithm," *Energy* 313 (2024): 133653.

11. K. P. R, A. S. Pillai, and A. Al-Shahri, "A Feasible and Sustainable Standalone Hybrid Renewable Energy System Experimentation for Remote Residential Applications of Khasab," *Results in Engineering* 26 (2025): 105360.

12. A. A. Makky, H. A. Kanjo, M. M. Farag, A. K. Hamid, M. Hussein, and T. Salameh, "Techno-Economic Feasibility of Green Hydrogen Production Using Hybrid Solar-Wind Energy Systems in Oman," *International Journal of Thermofluids* 28 (2025): 101302.

13. M. M. A. Seedahmed, M. A. M. Ramli, H. R. E. H. Bouchekara, M. S. Shahriar, A. H. Milyani, and M. Rawa, "A Techno-Economic Analysis of a Hybrid Energy System for the Electrification of a Remote Cluster in Western Saudi Arabia," *Alexandria Engineering Journal* 61, no. 7 (2022): 5183–5202.

14. S. Shahgholian, M. Taheri, and M. Jahangiri, "Investigating the Cost-Effectiveness of Solar Electricity Compared to Grid Electricity in the Capitals of Middle Eastern Countries: A Residential Scale Case Study," *International Journal of Photoenergy* 2023 (2023): 1–19.

15. A. Q. Al-Shetwi, I. E. Atawi, A. Abuelrub, and M. A. Hannan, "Techno-Economic Assessment and Optimal Design of Hybrid Power Generation-Based Renewable Energy Systems," *Technology in society* 75 (2023): 102352.

16. R. Al Afif, Y. Ayed, and O. N. Maaitah, *Feasibility and Optimal Sizing Analysis of Hybrid Renewable Energy Systems: A Case Study of Al-Karak* (Jordan. Renewable Energy, 2023). 204, 229–249.

17. M. D. Abnavi, N. Mohammadshafie, M. A. Rosen, A. Dabbaghian, and F. Fazelpour, "Techno-Economic Feasibility Analysis of Stand-Alone Hybrid Wind/Photovoltaic/Diesel/Battery System for the Electrification of Remote Rural Areas: Case Study Persian Gulf Coast-Iran," *Environmental Progress & Sustainable Energy* 38, no. 5 (2019): 13172, https://doi.org/10.1002/ep.13172.

18. M. F. H. Mojumder, T. Islam, P. Chowdhury, et al., "Techno-Economic and Environmental Analysis of Hybrid Energy Systems for Remote Areas: A Sustainable Case Study in Bangladesh," *Energy Conversion and Management* X (2024): 23.

19. S. Yadav, P. Kumar, S. Kumar, and A. Kumar, "Energy Management and Techno-Economic-Environmental Analysis of Hybrid Renewable Energy Based Isolated Microgrid With Various Energy Storage Technologies," *International Journal of Hydrogen Energy* 217 (2026): 153890.

20. S. Yadav, P. Kumar, and A. Kumar, "Hybrid Renewable Energy Systems Design and Techno-Economic Analysis for Isolated Rural Microgrid Using Homer," *Energy* 327 (2025): 136442.

21. A. S. Bahaj, M. Mahdy, A. S. Alghamdi, and D. J. Richards, "New Approach to Determine the Importance Index for Developing Offshore Wind Energy Potential Sites: Supported by UK and Arabian Peninsula Case Studies," *Renewable Energy* 152 (2020): 441–457.

22. A. Meflah, F. Chekired, N. Drir, and L. Canale, "Accurate Method for Solar Power Generation Estimation for Different PV (Photovoltaic Panels) Technologies," *Resources* 13, no. 12 (2024): 166.

23. LONGI. Hi MO 5 (V4), in LR_5_72_HBD. 2020: www.longi.com.

24. C. Deline, S. Ovaitt, M. Gostein, J. Braid, J. Newmiller, and I. Suez, "Irradiance Monitoring for Bifacial PV Systems' Performance and Capacity Testing," *IEEE Journal of Photovoltaics* 14, no. 5 (2024): 803–814.

25. Caterpillar. Cat® BDP250 Energy Storage Inverter, Caterpillar, Editor. 2020, Caterpillar.

26. PVsyst. Array and system losses. 2024, PVsyst software.

27. H. Energy, HOMER Help Manual, H. Energy, Editor. 2016.

28. Y. Z. Alharthi, M. K. Siddiki, and G. M. Chaudhry, "Resource Assessment and Techno-Economic Analysis of a Grid-Connected Solar PV-Wind Hybrid System for Different Locations in Saudi Arabia," *Sustainability* 10, no. 10 (2018): 3690.

29. Enercon. Technical Data sheet E-138 EP3, E. company, Editor. 2025.

30. A. Al-Sharafi, A. Z. Sahin, T. Ayar, and B. S. Yilbas, "Techno-Economic Analysis and Optimization of Solar and Wind Energy Systems for Power Generation and Hydrogen Production in Saudi Arabia," *Renewable and Sustainable Energy Reviews* 69 (2017): 33–49.

31. Z. Wang, Y. Huang, K. Zhou, Y. Zeng, X. Tang, and B. Bai, "Techno-Economic Assessment of Wind and Solar Energy: Upgrading the LCOE Model and Enhancing Geographical Granularity," *Energy Strategy Reviews* 58 (2025): 101686.

32. A. Sgaramella, L. M. Pastore, G. Lo Basso, A. Mojtahed, and L. de Santoli, "HCNG Refuelling Station to Accelerate the Transition Towards a Real Hydrogen Economy: A Techno-Economic Analysis," *International Journal of Hydrogen Energy* 69 (2024): 1403−−1416.

33. P.-I. Solar. *Longi 550W Hi-MO5 Monocrystalline Solar Panel – Silver Frame/White Backsheet* (2021). https://www.longi.com/us/download/?categoryId=65.

34. SOLARTECH. Wind Turbine Cost Guide 2025: Complete Pricing Breakdown ($700-$20M+). 2025; Available from: https://solartechonline.com/blog/wind-turbine-cost-guide-2025/.

35. GovDeals. Caterpillar Energy Storage Inverter and Hammond Power Solutions Transformer. 2025; Available from: https://www.govdeals.com/en/asset/29/29328.

20500505, 0, Downloaded from https://scijournals.onlinelibrary.wiley.com/doi/10.1002/ese3.70682 by NICE, National Institute for Health and Care Excellence, Wiley Online Library on [28/10/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

36. J. Yang, G. Gonzales-Calienes, M. Kannangara, and J. Shadbahr, "Analysis of Lifecycle Ghg Emissions Reduction in Grid-Connected Water Electrolysers: The Role of Dynamic Operating Strategies and Emission Factors," *International Journal of Hydrogen Energy* 168 (2025): 151054.

37. regulation, A.f.p.s. Statement of Charges Cost Reflective Tariffs. 2025.

38. A.f.P.S.R, 2025, "Cost Reflective Tariffs for Large Consumers: 2025-2026 Regulations.". 2026, Nama Power and Water Procurement Muscat, Oman.

20500505, 0, Downloaded from https://scijournals.onlinelibrary.wiley.com/doi/10.1002/ese3.70682 by NICE, National Institute for Health and Care Excellence, Wiley Online Library on [28/10/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License