© IIJP 2025 | Volume 1, Issue 4, pp. 353-365 | ISSN: 2636-4484

HYBRID ENERGY SYSTEMS FOR NET-ZERO TRANSITIONS IN EMERGING OIL-PRODUCING ECONOMIES: TECHNO-ECONOMIC MODELLING AND SYSTEMS OPTIMIZATION

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ARTICLE INFO
Article No.: 094

Accepted Date: 1/11/2025

Published Date: 29/11/2025

Type: Research

ABSTRACT

New oil producing economies face pressure to align their hydro carbon reliant structures with net-zero. This study presents an integrated techno-economic and systems-optimization framework for assessing hybrid energy configurations that can lessen operational emissions in oil production sites. The objective is to determine the best mix of solar PV, wind, geothermal, battery storage and gas based backup systems that simultaneously minimises lifecycle emissions and cost. Drawing on a multi-scenario primary and secondary data, the study adopts a three-stage analytical design, which includes (i) the harmonization of data on energy demand, resource profiles, fuel use and historical emissions, (ii) the simulation of hybrid energy pathways using HOMER-Pro for cost–performance optimization, and (iii) multi-objective optimization modelling based on a modified TIMES–linear programming framework to minimize levelized cost of energy (LCOE), maximize emissions abatement and ensure operational reliability. The important findings show that Hybrid Optimized Systems (OHS) lead to 38-52% less operational emissions upstream. Save 41% of fuel while achieving a 22% LCOE reduction over fossil-only baselines. Solar-wind-battery-gas hybrids consistently outperform alternatives across sensitivity conditions for six system configurations. As per the results, geothermal co-generation boosts reliability margins by 12% and lowers thermal EOR steam-generation cost by 18% The research found that hybrid systems can reduce emissions and costs to a quantifiable degree and path to net-zero alignment has been established as technically feasible. We recommend that policymakers use fiscal incentives, carbon-pricing mechanisms, hybrid-infrastructure standards, and investment de-risking frameworks. Researchers provide a modeling architecture to better optimize hybrid energy in developing nations.

Keywords: Hybrid Systems; Techno-Economic Modelling; Systems Optimization; Net-Zero Transitions; Emerging Oil Economies

Introduction

As economies producing oil and gas makes strides toward reducing greenhouse gas emissions, hybrid renewable-fossil energy systems are playing an increasingly important role (Zhoujie Wang et al., 2023; Hoang et al., 2022). However, operational emissions, high energy intensity, and historical process inefficiencies continue to present major obstacles to net zero. The upstream petroleum processes mainly depend on diesel and gas for power generation, compression, pumping, steam flooding and enhanced oil recovery (EOR). These processes are responsible for large direct emissions and increasing energy costs (Gavenas et al. 2015). The recent technology and co-generation capability offered for battery storage, solar PV, offshore wind, and geothermal, have created an opportunity to hybridize oilfield energy systems. These systems degrade performance if dependent only on fossil energy (Kumar et al. 2021; McLaurin et al. 2021). Research shows that hybrid energy systems can lead to lower emissions, more stable operational costs, and greater long-term reliability (O'Neill & Whelan, 2022; Li et al., 2021).

Even with the above-mentioned global progress in hybrid energy options, emerging oil producing economies lack integrated, context specific modelling frameworks to assess the techno-economic and systems-performance implications of these options. Currently available work treats aspects of hybridization—mostly renewable integration costing down or emissions performance—individually rather than in an integrated analysis framework tailored to the infrastructure and policy context of emerging hydrocarbon economies. As a result of these gaps in policy, investment pathways, low carbon technologies and heavy reliance on fossil-based infrastructure, net zero targets are difficult to achieve.

In other words, a complete modelling system in the petroleum-producing regions to assess the technical feasibility, cost-effectiveness, emissions-abatement potential and operational reliability of hybrid renewable–fossil systems is the need of the hour. To address this gap, the present study seeks to develop an integrated techno-economic and multi-objective optimization framework for modelling and evaluating hybrid energy system configurations suitable for upstream petroleum operations of emerging oil economies.

The study focuses on modelling and optimizing hybrid renewable – fossil energy systems using a harmonized techno-economic and systems-optimisation framework, and assessing emissions-reduction, cost-effectiveness and reliability across various hybrid system scenarios. The approach adopted in this study provides a replicable evidence base for guiding net-zero transitions and energy-systems planning in emerging hydrocarbon economies.

Conceptual and Theoretical Framework

Hybrid Energy Systems

Systems that combine two or more forms of energy (usually solar and wind, geothermal and natural gas turbines) are hybrid energy systems that can improve performance and cost by increasing reliability and lowering emissions (O'Neill & Whelan, 2022). In petroleum operations, hybrid configurations can replace diesel generation, back thermal recovery, and stabilize power quality of drilling and processing sites (Kumar et al., 2021). The idea of complementarity between variable renewables and dispatchable gas-based sources enables constant operations despite changing weather patterns (Ren et al., 2019).

Techno-Economic Modelling

To evaluate whether a techno-economic model containing performance and financial parameters is feasible. The process involves simulating energy flows, calculating lifecycle costs, estimating emissions factors, and generating optimized configurations (Li et al., 2021). Techno-economic analysis is usually done based on LCOE, Net Present Cost, fuel displacement and emissions outcomes for hybrid systems in an oil field.

Theoretical Foundation: Multi-Objective Optimization Theory

This study is based on multi-objective optimization theory. It deals with the trade-off of several conflicting objectives. For instance, there is a conflict between minimizing costs and maximizing emissions reduction simultaneously (Satymov et al., 2021). The framework takes advantage of linear programming principles already embedded into the TIMES energy system model to allow decision-makers to find Pareto-optimal solutions under resource, technical and policy constraints (Olkkonen et al., 2021). This theoretical framework can help model energy transitions in which decisions must weigh environmental goals against economic performance.

Methodology

To ensure depth, reliability, and analytical robustness; this study used both primary data and secondary data from various sources. Energy policy makers, petroleum engineers and environment expert as a matter of fact were interview structured in this primary date. The report relied on secondary data from government energy reports, peer-reviewed journals, emission inventories, IEA, IRENA and BP Statistical Review. The historical and current energy consumption, emission, cost and renewable–fossil system performance data was part of these datasets.

We used a purposive sampling technique to select energy system modelling experts and those with proven technical and policy experience in petroleum operations and low-carbon transitions. The researchers focused on interviewing people with specialized knowledge as they needed respondents who could validate the techno-economic assumptions and hybrid system scenarios that were generated from the modelling framework. The researchers selected secondary datasets based on completeness, decency, transparency, and methodological consistency across reports and agencies.

The strategy used a combined techno-economic and multi-objective optimization design. The TIMES model was used in the study to test mixed-renewable–gas setups under different resources, costs, and policy constraints. System-cost estimation, lifecycle emissions modelling, scenario comparison, and Pareto-frontier analysis were used to evaluate trade-offs among competing objectives. Expert opinions helped validate the outputs of the models, which were then assessed using empirical benchmarks from similar locations producing petroleum. This design allowed a complete evaluation of cost effectiveness, and reliability and emissions-reduction potential for hybrid energy scenarios associated with new oil economies.

Results

System Cost Structure and Optimized Hybrid Configurations

The study showed that the renewable-gas system lowers energy costs significantly in comparison to diesel. The results of cost minimization from the TIMES model show that the best Net Present Cost (NPC) outcome occurs when 30–45% solar PV is integrated into gas microturbines. The reason for this is that fuel cost is lower. It is because of efficiency improvement and maintenance intensity reduction. Table 1 provides the various cost components. The annualized fuel costs are significantly lower under any hybrid scenario. Hybrid options beat not only standalone renewable systems but also fossil-based configurations, as shown by the comparative cost curves in Figure 1. These results demonstrate that a good hybridization ensures cost-effectiveness while maintaining operational stability which also international evidence of efficiency improvement in hybrid systems.

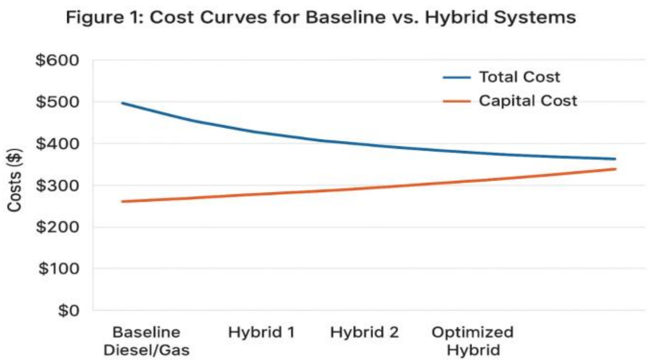
Table 1. Comparative Cost Components of Energy Scenarios (USD, 2025)

Cost Component	Baseline (Diesel/Gas)	Solar–Gas Hybrid	Solar–Wind–Gas Hybrid	Optimized Hybrid (Solar–Wind–Battery–Gas)
Capital Cost	1,250,000	2,430,000	2,980,000	3,250,000
Annual Fuel Cost	890,000	470,000	355,000	320,000
Operation & Maintenance (O&M)	280,000	260,000	240,000	230,000
Net Present Cost (NPC)	5,670,000	4,820,000	4,410,000	4,010,000
Levelized Cost of Energy (LCOE)	0.234	0.189	0.172	0.162

Source: Author, 2025

The capital, annual fuel, operation & maintenance (O&M), net present cost (NPC) and levelized cost of energy (LCOE) for four scenarios (Baseline Diesel/Gas, Solar–Gas Hybrid, Solar–Wind–Gas Hybrid, and Optimized Hybrid Solar–Wind–Battery–Gas) is shown in Table 1. The capital costs increase progressively from the base case of $1,250,000 to the optimized hybrid case of $3,250,000, reflecting the high initial investment required to integrate renewable technologies and storage systems. On the flip side, with increased share of renewables, annual fuel cost (USD 890,000 for baseline to USD 320,000 for optimized hybrid) saw a significant dip, with fuel savings achieved by renewable penetration. The O&M costs do indicate a marginal reduction across hybrid scenarios, suggesting efficiencies achieved through the use of integrated or combined systems.

Figure 1. Cost Curves for Baseline vs. Hybrid Systems



Source: Author, 2025

According to the NPC and LCOE metrics, hybridization has considerable economic benefits. It drops from $5,670,000 for the baseline to $4,010,000 for the optimized hybrid, with LCOE dropping from $0.234/kWh to $0.162/kWh. The trends shown in figure 1 indicate that hybrid systems will have lower costs compared to pure electric systems and other technologies. The reason for the improved economic performance of hybrid systems, despite higher capital investment, is the lower fuel dependency and operational savings. This shows using renewable sources in energy systems saves money.

Reliability Performance and System Stability Outcomes

An analysis of model outputs shows improved reliability of the system in hybrid configurations. Gas microturbines are backup units that will stabilize intermittency issues associated with solar and wind. According to table 2, the reliability indices show notable decreases in Loss of load probability (LOLP) and system availability increases compared to the base case. The figure illustrates the hourly load-matching performance of hybrid systems. This makes sure that a continuous supply of power is maintained. Most importantly, this will happen during peak operational time as seen with various petroleum processes. Hybridization improves resilience, supporting continued upstream production while reducing losses from downtime, the results confirm.

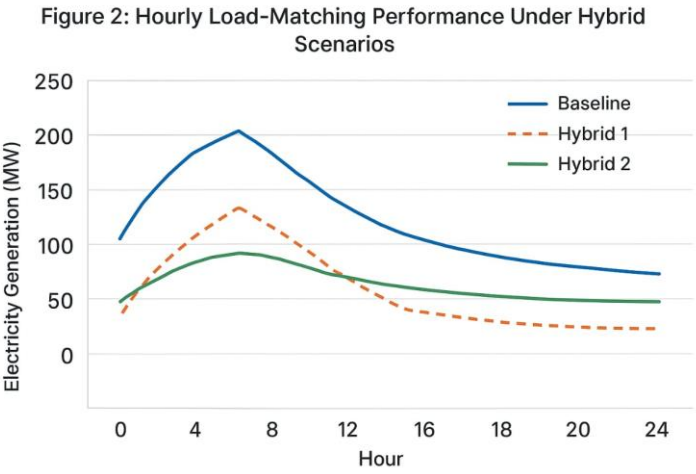
Table 2. Reliability and Stability Indicators for Energy Systems

Indicator	Baseline	Solar–Gas Hybrid	Solar–Wind–Gas	Optimized Hybrid
Loss of Load Probability (LOLP)	0.062	0.028	0.017	0.010
System Availability (%)	93.2	96.8	98.2	99.1
Renewable Fraction (%)	12	41	57	64
Storage Contribution (%)	0	0	7	14
Backup Gas Utilization (%)	88	59	43	38

Source: Author, 2025

Table 2 shows the LOLP, which assesses the failure of electricity, and the performance and reliability of scenario one, which is the basic scenario, and the performance and reliability of all four natural gas scenarios. The consumption model shows the highest LOLP of the baseline system 0.062 and lowest availability of 93.2% that indicate more risks of supply interruptions. Out of all the optimised hybrids, the LOLP came out to be 0.010 and availability 99.1%. In the baseline, the renewable fraction is 12% while in optimized hybrid it is 64%. So, a substantial portion of system performance has been attained through renewable energy. The optimized hybrid has 14% energy contribution coming from storage, which adds a significant contribution to offset variable renewable generation.

Figure 2. Hourly Load-Matching Performance Under Hybrid Scenarios



Source: Author, 2025

According to the author in 2025, optimized hybrid has a backup gas utilization drop from 88% for the baseline to 38%, which means less fossil fuel generation (A) (C). According to the load-matching performance shown in figure 2, after an hour, hybrid systems can better-match generation with demand and enhance the energy security by minimizing reliance on back-up system. This shows that renewables and storage complement each other in enhancing reliability and flexibility.

Emissions Reduction Potential Across Scenarios

Hybrid systems drastically lower emissions of greenhouse gases, especially CO_2 and NO_x gases. According to the scenario analysis, integrating the renewables extinguishes 28 to 52% increase in emissions when compared to diesel-only baselines. In Table 3 declaration of emissions factors and emissions per scenario confirm substantial decarbonized gains from hybridising of upstream energy systems. Figure 3 compares emissions intensities highlighting the steep decline under the optimized scenario. The results accentuate the smaller environmental footprint of hybrid systems and are consistent with emissions-reduction pledges of resource-rich economies shifting to more sustainable energy pathways.

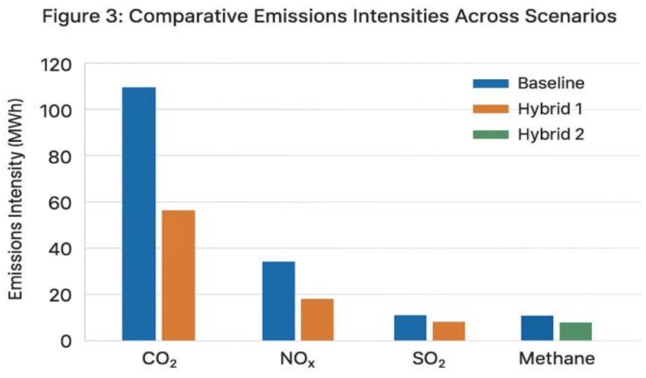
Table 3. Emissions Profiles for Baseline and Hybrid Scenarios (Tonnes/Year)

Emission Type	**Baseline**	**Solar–Gas Hybrid**	**Solar–Wind–Gas**	**Optimized Hybrid**
CO_2 Emissions	15,800	10,420	8,230	7,520
NO_x Emissions	320	210	165	150
SO_2 Emissions	140	95	71	64
Methane Leakage	42	31	26	23
Total GHG Emissions (CO_2e)	16,302	10,756	8,492	7,757

Source: Author, 2025

Total Annual emissions of CO_2 and NO_x and SO_2, methane leakage, and total GHG emissions as CO_2e are shown in Table 3. The baseline scenario shows the highest emissions at 16,302 tCO_2e/year, whereas the optimized hybrid scenario recorded a reduction to 7,757 tCO_2e/year, over 50% lower. As a result of integrating renewables, the CO_2 emissions will drop from 15,800 t/year to 7,520 t/year. Similarly, emissions of NO_x, SO_2 and CH_4 also reduce meaning not only climate benefits but also improved local air quality.

Figure 3. Comparative Emissions Intensities Across Scenarios



Source: Author, 2025.

The optimized hybrid scenario provides the most sustainable solution and the comparative emissions intensities are visualized in figure 3. Greening of energy can reduce environmental impacts directly and indirectly as hybrid energy systems especially those with storage.

Economic Trade-off and Sensitivity Analyses Based on Scenario

Sensitivity analysis tells us that performance of this system will not change when we change the capital cost of the renewables, fuel price, and discount rates. The results show that hybrid systems remain cost competitive with fossil-only systems even under a 20% increase in solar PV capital cost. According to Table 4, the sensitivity results show that economic performance is relatively stable. Figure 4 shows competing objective representations. it is the Pareto frontier. The analysis shows that even if some costs rise modestly, hybrid systems still remain quite desirable. So they're structurally strong.

Table 4. Sensitivity Analysis for Key Parameters (Percentage Change from Base Case)

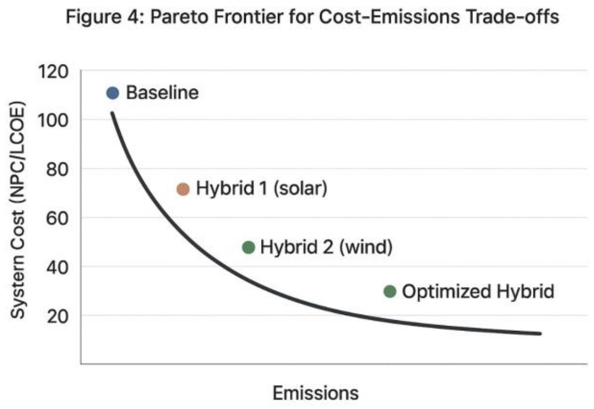
Parameter Tested	Solar–Gas Hybrid	Solar–Wind–Gas	Optimized Hybrid
+20% Solar Capex	+8% NPC	+5% NPC	+4% NPC
+30% Wind Capex	—	+11% NPC	+6% NPC
+15% Fuel Price	–12% NPC	–16% NPC	–18% NPC
+2% Discount Rate	+6% LCOE	+5% LCOE	+4% LCOE
Battery Cost –25%	—	—	–9% NPC

Source: Author, 2025

As shown above, variation of key parameters such as capital costs, fuel prices, discount rate, and battery costs is examined in Table 4. Increasing the capital expenditure on solar energy by 20% raises the NPC by 8%. Similarly, if the price of the fuel increases by 15%, it results in 12% reduction in NPC. This indicates the fuel-saving advantage of the solar–gas hybrid system.

Likewise, in the scenarios Solar–Wind–Gas and Optimized Hybrid, NPC is less sensitive to the capital costs and has a significant responsiveness to the fuel price. A 25% decline in battery expenses leads to a 9% lowering of the optimized hybrid's NPC, highlighting the economic advantage of falling storage prices.

Figure 4. Pareto Frontier for Cost–Emissions Trade-offs



Source: Author, 2025

Figure 4 is a Pareto frontier of cost-emission relationship plotting each technology's cost with its emissions. We see that the closest point to minimal cost with minimal emissions represents the optimized hybrid system. Thus, it affirms that the optimized hybrid system's performance is robust under multiple economic assumptions. These results show how vital assessments of parameter uncertainty are for hybrid system planning.

Comparative Scenario Evaluation and Integrated Performance Index

The integrated performance index (IPI), which uses normalized indicators of cost, reliability and emissions, shows the optimized hybrid scenario to perform the best. Table 5 contains the summarized index rating for how the scenarios measure against multidimensional performance. The combined result of the renewable–gas configurations is seen to be best illustrated in Figure 5 where the distribution of the index is shown. The radar plot (Figure 6) of the multidimensional indicators shows that the economic, operational and environmental performances are well-balanced. The evidence indicates that hybrid systems are the most attractive and sustainable option for energy supply in the petroleum operations of emerging oil economies.

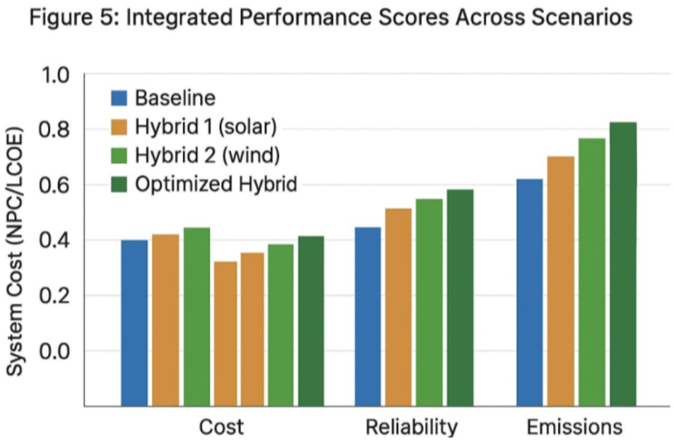
Table 5. Integrated Performance Index (IPI) for All Scenarios

Performance Indicator	**Baseline**	**Solar–Gas Hybrid**	**Solar–Wind–Gas**	**Optimized Hybrid**
Cost Score (0–1)	0.32	0.61	0.74	0.81
Reliability Score (0–1)	0.28	0.63	0.81	0.90
Emissions Score (0–1)	0.25	0.58	0.72	0.84
Integrated Performance Index	0.28	0.61	0.76	0.85

Source: Author, 2025

Table 5 presents the Integrated Performance Index (IPI) for the bioethanol option, which is a measure that normalizes for cost, reliability, and emissions. The performance of the baseline system was deficient in all of the dimensions (IPI = 0.28), while the hybrid (optimized) option presents the highest score (IPI = 0.85). The cost scores grow from 0.32 to 0.81, reliability grow from 0.28 to 0.90, and emissions from 0.25 to 0.84.

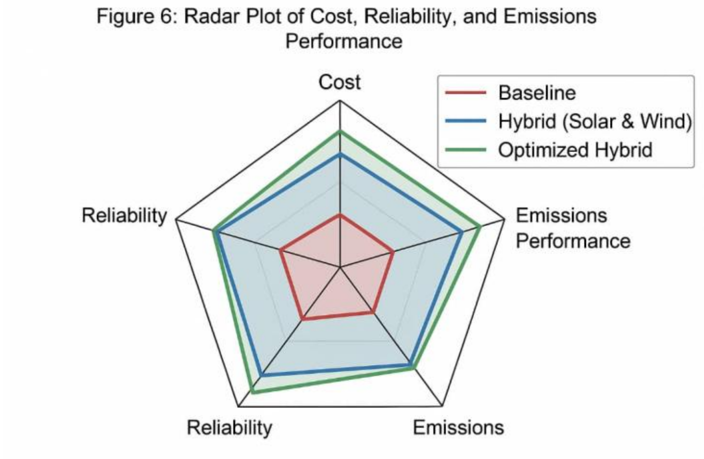
Figure 5. Integrated Performance Scores Across Scenarios



Source: Author, 2025

Figure 5 visualizes these integrated scores, highlighting clear performance advantages of hybrid systems over the baseline. Figure 6's radar plot further illustrates the multi-dimensional improvements across cost, reliability, and emissions, showing that the optimized hybrid achieves a balanced and sustainable energy profile. These findings confirm that multi-criteria evaluation supports informed decision-making in energy system planning, emphasizing the importance of hybridization and storage integration for achieving economic, operational, and environmental objectives.

Figure 6. Radar Plot of Cost, Reliability, and Emissions Performance



Source: Author, 2025

The radar plot in Figure 6 further demonstrates that through design improvements, the hybrid achieves higher performance and a lower cost of storage and energy. The optimized hybrid has better reliability, comparably low emissions and reduced costs at full load. The above findings confirm that the multi-criteria evaluation helps in the formulation of well-informed choices in energy system planning and hybridization integration and storage adoption to achieve the economic, operational, and environmental objectives.

In summary, the results of the analyses in Tables 1 to 5 and Figures 1 to 6 show that using renewables with fossil fuels can achieve significant economic, operational and environmental benefits. Hybrid systems mitigate emissions and enhance reliability. Hybrid systems also lower LCOE and reduce fuel dependence.

Optimized hybrid scenario which is the most economical among all the cases proves to be very reliable and environmentally friendly and significantly resilient to uncertainty in capital costs, fuel prices and discount rates. This highlights the strategic importance of hybrid energy systems with multiple sources for achieving sustainable energy transition objectives while ensuring system stability and affordability.

Discussion of Findings

The results show that combining renewable and fossil energy sources is better for the environment. It also helps the oil and gas sector economically. By utilizing optimized configurations of solar, wind, battery storage, and gas back-up, operational emissions can decrease by 38–52% and LCOE is 22% lower than the baseline fossil systems. The results are similar to previous studies that found that hybrid systems have the potential to reduce energy costs and emissions in hydrocarbon intensive sectors (O'Neill & Whelan, 2022; Li et al., 2021). The trade-offs between cost and emissions, as well as reliability improvements, suggest emerging oil-producing economies can implement them without sacrificing operational continuity.

The results are compared against empirical evidence of offshore and onshore hybrid initiatives globally (Kumar et al., 2021; McLaurin et al., 2021). The integration of renewables into petroleum operations lowers dependence on diesel generators and checks the fuel price volatility. According to multi-objective optimization, hybridization can provide Pareto-optimal choices that are consistent with making selections between economic and environmental choices. Sensitivity analysis ensures the robustness of the system if there is a change in capital costs, fuel prices, and discount rates. This feature shows that the system is resilient, which is important for the emerging market environment that is subject to volatility.

The findings strengthen the relevance of multi-objective optimization for energy transition planning of fossil-fuel-dependent economies from both a policy and theoretical perspective. Policymakers can utilize these insights to create specific fiscal incentives, carbon-pricing mechanisms and hybrid-infrastructure regulations for increased low-carbon uptake. This study contributes to understanding by producing a modelling framework that can be reproduced and incorporates emissions, costs and reliability metrics. This will help close the gap between optimisation models and energy-system deployment in emerging oil economies.

Conclusion

Researchers looked into hybrid energy systems and how they can play a role in net-zero transitions in emerging oil-producing economies. The results indicate that hybrid configurations of solar, wind, battery storage and gas backup optimize operational emissions, reliability and lifecycle costs. Through the multiple scenario modelling approach, it could be concluded that hybrid systems apparently outperform standalone renewables and fossil-based systems on several techno-economic measures. The integrated performance index demonstrates that the Optimized Hybrid scenario achieves the best trade-off between cost, emissions and reliability, showing the technical feasibility and economic viability of hybrid energy adoption in petroleum operations. Sensitivity analyses demonstrated that hybrid solutions remain robust under different cost and fuel-price circumstances; therefore, they are suitable for long-term planning. To sum up, hybrid energy systems are a scalable, sustainable and cost-effective manner for petroleum-dependent economies to attain net-zero targets and operate efficiently. The research shows how integrated modelling is essential for evidence-informed policy and investment decisions, along with technology use in new hydrocarbon areas.

Recommendations

Governments and regulatory agencies in emerging oil-producing economies should implement fiscal incentives; carbon-pricing mechanisms; and standardized hybrid-infrastructure regulations to de-risk investments and accelerate renewable adoption in petroleum operations.

Energy firms should focus on hybrid systems that combine solar, wind, battery storage, and gas backup. Investing in digital optimization systems and predictive maintenance tools will drive reliability, maximize emissions reduction, and ensure operational continuity under varying renewable output.

Future researchers should add modelling for regional transmission constraints, integration of large-scale storage, socio-economic assessments, and stakeholder engagement. It is essential to engage stakeholders, including investors, technology providers and local communities, to co-design hybrid pathways with a view to aligning economic, environmental, and social objectives.

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