



Research Paper

Operational optimization of integrated thermal energy systems using steam methane reforming electrolysis coupling for hydrogen and electricity production

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ABSTRACT

Integrated thermal-energy systems combined with steam methane reforming with renewable electricity offer a practical pathway for the cogeneration of hydrogen and electricity. This study develops an operational optimization framework that explicitly captures operational load-sharing between SMR and electrolysis in on-grid and off-grid configurations. The framework is applied to a large-scale energy system to meet electricity and hydrogen demands simultaneously. The Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) and an enhanced Fuzzy-Bellman decision-making approach are employed to optimize the Levelized Costs of Electricity (LCOE) and Life Cycle Emissions (LCE), while the levelized cost of hydrogen (LCOH) is evaluated as a key performance indicator of the optimized solution. Results indicate that SMR-electrolysis operation in the on-grid system enables a minimum LCOH of $\$0.87 \text{ kg}^{-1}$, achieved through a balanced fuel-based and renewable hydrogen generation while reducing methane consumption by 12%. Grid-assisted operation further reduces energy losses by 40% and LCE by 81.4% compared with conventional fossil-fuel benchmarks. While the on-grid system delivers the lowest energy costs and renewable penetration, the off-grid configuration enables fully renewable operation at higher costs due to increased storage requirements. The results show that operating the thermal and electrochemical hydrogen pathways together, rather than relying on component sizing alone, improves energy conversion efficiency, emissions and system flexibility. The proposed framework supports the design and operation of integrated thermal-energy systems.

1. Introduction

Reducing greenhouse gas emissions from the energy sector while maintaining a reliable and cost-effective energy supply remains a major engineering challenge [1]. The increasing penetration of renewable energy sources, such as solar photovoltaic (PV) and wind, has significantly altered power system generation [2]. However, their variability introduces operational challenges related to grid stability, energy storage, and surplus electricity management [3,4]. Addressing these challenges requires integrated energy solutions that combine renewable

resources with complementary thermal and chemical energy conversion processes [5,6].

Hybrid integrated energy systems have therefore attracted growing attention as a practical approach for improving system reliability and efficiency while reducing emissions. Due to the intermittent nature of renewable resources, such systems often require energy storage or auxiliary systems to ensure a continuous supply [7]. While electrochemical batteries are widely used, they are less suitable for long-term storage. Hydrogen offers a viable alternative energy carrier that can be produced through electrolysis, stored, and utilized later for power

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generation or other applications [5].

Hydrogen as a fuel is an appealing and environmentally favorable choice because the energy conversion process from hydrogen generates no pollutants. However, it can become economically challenging at high load levels due to the required scale of infrastructure [8]. In such cases, integrating electrolysis with a steam methane reformer (SMR) offers a viable solution by combining low-cost hydrogen from natural gas with renewable electricity. Although SMR is associated with CO₂ emissions, its integration within renewable-dominated systems can reduce overall fuel consumption, energy losses, and system costs when operated appropriately. On-grid configurations further enable surplus electricity export or hydrogen production, improving overall system efficiency [9]. Mao et al. [10] examined the potential role of hydrogen in industrial zones, assessing its feasibility as an energy carrier and its implications for decarbonizing high-emission sectors.

Several studies have investigated SMR optimization, hybrid hydrogen production pathways, and integrated renewable energy systems. Previous studies have demonstrated that combining SMR with electrolysis can reduce methane consumption and improve system efficiency when compared to standalone configurations. Other investigations have examined hybrid renewable energy systems for electrification and hydrogen production under varying conditions, highlighting the importance of techno-economic and environmental trade-offs. Lim et al. [11] used SMR enables onboard hydrogen production for liquefied natural gas (LNG) powered ships.

The Shagaya renewable power plant, situated in Kuwait's western region with ample sunlight and wind, integrates many sustainable resources, including solar, wind, and thermal energy, to generate electricity. The project plans to generate 3.2 GW of power by 2030 [12]. These favorable conditions allow energy production at a lower cost than in other countries. Production costs can be further lowered by incorporating renewable source-based electrolyzers with SMR processes. The number of studies conducted on hydrogen generation by integrating HRES with SMR and electrolyzers is scarce. Moreover, there is still a gap for further development and optimization of such systems that can simultaneously meet electricity and hydrogen demand, with a specific focus on several techno-economic, environmental, and social indicators. Designing such a system will require real-world data, proper modelling, and better deployment optimization techniques, which is this study's objective. Seokyoung et al. [13] incorporated a hybrid deep neural network with a particle swarm optimization (PSO) algorithm to optimize thermal efficiency and CO₂ emission of an on-site SMR process. The Pareto front-based multi-objective optimization yielded solutions with a thermal efficiency between 77.5 and 87.0% and CO₂ emissions between 577.9 and 597.6 t/y. Farhang et al. [14] proposed and optimized a novel design of a multi-generation plant powered by biogas and integrated an SMR to amplify hydrogen generation up to 540 kg/h. A novel hydrogen production system was designed by Huchao et al. [15] called electrified SMR (E-SMR), with a minimum levelized cost of hydrogen (LCOH) of 2.47 \$/kg. They combined power-to-gas technology with a conventional SMR process and saw an improvement in thermal and electrical efficiency of about 97.27% and 88.68%, respectively, compared to the conventional SMR process alone. Maghfuri and Kuku [16] used advanced machine learning models to improve predictions of hydrogen production and evaluate how different electrolyzer technologies perform when powered by renewable energy sources such as wind and solar. T. Sathish [17] evaluated the hydrogen-production performance of a PEM electrolyzer powered through an integrated system combining PV panels and evacuated tube solar collectors.

On the other hand, several studies have been conducted recently on HRES development and optimization for electrification, hydrogen generation, or both simultaneously. Kumar and Channi [18] conducted a techno-economic-environmental analysis on an optimal HRES consisting of PV, biomass generator, converter, and battery for the electrification of a rural area in Panjab, India. With a levelized cost of energy (LCOE) of 0.362\$ and a CO₂ emission of 0.232 kg/kWh, they also implemented

sensitivity analysis to assess the system's feasibility. Al-Ghussain et al. [19] investigated using excess energy from renewable sources to produce green hydrogen via a polymer electrolyte membrane electrolyzer and storing it underground in Jordan. Their country-scale cogeneration plant configurations consisting of PVs, wind turbines, or combined yielded the highest hydrogen production rate of 172.1×10^3 tons/year and the lowest LCOH of 1.082 \$/kg. A similar techno-economic study was carried out in five different climatic conditions of Egypt, as well as by Nasser et al. [20] formulated an HRES of wind turbines and photovoltaic panels for green hydrogen production in those areas. Rakibul et al. [21] emphasized the social implications of renewable energy sources in Bangladesh and devised a comprehensive study focusing on the modelling and multi-objective optimization of an HRES comprising PV, wind turbine, micro-hydro turbine, biogas generator, and vanadium redox flow battery. With an LCOE of 0.126 \$/kWh and CO₂ emissions of 60,116 kg/year, the HRES can potentially create 0.7396 jobs per MW of power consumption in the community.

Several studies focusing on solar and wind potential in Kuwait have been conducted [22–24]. However, studies assessing their hybridization and deployment for different generation purposes are nonexistent. While previous studies have assessed renewable potential and green hydrogen production at Shagaya, comprehensive analyses that integrate renewable generation with SMR and electrolysis under both on-grid and off-grid configurations remain limited [25].

This study aims to address this gap by developing a multi-objective operational optimization for integrated thermal-energy systems combining renewable electricity, SMR, and electrolysis. On-grid and off-grid configurations are evaluated using the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) and a Fuzzy-Bellman decision-making approach. The objectives include minimizing the LCOE and LCE, while LCOH is evaluated as a derived techno-economic indicator for the optimized solution. The framework further enables the assessment of system operation, energy-conversion losses, and configuration trade-offs.

The main contributions of the work are summarized as follows:

- Development of an operational optimization framework for integrated thermal-energy systems producing both electricity and hydrogen under on- and off-grid options
- Evaluation of SMR-electrolysis integration as a load-sharing strategy to reduce hydrogen production cost, fuel consumption, and system energy losses.
- Comparative assessment of system performance, economic trade-offs, and emissions between on-grid and off-grid configurations.

2. Materials and methods

Fig. 1(a) and (b) outline the overall research workflow and optimization procedure adopted in this research. The methodology begins with system definition and resources assessment, followed by the development of integrated thermal-energy system architectures and their operational optimization under on-grid and off-grid configurations. It evaluates the renewable energy potential of solar and wind while assessing the electrical and hydrogen load requirements. The study area, climatic information, and load requirements are reported in the supplementary materials. Moving forward, the system architecture is developed and modelled for components such as solar panels, wind turbines, batteries, and hydrogen storage. Both on-grid and off-grid power management strategies are considered to assess the system's robustness. Both figures show that optimization is performed using NSGA-II and an enhanced fuzzy decision-making approach, while accounting for energy balance, storage capacity, and reliability constraints. Finally, after analyzing the system's performance with respect to technical efficiency, cost, and social and environmental impacts, the results are compared with those of existing studies.

The objective of this research is to reduce the cost of hydrogen

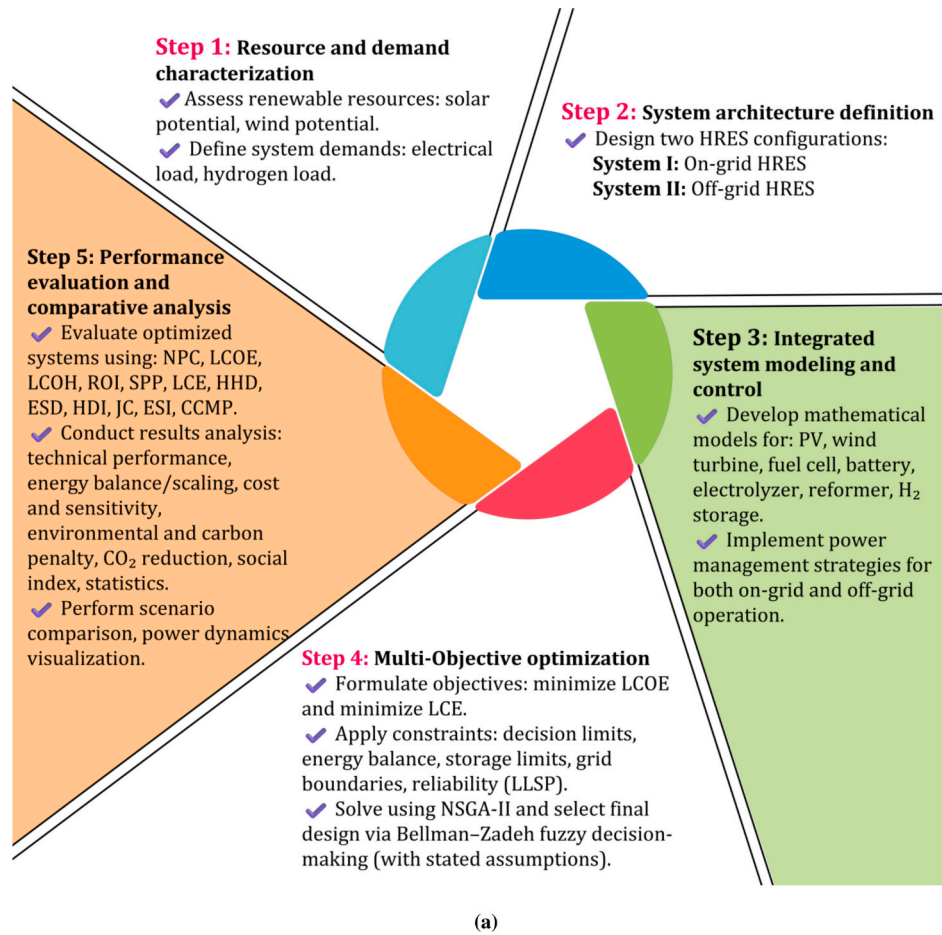


Fig. 1. (a) Graphical representation of research methodology, (b) graphical representation of optimization methodology.

production by improving system operation through energy-cost trade-offs by load sharing between electrolysis and steam methane reforming. To achieve optimization, the approach simultaneously considers LCOE and LCE, enabling assessment of trade-offs between cost and environmental performance.

2.1. System architectures

The system architecture of HRES focuses on developing the most appropriate power management strategy to operate the system, addressing energy conservation, load management, and comfort utilization with renewables and backup sources. The architectures of grid-connected and grid-isolated energy systems designed in this study are shown in Fig. 2(a) and (b), respectively. In Fig. 2(a), the system uses wind turbines and solar PV as primary energy sources to provide electrical power for the load. The electricity flows between the components via a bi-directional inverter, directing any excess energy to the grid or the electrolyzer. The surplus electrical energy is converted into hydrogen in the electrolyzer and stored in the hydrogen storage for later use. If demand for hydrogen exceeds what the electrolyzer can produce, the system activates the SMR, which produces additional hydrogen using LNG supplied by the LNG storage and supply unit. The electricity grid provides the electrical power needed for the reformer's operation, and the system's ability to meet the electrical load is not affected. In Fig. 2(b), the grid connection is replaced by a PEM fuel cell and a battery bank, while all other components remain the same as in the on-grid architecture. When there's an electrical deficit, the PEMFC supplies the deficit load, and the reformer supplies the hydrogen load shortage,

which battery banks supply. Surplus energy in the off-grid system is used to produce hydrogen via an electrolyser and is stored in battery banks. Using these architectures, the system can dynamically control hydrogen production to provide stable, reliable energy.

Renewables incorporated with hydrogen storage, LNG as backup gas fuel for reformer, grid integration, and dual mode energy storage strategy enable these HRES variants to reliably meet both electric and hydrogen demand in a highly efficient manner [6]. It enables flexible operation and effective energy management, and improves system reliability and sustainability under different energy conditions.

3. HRES optimization structure

The optimization structure includes metaheuristic algorithms and a novel power management strategy to precisely handle the energy generation and the corresponding load demands, which are electrical loads in kWh and hydrogen loads in kg. The developed power management algorithm, shown in Fig. 2(a) and (b), is run through the most impactful metaheuristic algorithm to date, NSGA-II (Non-Sorting Genetic Algorithm-II), in terms of robust multi-objective optimization [26]. Multi-objective optimization is anchored by the energy balance principles of the HRES, which are elaborated in the power management strategy. After achieving the best solution sets at the final generation of the optimization, another metaheuristic algorithm, the Bellman-Zadeh fuzzy decision-making approach, is applied to find the best and optimal system sizing [27]. An enhanced version of the Bellman-Zadeh algorithm is applied in this study, which can operate within a specific range across any domain of the dataset, enabling the researchers to find

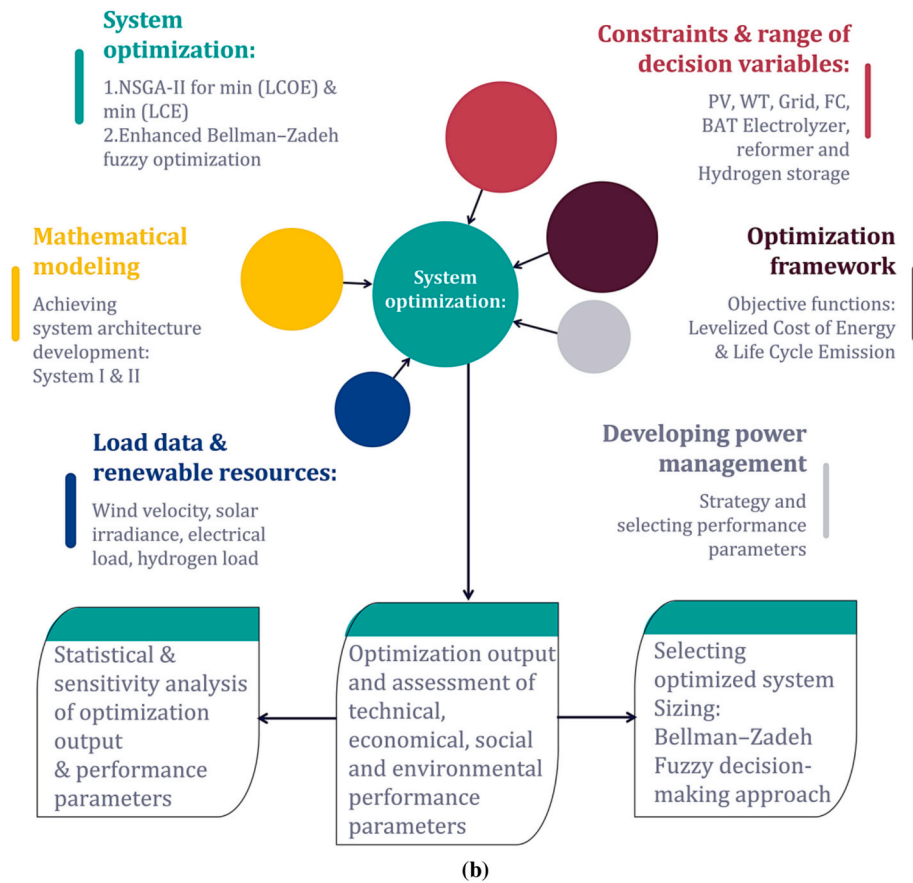


Fig. 1. (continued).

the most practical solution. The objective functions and constraints are developed and run in the MATLAB workspace. The meteorological data used in this study were extracted from the NASA POWER (Prediction Of Worldwide Energy Resources) website [28].

3.1. Objective functions

In the development of the optimization process, multiple factors influencing the sizing and performance of the HERS were considered. These factors include economic and environmental metrics, represented by the LCOE, LCOH, and LCE. Due to the distinct nature of energy outputs, electricity (kWh) and hydrogen (kg), levelized cost metrics are adopted to ensure a consistent techno-economic basis for comparison. In this study, the optimization problem is formulated to minimize the LCOE and LCE, representing the economic and environmental performance of the system, respectively. The objective function is therefore defined as:

$$F = \text{minimize } \{LCOE, LCE\} \quad (1)$$

The LCOH is not treated as an independent objective function within the NSGA-II optimization stage. Instead, it is evaluated for the Pareto-optimal solutions as a derived techno-economic performance indicator. The LCOH is influenced indirectly through the optimized decision variables governing system configuration and operation. Specifically, minimizing LCOE reduces the electricity cost supplied to the electrolyzer, while minimizing LCE affects the operational balance between SMR and electrolysis. Since hydrogen production cost depends on electricity consumption, fuel usage, and system sizing, LCOH is inherently determined by the optimized system design and dispatch strategy.

The LCE (kg CO₂-eq/kWh) for all HRES system components is calculated on a per-kWh basis for production or storage. Normalizing greenhouse gas (GHG) emissions by energy units is preferable to

normalizing by component capacity, as some components run at full capacity more consistently than others [29]. The LCE factors for the different HRES are reported in Table 1.

To integrate the practical reliability index of different load types in the optimization process, the researchers developed an enhanced solution to introduce LLSP (Loss of Load Supply Probability), the most practical solution for enhancing system reliability with different load types. The mathematical analogy for the loss of load supply probability (LLSP) can be demonstrated as follows:

$$LLSP = \frac{\sum_{i=1}^N LXSP}{N} = \frac{LHSP + LPSP}{2} \quad (2)$$

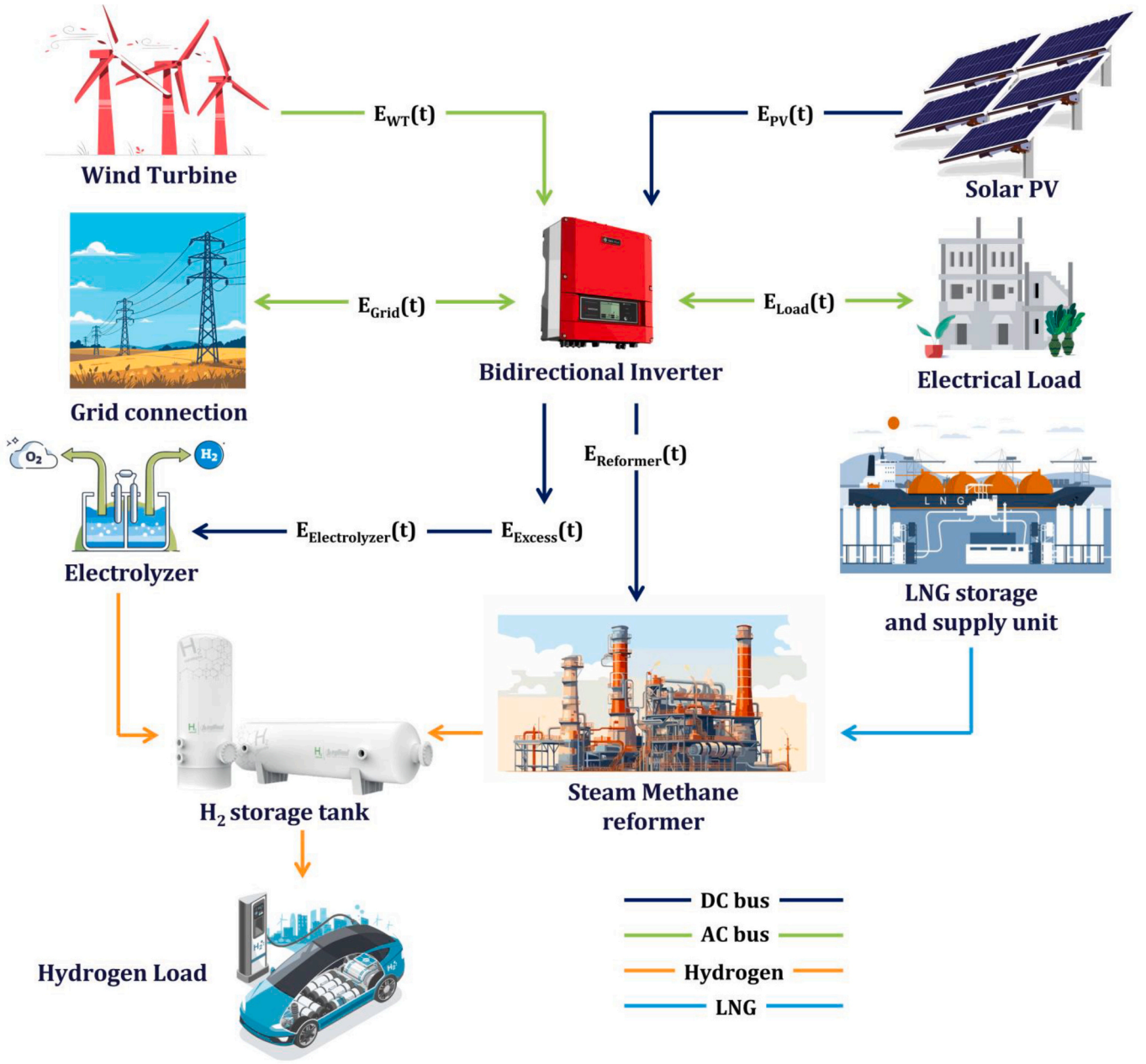
$$LHSP = \frac{H_{unmet}}{H_{total}} \quad (3)$$

$$LPSP = \frac{P_{unmet}}{P_{total}} \quad (4)$$

where, LXSP is the loss of supply probability of any X type of load, LHSP denotes the loss of hydrogen supply probability, and LPSP denotes the loss of power supply probability, which are considered in this study with specified load reliability (LLSP = 1 ± 0.01) for optimization.

3.2. Optimization constraints

Decision Variable Limits: In the process of optimizing the size of an HRES, it is essential to consider the number of system components as a critical criterion. To ensure effective calculations in the optimization process, constraints in the form of predetermined upper and lower ranges are established. The following relation outline these constraints:



(a)

Fig. 2. (a) System architecture for the on-grid system, (b) system architecture for the off-grid system.

$$N_{m,min} \leq N_m \leq N_{m,max}, m \in (PV, WT, FC, Reformer, Electrolyzer, Hydrogen Tank) \quad (5)$$

where N_m , $N_{m,min}$, $N_{m,max}$ represent the total number of m th system components, the smallest number of m th system components, and the highest number of m th system components, respectively. The solution space is restricted by higher and lower constraints to accelerate the computation. The minimum number of components is fixed at 1, while the upper limits are determined according to the optimization criteria.

Energy Balance Constraints: The total energy generated from all system components per hour must satisfy or surpass the hourly load requirement in order to optimize within the LLSP limit.

$$E_{PV}(t) + E_{WT}(t) + E_G(t) + E_{FC}(t) - E_{EL}(t) = E_{LOAD}(t) + E_{REF}(t) + E_{EX}(t) + E_{SBG} \quad (6)$$

The primary source of power generation is the renewables (Wind Turbines and Solar PV), which are E_{PV} and E_{WT} , respectively. The surplus energy is either utilized to produce hydrogen feeding the electrolyzer and stored in a battery bank (off-grid system) or sold back to the grid (on-grid system), which is denoted as E_{SBG} , the energy sold back to the grid. The backup supply taken from the grid is defined with E_G . Meanwhile, E_{FC} , E_{EL} , E_{LOAD} , E_{REF} , and E_{EX} describe the time variable energy flow of fuel cell, electrolyzer, load demand, reformer, and the generated excess energy, respectively.

Energy Storage Capacity Constraints: The energy storage capacity

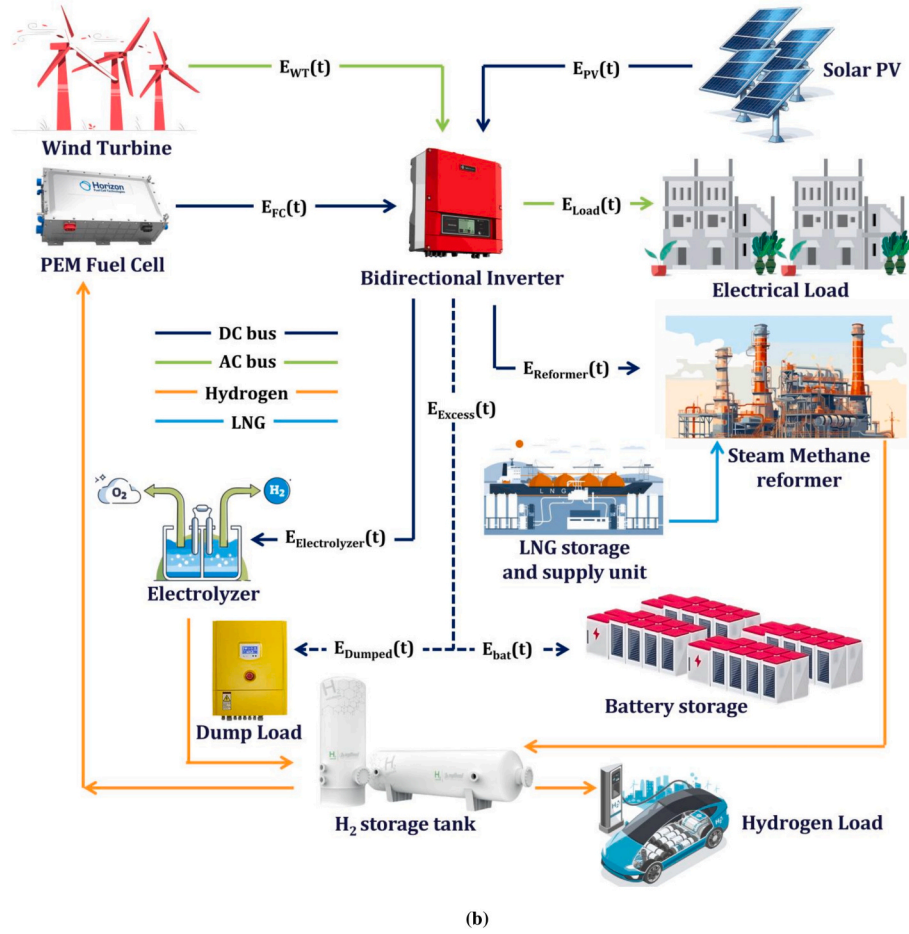


Fig. 2. (continued).

Table 1
Life cycle emission (LCE) Factors of HRES components with LCE stages.

HRES component	Emission factor	Unit	LCE stage	Reference
Solar PV	0.045	kg CO ₂ /kWh	Embodied (manufacturing, installation, decommissioning)	[30]
Wind Turbine	0.011	kg CO ₂ /kWh	Embodied (manufacturing, installation, decommissioning)	[30]
SM Reformer	≈10.0	kg CO ₂ /kg H ₂	Direct operational (CH ₄ → CO ₂ + H ₂)	[31,32]
PEM Electrolyzer	0.011	kg CO ₂ /kWh	Embodied (manufacturing, replacement)	[33,34]
Grid (Kuwait)	0.57	kg CO ₂ /kWh	Operational (grid mix)	[35]
PEM Fuel Cell	0.037	kg CO ₂ /kWh	Embodied (manufacturing, replacement)	[36]
Li-ion Battery	0.135	kg CO ₂ /kWh	Embodied (manufacturing, replacement)	[37]

of the system is optimized through the algorithm, which finds out the optimal sizing of the storage system regarding the energy flow or state of charge (SOC) over the yearly operation (8760 h). The following limitation governs the amount of hydrogen that can be stored in the system:

$$H_{HS,min} < H_{HS}(t) < H_{HS,max} \quad (7)$$

Here, the terms $H_{HS, min}$, and $H_{HS, max}$ represent the minimum and maximum capacities (in kg) of the hydrogen energy storage system. Likewise, after fulfilling load demand, there exists a constraint on energy storage within the battery system utilizing surplus energy, as shown below:

$$E_{BAT,min} < E_{BAT}(t) < E_{BAT,max} \quad (8)$$

Here, $E_{BAT, min}$ and $E_{BAT, max}$ represents the minimum and maximum storage capacity of the battery bank with $E_{BAT}(t)$ means the hourly energy SOC of the battery storage module.

Grid Supply Boundary Constraints: The most critical factor in

optimizing grid-integrated multi-generation systems is the grid supply condition, which measures the grid supply availability and downtime based on the criteria the HRES wants to follow in power purchase and sale. If no boundary condition is applied, the optimization algorithm will always try to reduce the LCOE. The grid penetration will be extremely high, making renewable sources insignificant and lowering their sizing to the absolute minimum (1 unit per component). The system will also become impractical with the value of LLSP set to zero due to no unmet load, which is not possible in realistic cases of HRES to achieve 100% reliability index. The grid supply boundary conditions are stated as the following equations:

$$E_{DEFICIT}(t) \geq 0.2 \times E_{LOAD}(t) \quad (9)$$

$$H_{DEFICIT}(t) \geq 0.1 \times H_{LOAD}(t) \quad (10)$$

The boundary conditions allow the system to activate the grid supply only when the electrical deficit (EDEFICIT) is higher than or equal to 20% of the electrical load (ELOAD) and the hydrogen deficit is higher

than or equal to 10% of the hydrogen load (H_{LOAD}). The conditional percentages are derived using the range optimization from 10% to 50% for each boundary condition with a rigorous trial-and-error run and converging Pareto observation.

Reliability Constraints: The reliability index represents a critical element in the design of the HRES. The LLSP serves as a reliability factor for assessing the dependability of the HRES in terms of consistent load supply capability. This index calculates the probability that the system will not satisfy the load demands over the duration of one year (comprising 8760 time-steps or hours). The equation presented below is utilized for the calculation of the LLSP:

$$LLSP = \frac{\sum_{t=1}^N \sum_{i=1}^T LXSP(t)}{N} = \frac{\sum_{t=1}^T LPSP(t) + \sum_{t=1}^T LHSP(t)}{2} \quad (11)$$

In scenarios where backup, supplemental, and storage systems fail to generate or supply sufficient power to meet the load demands, the LPSP is calculated to reflect the least advantageous power and hydrogen load supply condition. The limitation on system reliability is expressed as follows:

$$LLSP \leq LLSP_{Desired} \quad (12)$$

Here, $LLSP_{Desired}$ is the maximum allowable power supply probability of the system, which corresponds to the reliability index of the system and is considered to be $1 \pm 0.1\%$ in this study.

3.3. Optimization algorithms

The enhanced version of Non-Sorting Genetic Algorithm (NSGA), NSGA-II, is widely used for solving design equations of complex multi-variable systems due to its capability of handling multi-objective optimization problems, addressing the drawbacks exhibited in the original NSGA. NSGA-II improves accuracy and computational efficiency to a great extent through elitism and replaces conventional diversity-sharing criteria with a crowding distance operator. Thus, the complexity of the algorithm can be simply expressed as $O(MN^2)$, where M denotes the number of objectives, and N is the population size, providing a significant detail from its previous generation of data, making multi-objective problems of considerable size easier to process [29]. NSGA-II algorithm has also been designed for MOCOPs with superior global search ability, convergence speed, and diversity compared to PSO and other heuristic algorithms, where it outperforms PSO over complex real-world problems, such as the knapsack problem, vehicle routing problem (VRP), and scheduling problem, owing to its non-dominated mechanism and crowding distance, which makes sure a well-distributed Pareto-optimal front. On the other hand, PSO suffers from premature convergence, making it difficult to maintain solution diversity in a high-dimensional objective space. Additional research has compared NSGA-II with other algorithms such as Strength Pareto Evolutionary Algorithm (SPEA-II), Multi-Objective Evolutionary Algorithm based on Decomposition (MOEA/D), and Multi-Objective Artificial Bee Colony (MOABC) in different application areas, leading to the conclusion that NSGA-II outperforms and is more effective than these algorithms due to its fast convergence rate, good solution diversity, and low computation time. NSGA-II outperformed SPEA-II in achieving better optimal trade-offs in repairable multi-state availability allocation problems [32]. The NSGA-II optimization parameters used in this study are demonstrated in

Table 2
Control variables of NSGA-II algorithm.

Parameters	Value
Population Size	500
Maximum generation	500
SBX crossover rate	0.9
Poly mutation rate	0.1

Table 2.

3.4. Operational load-sharing and dispatch strategy

The operational behavior of the integrated system is governed by a rule-based dispatch strategy that defines the interaction between renewable generation, electrolysis, SMR, and grid storage systems. As illustrated in Fig. 3, renewable energy is prioritized to meet the electrical load demand. Surplus renewable power is directed to the electrolyzer for hydrogen production, while hydrogen demand deficits are compensated by activating the SMR unit. In the study, a strategy has been developed to run the SMR only when the electrolyzer's hydrogen production is insufficient to meet demand. In the on-grid configuration, the grid serves as a secondary support mechanism when supply deficits exceed pre-defined thresholds, whereas in the off-grid case, storage systems maintain system balance. This hierarchical control strategy ensures reliable operation while maximizing renewable energy utilization and minimizing system losses.

3.5. Determination of final solution

To determine the best solution from the optimal Pareto of non-dominant solutions found from the NSGA-II optimization, an enhanced Bellman-Zadeh fuzzy decision-making approach is applied in this study. The principle of crowding distance is utilized to assess the density of solutions in proximity to a selected one, depending on whether the objectives are maximized or minimized within an admissible range of objective functions. It calculates the mean distance between neighboring solutions across each dimension of the objective space [27]. The objective functions are constrained to exist between the effective range, $[a, b]$ to ensure the solutions satisfy the following condition:

$$a \leq F_j(x) \leq b \quad (13)$$

where, $F_j(x)$ represents the objective functions. Let Ω represent the entire solution set, the admissible solutions set $\Omega_{admissible}$ is a subset of the entire solution set. When $\Omega_{admissible}$ is determined, the fuzzy decision-making approach is applied as follows:

$$\Omega_{admissible} \subseteq \Omega \quad (14)$$

For each objective functions $F_j(x)$, The calculation of the fuzzy membership value for the j^{th} objective function is conducted with the following set of equations below, where $F_{j,max}$ indicates the maximum fitness value associated with the j^{th} objective function, while $F_{j,min}$ signifies the minimum fitness value.

$$\Omega_{admissible} = \{x \in \Omega \mid a \leq F_j(x) \leq b\} \quad (15)$$

$$F_j^{min} = \min_{x \in \Omega_{admissible}} F_j(x) \quad (16)$$

$$F_j^{max} = \max_{x \in \Omega_{admissible}} F_j(x) \quad (17)$$

$$\chi_j = \begin{cases} 1 & \text{for } F_j \leq F_j^{min} \\ \frac{F_j^{max} - F_j}{F_j^{max} - F_j^{min}} & \text{for } F_j^{min} < F_j < F_j^{max} \\ 0 & \text{for } F_j \geq F_j^{max} \end{cases} \quad (18)$$

Here χ_j is the most optimal solution, and the normalized membership function for each non-dominant solution is denoted as χ^k , which can be expressed as follows:

$$\chi^k = \frac{\sum_{i=1}^{N_{obj}} \chi_j^k}{\sum_{k=1}^M \sum_{j=1}^{N_{obj}} \chi_j^k} \quad (19)$$

The normalized membership functions produce the final solution

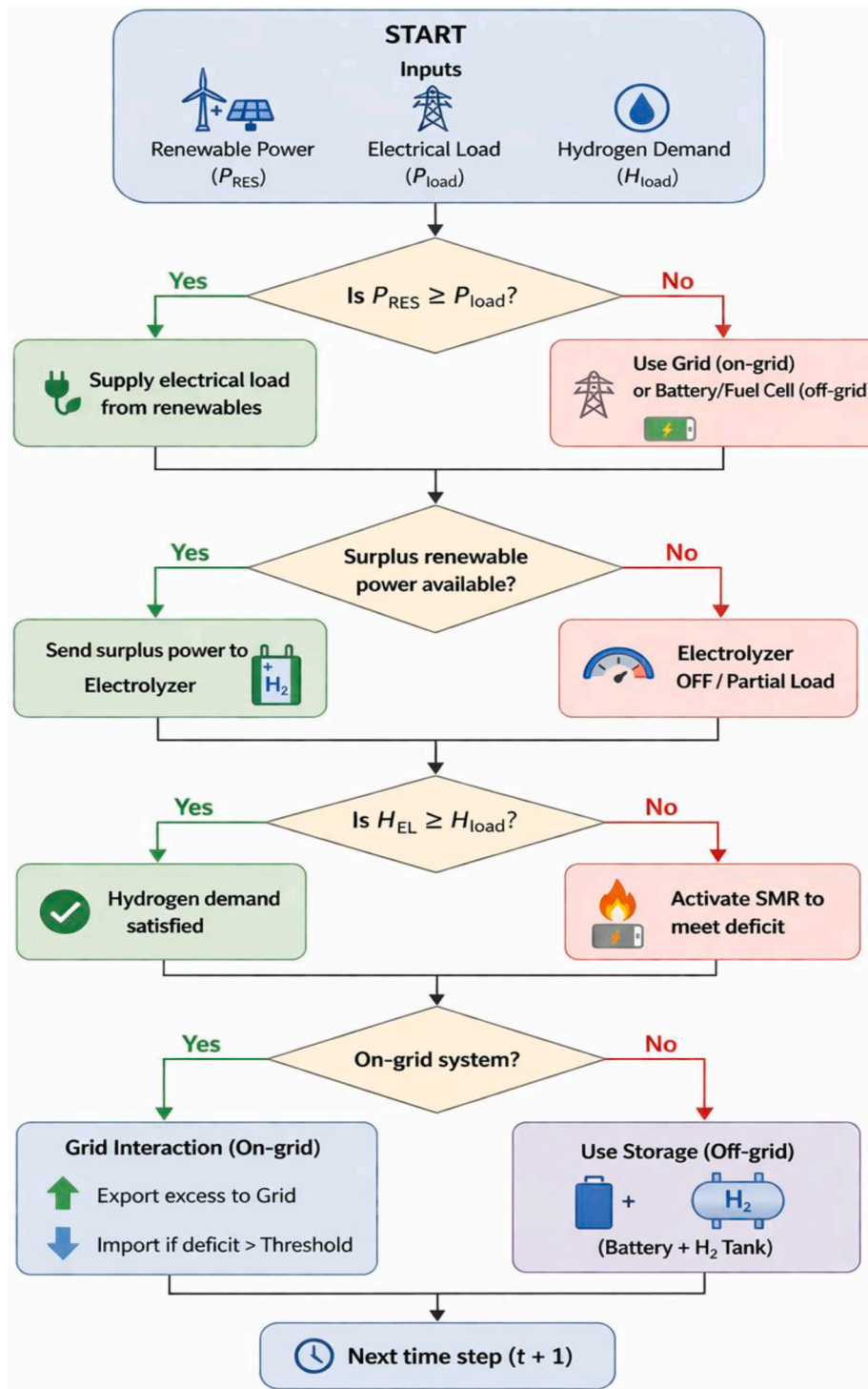


Fig. 3. Operational dispatch strategy for the integrated SMR–electrolysis system under on-grid and off-grid configurations.

based on the maximum χ^k value, where M represents the non-dominated solutions and N_{obj} indicates the number of objective functions taken in the optimization process.

3.6. Assumptions

The method for optimization of the suggested HRES includes the subsequent assumptions:

- The research area for the HRES investigation is grid-connected. To achieve analytical originality, the research goal, the region was designated as off-grid during the grid-isolated design.
- Hourly profiles of load and meteorological information are analyzed, assuming that intra-hour variations are insignificant.
- This study omits the examination of HRES device malfunctions, as well as transmission and distribution losses.
- Humidity, atmospheric pressure, and soiling may influence the power output of a photovoltaic module to a certain degree. Even

- so, these factors were strategically skipped to prevent complex calculations.
- v. The cost study disregards factors related to civil structure, instrumentation, piping, and fabrication.

3.7. Model verification and credibility assessment

To ensure the credibility of the proposed optimization framework, a multi-level verification approach has been adopted. The input datasets are based on validated sources, where hourly electricity and hydrogen demand profiles are obtained from previously published work for the same site, and the meteorological data are obtained from the NASA POWER database. The techno-economic and performance parameters for all major components, including PV, wind turbines, electrolyzer, reformer, and storage systems, are selected from the peer-reviewed literature and fall within widely reported ranges, as summarized in Appendix Table A1.

Subsystem-level consistency is verified by comparing key performance indicators, such as renewable generation, hydrogen production

rates, system efficiencies, and cost ranges, which are consistent with values reported in similar studies. In addition, internal model verification is performed by ensuring energy-balance closure at each time step over the full annual simulation (8760 h), satisfying electrical and hydrogen load demands within the LLSP constraint, and ensuring consistency between on-grid and off-grid configurations. Although full plant-scale experimental validation is not available for this specific integrated configuration, these verification steps provide confidence in the physical consistency and robustness of the proposed framework. The subsequent Section 4.13 also reconfirms the consistency of the proposed methods and their outcomes.

4. Results and discussion

The application of NSGA-II and the enhanced Bellman-Zadeh decision-making algorithm yielded a set of optimized solutions, as shown in Fig. 4(a). The trade-off between LCOE and LCE is evident along the Pareto front. Solution near region A-B exhibit lower LCOE but higher emissions due to greater reliance on grid electricity and SMR-based

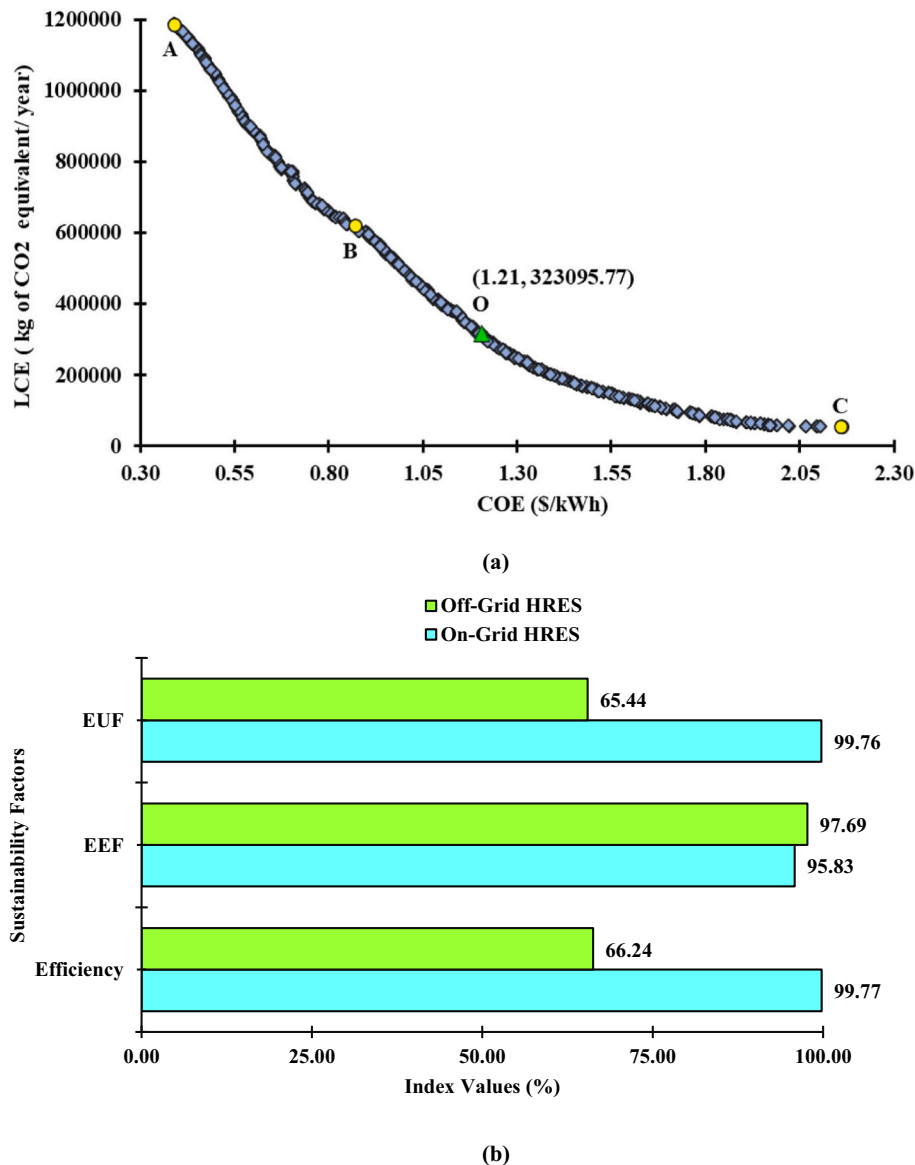


Fig. 4. (a) Optimized solutions of the proposed HRES (on-Grid) demonstrated on the optimal pareto front. (b) comparison of the sustainability factors of HRES, (c) comparison of the economic index values of HRES, (d) comparative economic factors of the HRES variants, (e) distributed Net Present Costs (NPCs) of System Components.

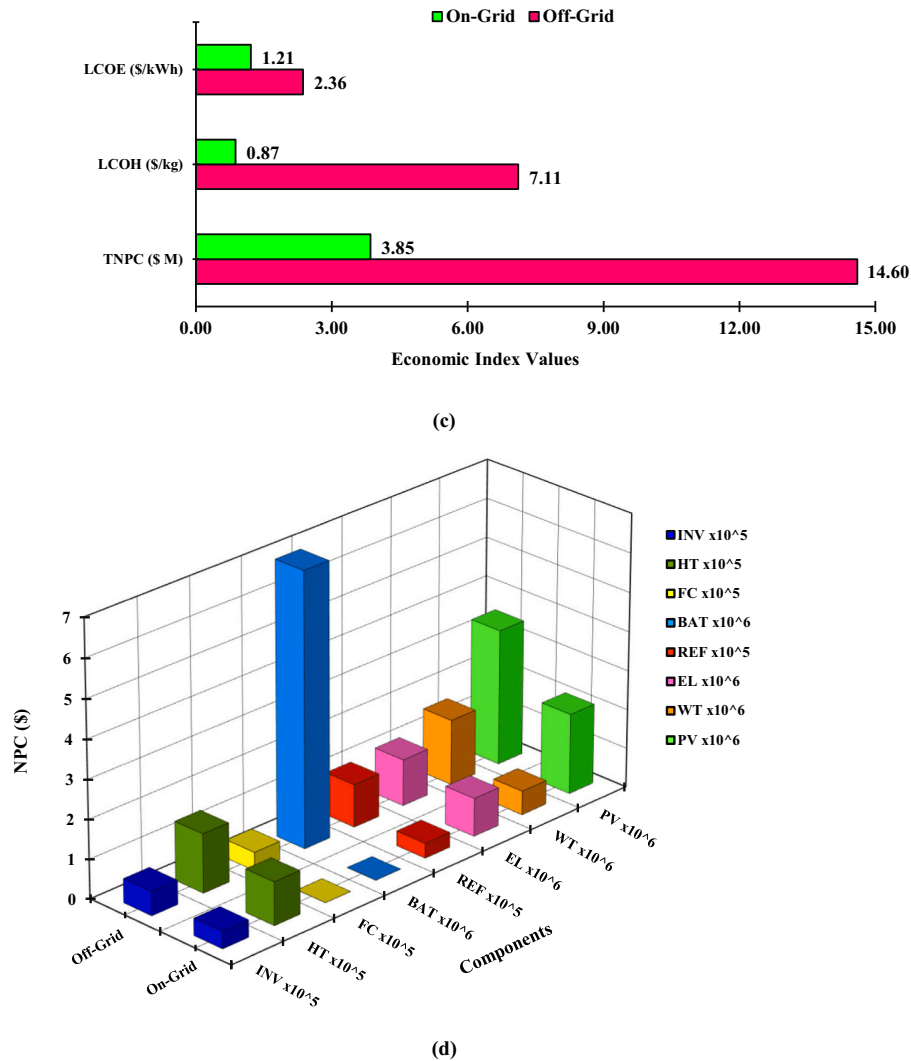


Fig. 4. (continued).

hydrogen production. Moving from B to C entails higher renewable utilization and increased electrolysis, which reduces emissions but increases LCOE. Therefore, the researchers focused on this range to identify the optimal solution point, indicated by O (1.21, 323095.77), corresponding to the optimal value of the levelized cost of electricity on the x-axis and life-cycle emissions on the y-axis.

4.1. Technical performance assessment of HRES

The off-grid configuration requires substantially larger renewable and storage capacities to meet the same electricity and hydrogen demand without grid support. Compared with the on-grid system, the off-grid solution increases PV and wind capacities to 3373 kW and 907 kW (vs. 1997 kW and 330 kW). Also, it requires battery storage and a PEM fuel cell (14.5 kW) to maintain reliability. Although the off-grid system produces more annual renewable electricity, it experiences higher conversion and storage losses, whereas the on-grid system can export surplus electricity and use grid power during deficit periods, resulting in improved operational flexibility.

Annually, the off-grid system generated more energy (7.34 million kWh compared to 3.98 million kWh) but experienced much higher losses due to storage and conversion inefficiencies. The on-grid system efficiently handled excess energy by feeding it back to the grid. Hydrogen production was higher in the off-grid system, but the on-grid system provided a more reliable hydrogen supply using grid power. Overall, off-

grid systems face greater technical and economic challenges due to their need for larger capacities and complex energy management. Technical performance and system capacities are shown in Table 3.

The systems showed different reliability in meeting electrical and

Table 3

Technical performance over the year and system capacities.

Parameters	On-Grid HRES	Off-Grid HRES
Solar PV Installed Capacity (kW)	1997	3373
Wind Turbine Installed Capacity (kW)	330	907
PEM Fuel Cell Installed Capacity (kW)	–	14.5
Electrolyzer Installed Capacity (kW)	1519	1854
Battery Bank Installed Capacity (kWh)	–	1726
Converter Installed Capacity (kW)	300	506
SM Reformer Installed Capacity (kg/hr.)	10	29
H ₂ Storage Tank Installed Capacity (kg)	1099	1499
LNG Tank Installed Capacity (kg)	45	68
PV energy (kWh)	3,385,954.104	5,721,195.801
Wind energy (kWh)	589,877.749	1,619,392.494
Grid Power Supply (kWh)	152,293.76	–
Excess energy utilized (kWh)	3,801,098.993	4,692,585.394
H ₂ Generation: Electrolyzer (kg)	79,967.82	101,018.49
H ₂ Generation: Reformer (kg)	22,059.88	1083.7199
Total Electrical Demand (kWh)	171,550	171,550
Total Hydrogen Demand (kg)	102,200	102,200
Unmet Electric Demand (kWh)	218.79	66.53
Unmet Hydrogen Demand (kg)	172.30	357.47

hydrogen loads. For the on-grid HRES, unmet electrical and hydrogen demands were 218.79 kWh and 172.30 kg, with 99.77% overall efficiency; renewables supplied 91.44% of the electric load and 84.76% of the hydrogen load, with the remainder covered by the grid and reformer. The off-grid system had lower unmet electrical demand (66.53 kWh) but higher unmet hydrogen demand (357.47 kg); although its electrolyzer reached a higher peak hourly hydrogen production (39.98 kg vs. 32.765 kg on-grid), its overall efficiency was only 66.24%, with all loads supplied solely by renewables. These results highlight that grid-isolated operation struggles with surplus energy management and efficiency, whereas grid-connected HRES reduces total losses and offers superior technical performance, despite the off-grid system being able to meet demand reasonably well.

4.2. Energy balance and system scaling of optimized hybrid systems

Energy balance and system scaling based on the optimized hybrid systems were performed on each configuration to observe its performance in real conditions. Table 4 includes a convenient visualization of the optimized system capacities, highlighting the relevance of hourly timing of energy generation and consumption and considerable differences between on-grid and off-grid configurations. The grid-connected system had a 1997 kW solar PV capacity, a 330 kW wind turbine capacity, and a 1519 kW electrolyzer capacity. For the off-grid system, the required capacities are much greater: 3373 kW solar PV, 907 kW wind turbines, and 1854 kW electrolyzer. These differences in scale are very much by design, highlighting the fundamental challenges of operating without the confines of the grid. That means the off-grid system has to produce and store all of its energy locally, resulting in much larger renewables installations and energy storage and backup supply components like a 1726 kWh battery bank and a 14.5 kW PEM fuel cell. Additional system components may be required to guarantee high reliability, but they inevitably increase capital investment and introduce greater operational complexity. In the optimized HRES configuration, the system is sized to meet 99% of both power and hydrogen demand, with the remaining deficit intentionally accounted for to cover downtime, component replacement cycles, maintenance intervals, and extreme weather conditions. This scaling analysis demonstrates why off-grid systems are more of a resource dominate and less economically efficient than on-grid systems.

The energy balance of a typical day confirms the operational advantages of grid-connected systems. Total statistics for a typical day selected to resonate are 8817.538 kWh from solar PV and 2200.696 kWh from wind turbines. The system also purchased 444.936 kWh from the grid to meet peak hourly demand. The total energy consumption by the system was 11,463.143 kWh, among which 492.455 kWh was consumed by the electrical load, 9944.507 kWh was consumed by the electrolyzer to generate hydrogen, and the reformer consumed 444.936 kWh. Moreover, 581.245 kWh of surplus energy was sold back to the grid. The total consumption for the day equals the sum of energy generation and purchase. Here is the detailed breakdown that demonstrates how the system maintained a balance between generation and consumption. In the on-grid configuration, the grid serves as a backup and a place to sell excess energy, minimizing waste and maximizing utility. One of the main advantages of flexibility is that it allows the system to respond to variations in energy production and demand without incurring major losses. On the other hand, the off-grid system is working in a more limited space. With no access to the grid, it must rely solely on local

generation and storage, leading to inefficiencies and constraints.

4.3. Operational performance indicators (EEF/EUF and efficiency)

The sustainability assessment of HRES depends on various design-basis metrics. The off-grid system efficiency is only 66.24%, and costs are significantly higher than those of the grid-connected system. However, some metrics are common in all forms of HRES and crucial to define the resilience and sustainable system dynamics, which are system efficiency, excess energy fraction (EEF), and Excess energy utilization factor (EUF). EEF and EUF contribute significantly to energy balance, system reliability, and optimizing system performance for long-term energy supply stability, making them key indicators in the sustainability assessment of HRES [6]. Mokhtara et al. [38] showed that energy losses in off-grid systems are primarily due to excess generation and limited storage capacity, capping practical efficiency at around 55–60% under optimal conditions. Rad et al. [39] reported that the off-grid HRES experiences significant energy loss, especially when excess electricity production exceeds storage capacity. It argues that achieving an efficiency above 60% is prohibitively expensive due to these limitations.

The HRES variants studied and optimized in this study show impressive performance in terms of sustainability indicators. Remarkably, the on-grid system achieves an efficiency of 99.77% (Fig. 4(b)), which is impressive and practical given grid integration and low energy losses. Meanwhile, the off-grid system exhibits approximately 66.24% efficiency, significantly lower than that of the on-grid system. Though the off-grid system beats the on-grid system in EEF with a slight difference of 1.86%, it cannot utilize the excess energy shown by the EUF. The on-grid system outperforms the off-grid system in energy utilization by a staggering 34.32%. Overall, the on-grid system shows high sustainability, power generation, and supply resilience.

The off-grid performance could be improved through higher-efficiency storage technologies, optimized storage dispatch strategies, or basic recovery from reformer operation. Such enhancement would increase system costs and alter the economic optimum; therefore, they were not included within the scope of the present study.

4.4. Cost analysis

The LCOE for the grid-isolated system is \$ 1.15/kWh higher than that of the on-grid system (see Fig. 4(d)). A significant improvement was seen in hydrogen costs, which are just 0.87 \$/kg due to effective load sharing between reformers and electrolyzers. In contrast, the grid-isolated system faces a hydrogen cost 6.24 \$/kg higher than the on-grid system. This disparity arises from the energy costs of hydrogen production, as the reformer relies on backup power from batteries fed solely by renewable sources. Excess renewable energy produces hydrogen through an electrolyzer, and any surplus is stored. This reliance has led to increased sizing for solar PV, wind turbines, and storage, ultimately driving up electricity and hydrogen costs.

Fig. 4(e) depicts the NPCs of the optimized HRES variants. The total net present cost of off-grid systems is \$14.60 million, primarily due to the high cost of battery storage required for hydrogen production. PV and battery storage account for about 73.28% of these costs, highlighting the challenges of energy storage in large-scale, grid-independent systems. In contrast, the on-grid system shows improved management of variable loads and reduced hydrogen costs, with an LCOH at 0.87 \$/kg and an LCOE of 1.21 \$/kWh. The TNPC for the grid-

Table 4
System performance analysis.

HRES variant	Energy generated (kWh/yr)	Energy utilized (kWh/yr.)	Renewable fraction in electrical load demand	Renewable fraction in hydrogen load demand	Excess energy (kWh/yr)	Energy loss (kWh/yr)	Overall system efficiency
On-Grid	3,975,831.85	3,966,802.906	91.45%	78.38%	3,810,127.94	9028.947	99.77%
Off-Grid	7,340,588.30	4,862,180.299	100%	100%	7,170,993.39	2,478,407.996	66.24%

connected system is \$3.85 million, with solar PV and the electrolyzer making up 78.44% of this amount. Removing battery storage and fuel cell costs has reduced the economic strain on the on-grid system, while renewable energy sources account for about 35.14% of the TNPC for the off-grid system.

In on-grid systems, renewable energy sources account for nearly 69.10% of initial costs, highlighting the economic challenges of off-grid systems, where 64.86% of costs go to energy storage and backup systems for reliability. Grid-isolated systems are more economically viable with single-source load sharing, while grid-connected systems are more resilient when distributing load among various sources. This study meets the hydrogen load demand using a reformer backed by a grid supply, ensuring economic stability and investment attractiveness.

4.5. Cost sensitivity analysis

Sensitivity analysis enables the evaluation of a system's performance and behavior under uncertain input parameters. It is widely used to identify the key variables influencing the performance of energy

systems. In this study, sensitivity analysis is conducted to assess the system's response to variations in input costs, focusing on changes in the costs of critical components such as PV, WT, EL, SMR, and HT. Capital cost reductions ranging from 10% to 50% are considered (Fig. 5(a) and (b)). Fig. 5(b) depicts the impact of reducing the capital costs of PV and WT on the NPC and LCOE. A significant reduction in the total NPC is observed as the capital costs of PV and WT decrease. Specifically, the NPC declines by 9.52%, 19.05%, 28.57%, 38.10%, and 74.62% when the capital costs are reduced by 10%, 20%, 30%, 40%, and 50%, respectively. This substantial decline underscores the sensitivity of the system's economic performance to the costs of these components. Similarly, reductions of 10% to 50% in PV and WT prices lead to a decrease in LCOE, ranging from 9.17% to 47.27%. Fig. 5(c) demonstrates the effect of reducing the capital costs of EL, SMR, and HT on the LCOH. A 20% reduction in the prices of EL, SMR, and HT results in a 9.61% decrease in LCOH, while a 50% reduction yields significant cost savings, reducing LCOH by nearly 48%.

The economic profitability of the on-grid system is better-sighted when Fig. 5(d) demonstrates the return on investment and simple

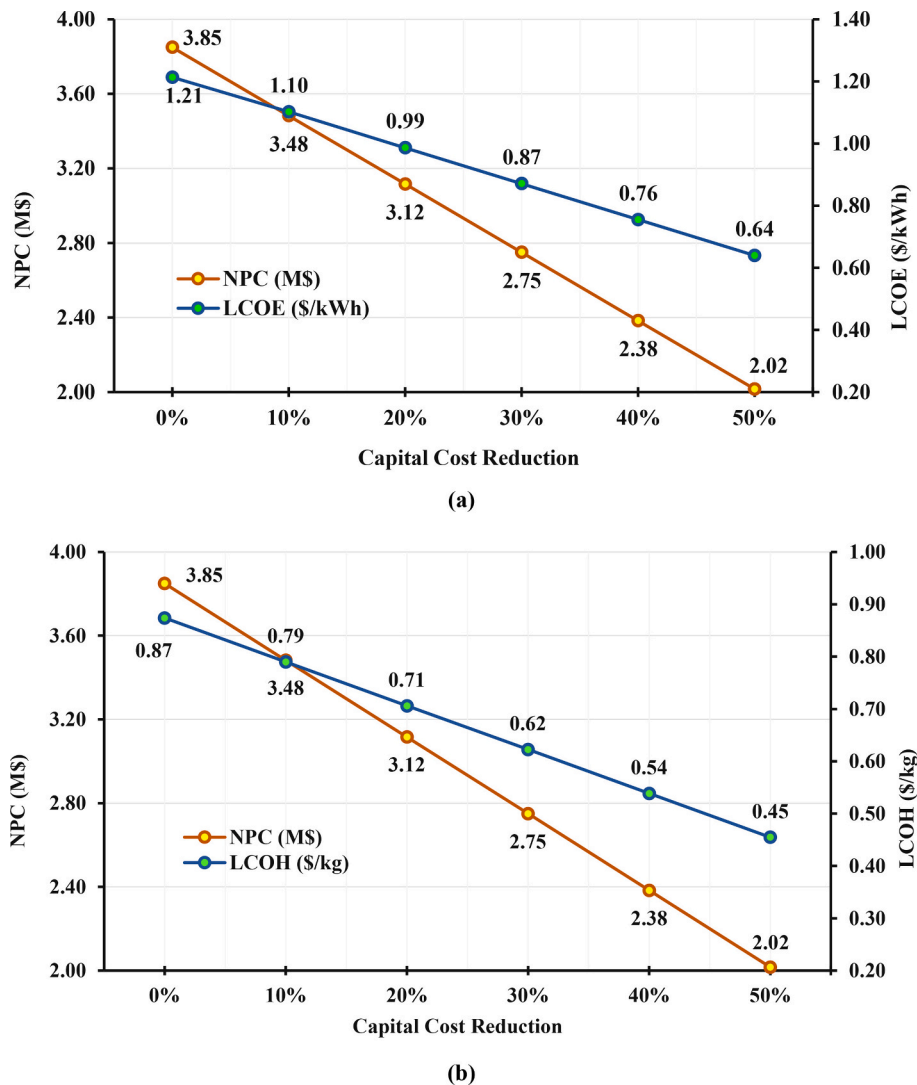


Fig. 5. (a) Effect of varying capital cost of PV and WT on NPC and LCOE, (b) effect of varying capital cost of EL, SR and HT on NPC and LCOH, (c) analysis of Simple Payback Period and Return of Invest of the most economically viable (on-grid) system when operates in replacement of conventional plant types, (d) distributed Life Cycle Emissions of System Components, (e) comparative demonstration of environmental parameters of the HRESSs, (f) carbon Emission Penalty on Direct System Emission (DSE) and Life Cycle Emission (LCE), (g) fuel Savings and Emission Reduction by the on-grid System when operates in replacement with conventional plant types, (h) comparative Analysis of Climate Change Mitigation Potential (CCMP) and Direct System Emission of the HRESSs, (i) variation of Socio-economic factors over the project timeline.

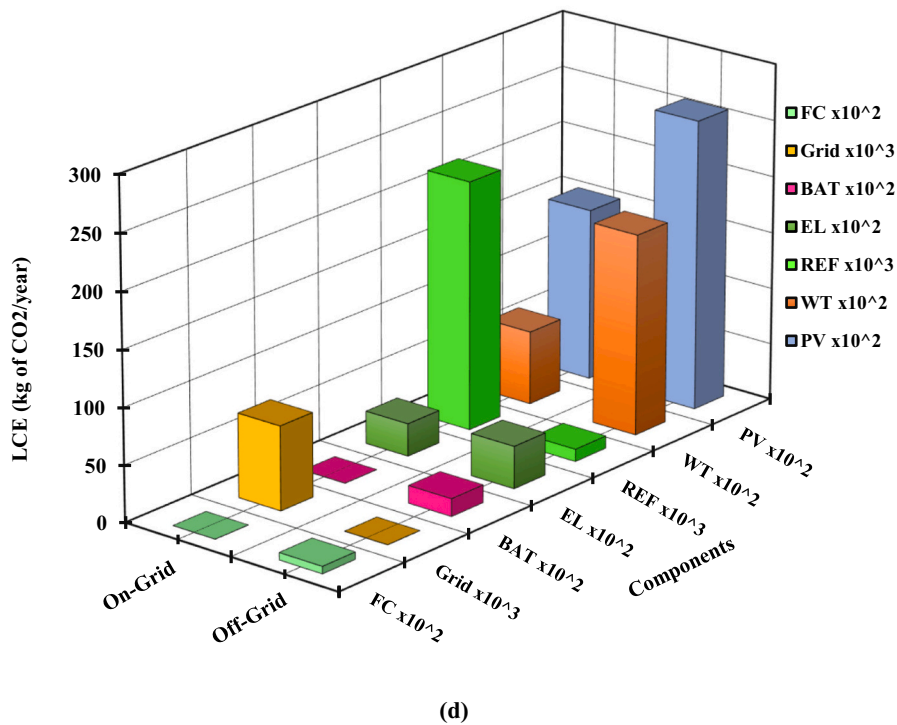
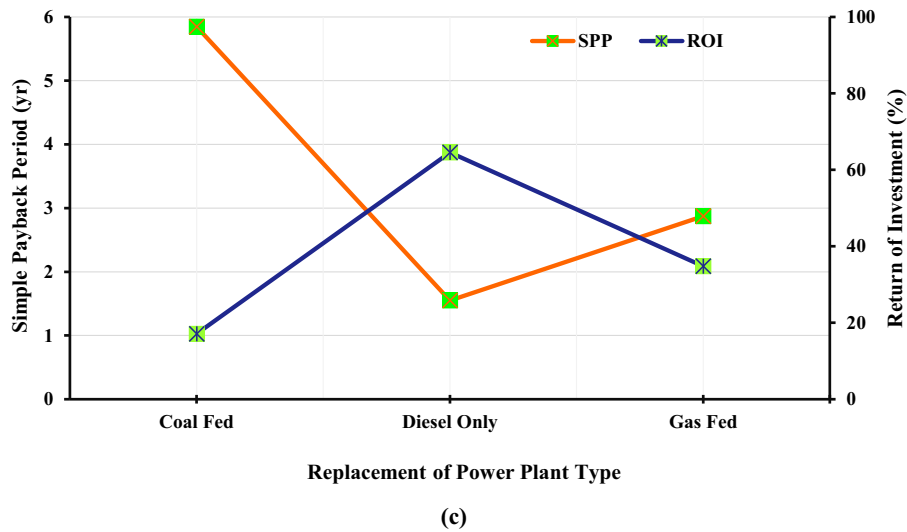


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payback period when installed in replacement of the conventional power generation systems. Overall, the results indicate that PV and WT capital exert the strongest influence on the global economic optimum, primarily through their dominant impact on NPC and LCOE. In contrast, electrolyzer and reformer costs mainly affect LCOH, with comparatively lower influence on the overall system configuration.

This study examined three conventional power systems by fuel type, focusing on annual fuel cost savings. The proposed on-grid system has the longest payback period of nearly 6 years when replacing a coal-fed power plant. It achieves the shortest payback of 1.55 years when replacing a diesel-fed power plant and around 3 years for a gas-fed plant. The highest ROI is 64.55% for diesel replacement, surpassing coal and gas replacements by 47.45% and 29.75%, respectively. This analysis demonstrates that grid-integrated HRES are more economically attractive than conventional diesel-powered plants.

The sensitivity analysis demonstrates that capital cost reductions in key HRES components, particularly PV, wind, battery storage, and

electrolyzers produce the most significant decreases in both the LCOE and LCOH. The long-term viability of off-grid hybrid renewable systems is fundamentally tied to continued declines in upfront investment costs and ongoing technological advancements across system components.

In parallel, policy and market mechanisms such as tax incentives, carbon penalties, and monetized environmental benefits can substantially improve project economics. These measures not only accelerate the financial attractiveness of off-grid HRES deployments but also support strategic decision-making for meeting combined electricity and hydrogen demand in remote settings.

4.6. Environment analysis

One of the key objectives of this study is to improve the environmental adaptability of reformer-integrated HRES. This objective is reflected in the selection of an optimization function that includes LCE as a significant factor aimed at reducing the lifecycle emissions of power

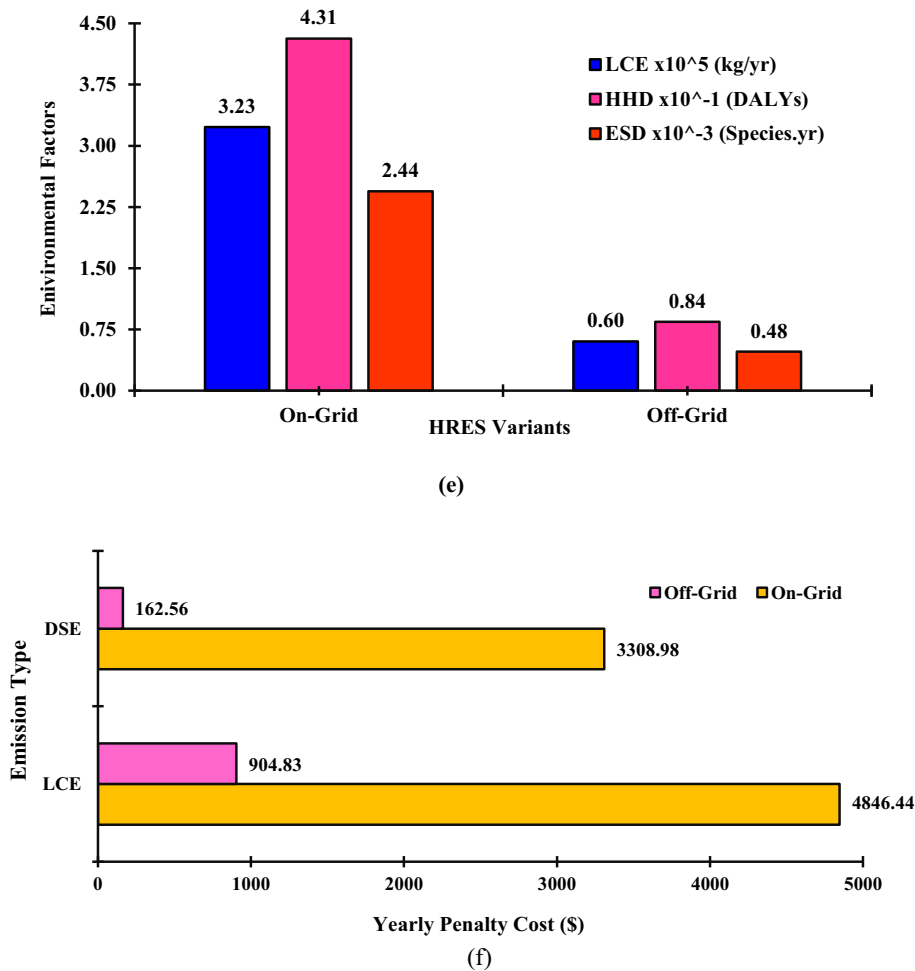


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systems. The researchers employed a distinctive distributed approach to demonstrate the environmental impact of two types of emissions, rather than solely focusing on the lifecycle carbon footprint. In addition to Lifecycle Emissions, Direct System Emissions (DSE) associated with the SMR are also considered in this study. Afanasev et al. [32] stated that hydrogen production via the SMR process emits up to 10 kg of CO₂ per 1 kg of H₂ production. It may vary based on the efficiency of the carbon capture and storage (CCS) system integrated with the SMR plant; however, the global average of emissions via the SMR process points to this level or more than that. Therefore, the direct system emissions in this study incorporate the steam methane reforming process, and the life cycle emissions include the carbon footprints of HRES components and DSE combined. The graphical representation in Fig. 5(e) shows the distributed LCE contributions of HRES components. In the grid-connected system, grid emission footprint and reformer emission include the largest share of LCE footprint, which is 295 tons of CO₂ equivalent/year. Reformer emission incorporates the highest share in the LCE footprint of the on-grid system, which is 68.28% of the estimated 323.10 tons of total LCE footprint. Since the off-grid system mostly depends on the reformer at the start and end of the year, the emissions are relatively lower than the on-grid system; the LCE footprint is around 60 tons of CO₂ equivalent per year. The highest share in off-grid LCE footprint is estimated around 72.10% by solar PV and Wind turbines together.

Fig. 5(f) demonstrates that the impact of life cycle emissions on human health and ecosystems is well justified in this study, supporting the HHD and ESD emission factors. The isolated system performed better than the grid-connected system due to 81.43% less LCE footprint and

around 210 tons less direct system emission. The on-grid system exhibits higher HHD and ESD factors, 0.347 DALYs and 0.00196 Species.yr, more than the off-grid system. The off-grid system is more environmentally sustainable but not economically viable due to higher cost factors and lower efficiency. Although the on-grid system is environmentally outperformed by the off-grid system, the emissions and the environmental impacts are substantially less than those of the conventional non-renewable power systems. Razmjoo et al. [40] showed that coal- and oil-based power plants emit over 1 kg CO₂/kWh, slightly higher than diesel-based power plants, which emit around 0.76 kg CO₂/kWh. Meanwhile, the on-grid HRES suggested in this research emits 0.081 kg CO₂/kWh as an LCE footprint and 0.056 kg CO₂/kWh as a direct system emission. This breakthrough proves that the on-grid system will reduce human health damage (HHD) and ecosystem damage (ESD) by 93.63% on average when replacing conventional systems.

4.7. Penalty for carbon emission

The emission penalty is applied in energy projects to charge an amount for every unit of energy supplied by power generation systems according to the amount of CO₂ released. It is thought to discourage the overuse of fossil fuels. Research indicates that penalties from \$20 to \$100/ton CO₂ prompt industries to adopt renewable energy, become more efficient or minimize emissions [41]. This energy policy is essential in the current global economy to combat climate change, align with net-zero targets, provide financing for environmentally sustainable programs, and enable a low-carbon energy transition. This study thoroughly analyses the carbon emission penalty for both LCE footprint and

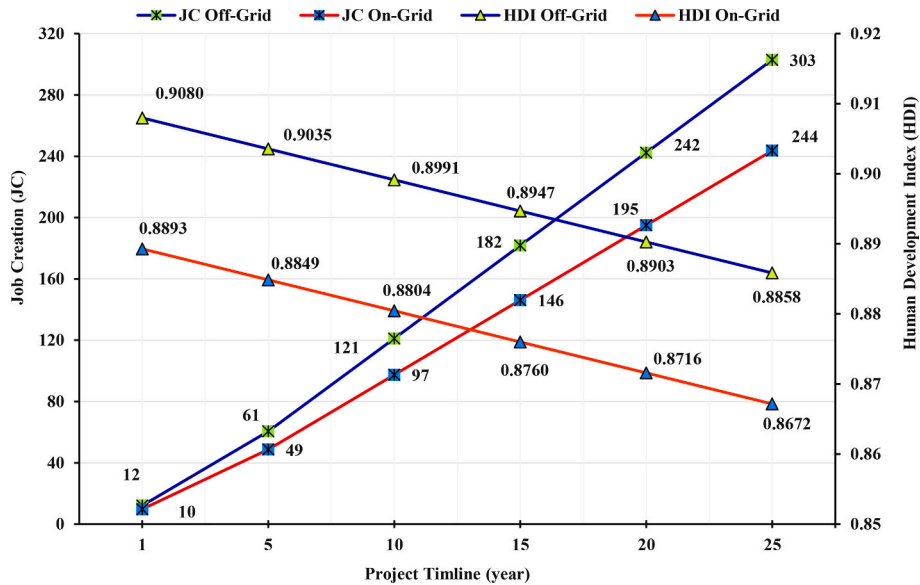
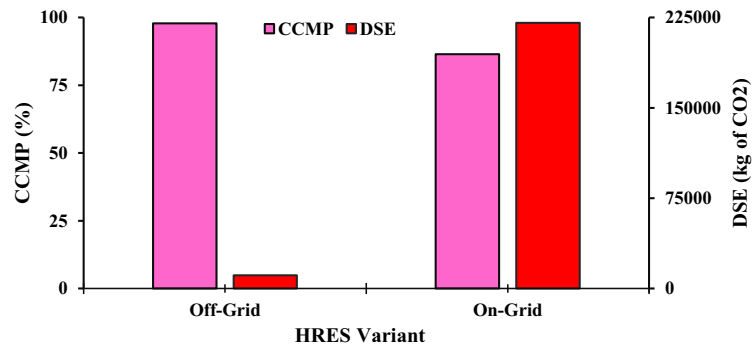
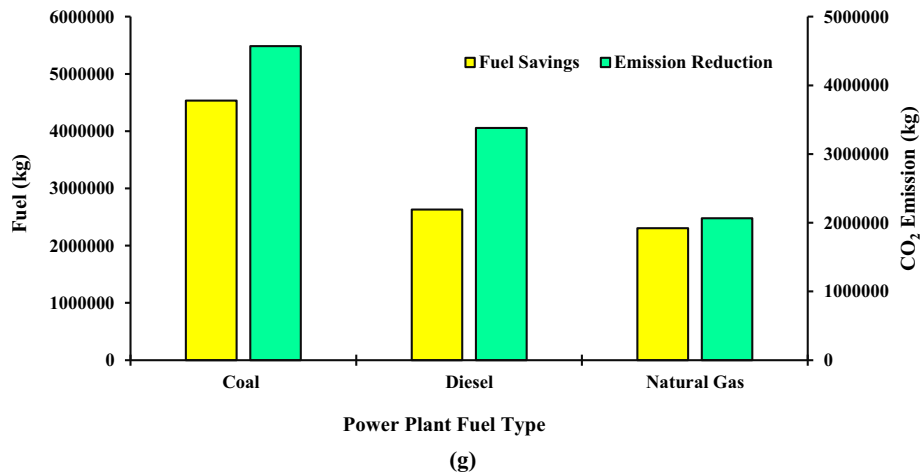


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direct system emissions. Though Kuwait has not yet imposed a carbon tax, this study factored in an emission penalty of 0.015 \$/kg of CO₂ emission, as documented by Maisanam et al. [42]. The off-grid system has a lower emission penalty on LCE and DSE than the on-grid system. The yearly carbon penalty for the suggested HRES is \$3308.98, considering direct system emission, and \$3941.61 higher than the off-

grid system when considering life cycle emission.

4.8. Fuel economy and CO₂ emission reduction

This research investigated the fuel economy and estimated carbon emission reduction when the suggested HRES (on-grid variant) is

installed to replace conventional power plants based on different fuel types. The price of fossil fuels has been consistently rising due to diminishing reserves, with projections suggesting that conventional oil and gas resources will become limited by 2050 if global consumption patterns continue [42]. To break this pattern, implementing sustainable HRES is inevitable in replacing conventional power systems. As shown in Fig. 5(g), the optimized on-grid HRES in this study can save up to 4532.45 tons of coal, 872464.9 gal of diesel, and 54.65 million CFT of natural gas yearly. The emission reduction regarding this fuel saved is 4572.20 tons, 3379.46 tons, and 2067.43 tons for coal, diesel, and natural gas-fired power plants, respectively.

Fig. 5(h) solidifies the statement of the high level of environmental sustainability of the on-grid HRES with a comparative analysis of climate change mitigation potential (CCMP). Though the off-grid HRES outperforms it in emission reduction, the CCMP index shows that the on-grid system performs 86.4% efficiently, just 11.41% below the costlier off-grid HRES. Though the direct system emission is higher than the off-grid system, the CCMP index is quite close due to its ability to match the emission reduction capacity with the baseline emission of conventional systems. This research utilized the emission factors from LCE assessment studies on the HRES components, which are presented in the table below.

4.9. Analysis of social development index

Numerous energy policy studies demonstrate that improvements in reliable electricity supply are positively associated with income generation, employment opportunities, healthcare access, and educational development, core dimensions reflected in HDI. Accordingly, the projected HDI values in this work are estimated using a normalized index

based on per-capita energy availability and system-induced employment generation under each HRES configuration.

Job creation is estimated using technology-specific employment intensity factors (jobs per MW installed capacity) reported in the renewable energy literature. These factors are applied to the optimized installed capacities of PV, wind turbines, electrolyzers, reformers, and associated infrastructure, and cumulative employment is projected over the 25-year system lifetime. It should be noted that the socio-economic indicators presented in this study are derived from technical system outputs and do not explicitly account for region-specific policy incentives or subsidy mechanisms.

As a supplementary assessment, social indicators (HDI and job creation) were estimated under the optimized configurations. The off-grid system shows greater potential, generating approximately 12 jobs per year and an HDI value of around 0.91 due to higher energy production. The on-grid system, while slightly lower at an HDI of 0.89 and about 10 jobs per year, can create a total of 244 jobs over 25 years with a consistent HDI index of 0.87. The declining HDI trend is linked to the increasing number of power consumers. The off-grid system estimates 303 jobs created throughout the project, maintaining an HDI index of 0.89 (Fig. 5(i)). However, concerns about energy costs and long-term sustainability remain, which could impact these socio-economic indicators unless government subsidies are provided. In summary, the on-grid system aligns better with social welfare and sustainable development goals.

4.10. Statistical analysis

Renewable-integrated hybrid energy systems exhibit complex operational dynamics due to intermittent power generation and load demand

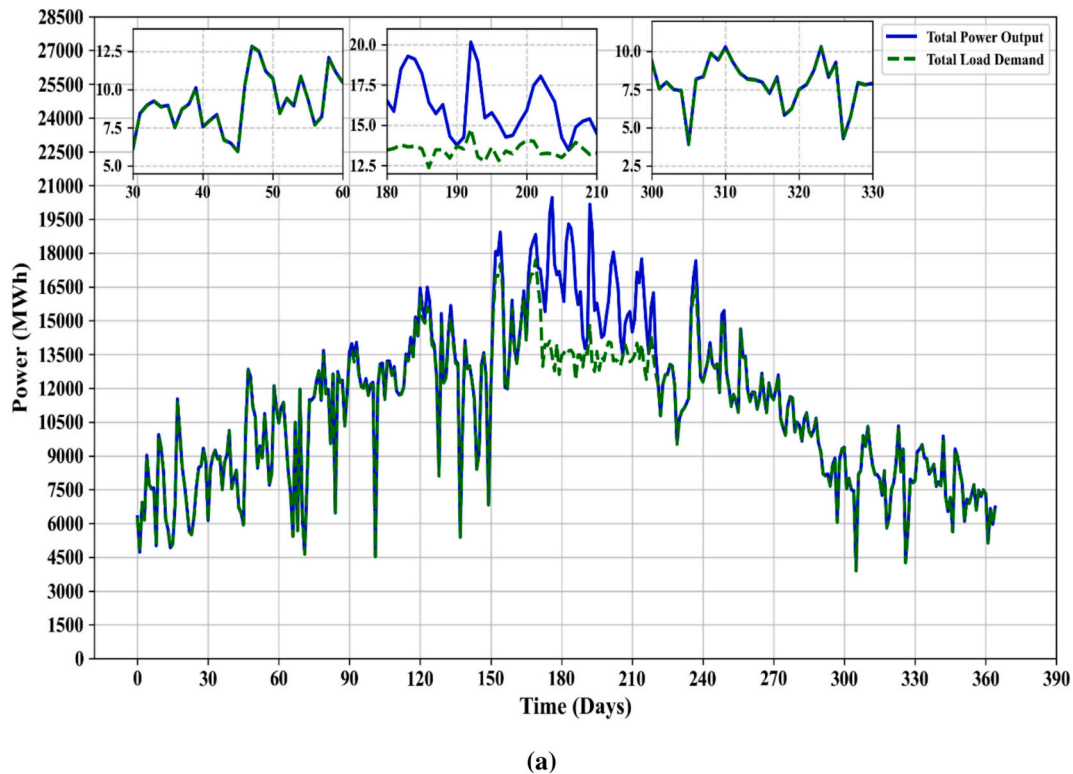


Fig. 6. (a) System power output and total load dynamics of the suggested HRES on daily basis, (b) daily hydrogen tank autonomy of the proposed HRES (On-grid), (c) dynamics of grid connectivity of the proposed HRES, (d) analysis of Energy Security Index (ESI) of HRES variants, (e) daily distribution of comparative PV power output, (f) daily distribution of comparative wind power output, (g) comparison of Distributed renewable generation with total system generation, (h) comparative scenario of fuel consumption by reformers, (i) monthly hydrogen load sharing between reformer and electrolyzer in the on-grid HRES, (j) monthly hydrogen load sharing between reformer and electrolyzer in the off-grid HRES, (k) hydrogen Tank State of Charge of the On-Grid HRES, (l) hydrogen Tank SOC of the Off-Grid HRES, (m) distributed dynamics of power consumption of the proposed system.

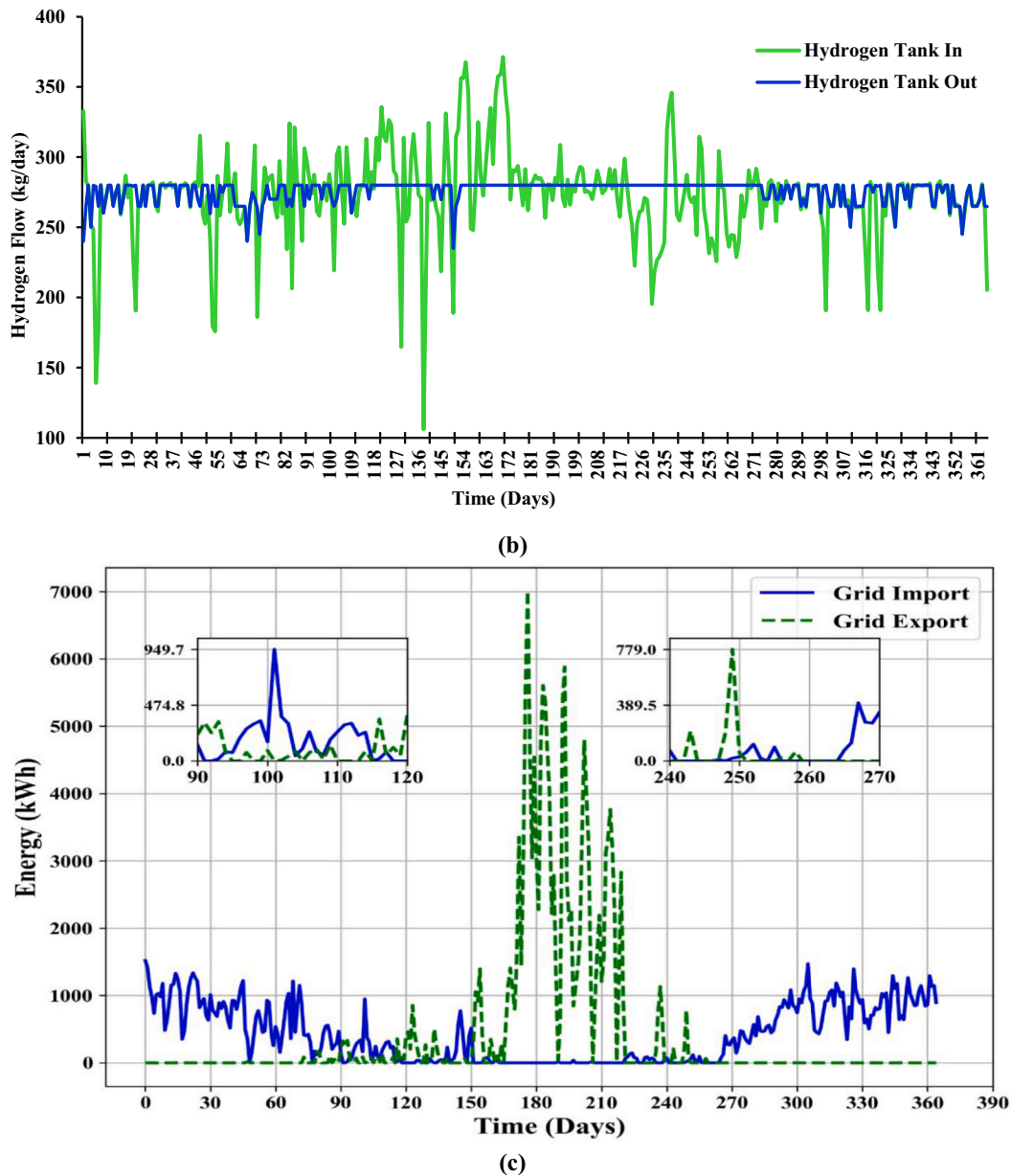


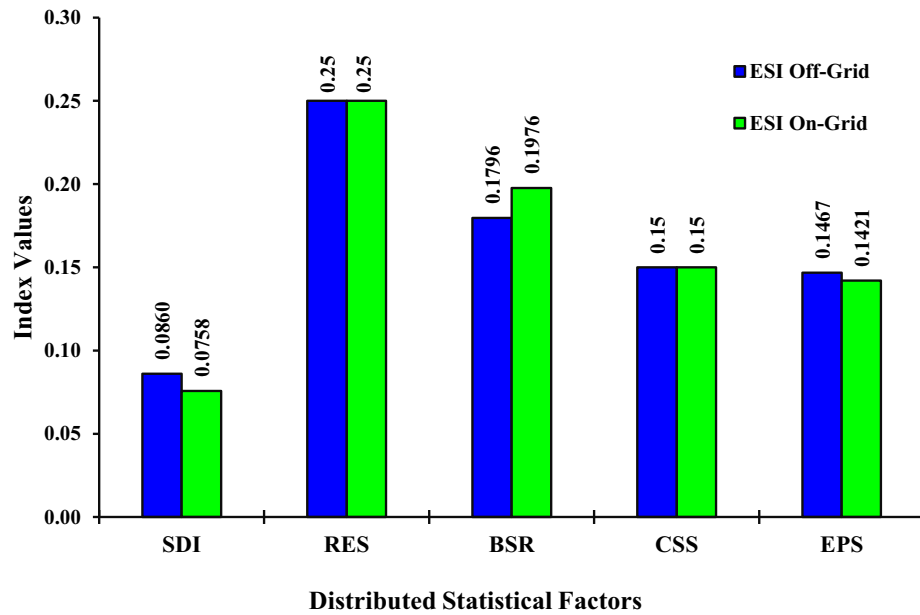
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variability. A detailed analysis is vital for understanding the challenges of continuous operation. This research provides a statistical analysis to clarify the system dynamics. Fig. 6(a) compares total power output and load demand over a year, with days (0 to 365) on the x-axis and power in megawatt-hours (MWh) on the y-axis. The total power generated was approximately 4128.12 MWh, while the required load was about 3958.55 MWh. The lower panel shows wide variability in both metrics, with power output ranging from 4.5 MWh to 21 MWh and load demand from 4.5 MWh to 18 MWh. The upper-left panel zooms in on days 30 to 60, revealing that both power output and load demand remained between 5 MWh and 12.5 MWh, with a peak output of 12.5 MWh on day 50. The upper-right panel, focusing on days 300 to 330, shows closely aligned power output and demand, indicating that supply effectively met demand. Notably, from days 150 to 210, power output exceeded load demand, allowing excess energy to be exported to the grid and optimizing resource use.

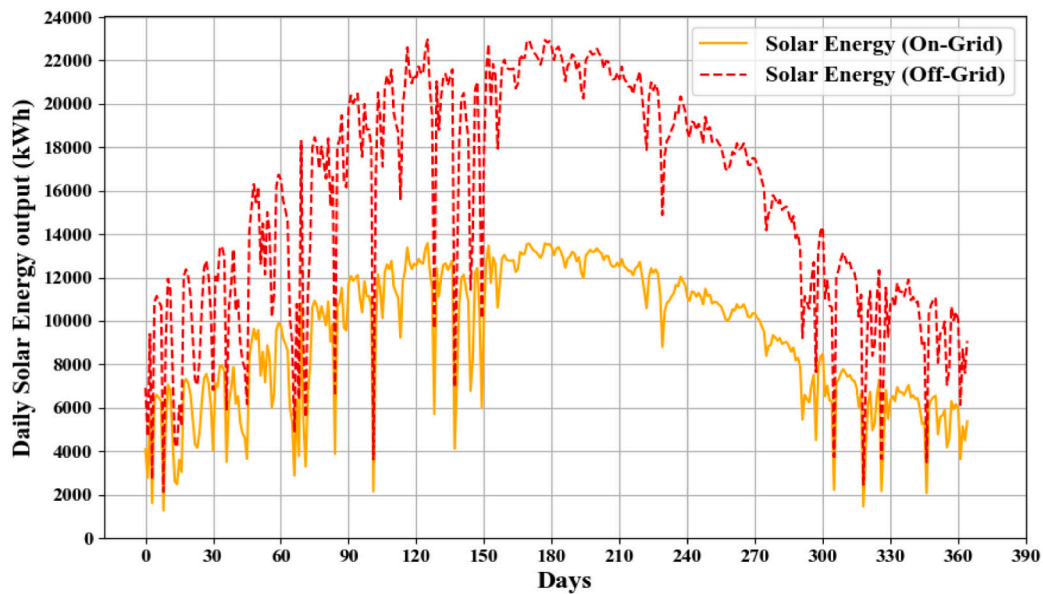
The autonomy of hydrogen tanks is better understood when visualized on a daily basis with the amount of hydrogen being stored and supplied, as demonstrated in Fig. 6(b). The proposed system can

maintain the hydrogen load demand with up to 99.95% reliability. The highest daily inflow of hydrogen was 106.15 kg in mid-May, and the maximum daily tank outflow was recorded at 235 kg on the second last day of May. From June to September, the system showed a staggering 100% reliability in load meeting capacity, visible in the graph with a straight line from 155 to 273. This matching scenario in maximum flow dynamics proves the system's load supply reliability.

Grid-connected systems provide a reliable backup supply and improve efficiency by selling excess energy to the grid. Fig. 6(c) shows daily energy import and export for the proposed hybrid renewable energy system (HRES). The system mainly imports energy early and late in the year, while from days 150 to 210, it generates more power than the load demand, allowing for excess exports of about 7005 kWh. Energy imports occur when generated power falls short of demand, particularly when the small modular reactor (SMR) is needed for backup hydrogen production, with imports reaching around 1515 kWh. Overall, the system imported about 151.90 MWh and exported approximately 160.76 MWh, supplying nearly 9 MWh of power to the grid after meeting hydrogen and electrical consumption demands.



(d)



(e)

Fig. 6. (continued).

This study evaluated the statistical energy security index (ESI) of the proposed system to demonstrate its effectiveness and reliability for consumers. As shown in Fig. 6(d), although the off-grid system has a higher supply diversity index (SDI), the proposed system's ESI is superior at 0.82 compared to the off-grid's 0.81, thanks to better backup supply reliability (BSR) from grid connectivity. Both systems share the same renewable energy share (RES) factor since they can fully meet demand with renewable energy. The on-grid system has a negative net grid purchase, meaning it supplies more power than it consumes, achieving a 100% renewable energy share. With no annual load variability in the one-year analysis, both systems show equal cost stability. The off-grid system has a slightly better environmental penalty index due to lower emissions.

4.11. Scenario comparison between HRES variants

To evaluate the effectiveness of the selected HRES compared to other variants, it's essential to analyze various performance parameters and system dynamics. Fig. 6(e) shows daily solar energy output in kWh over a year. The on-grid system has a stable output, peaking at 12,000 to 14,000 kWh around mid-year (days 120 to 180) during the summer. In contrast, the off-grid system exhibits higher variability, with peaks of 22,000 to 24,000 kWh during the same period, relying solely on solar and wind sources. Both systems follow a seasonal trend, but the off-grid system's extensive sizing leads to significant energy losses, reducing efficiency and sustainability. Fig. 6(f) presents daily wind energy output over the year. The on-grid output peaks at 6000 to 8000 kWh around days 120 to 180, while the off-grid output shows more variability,

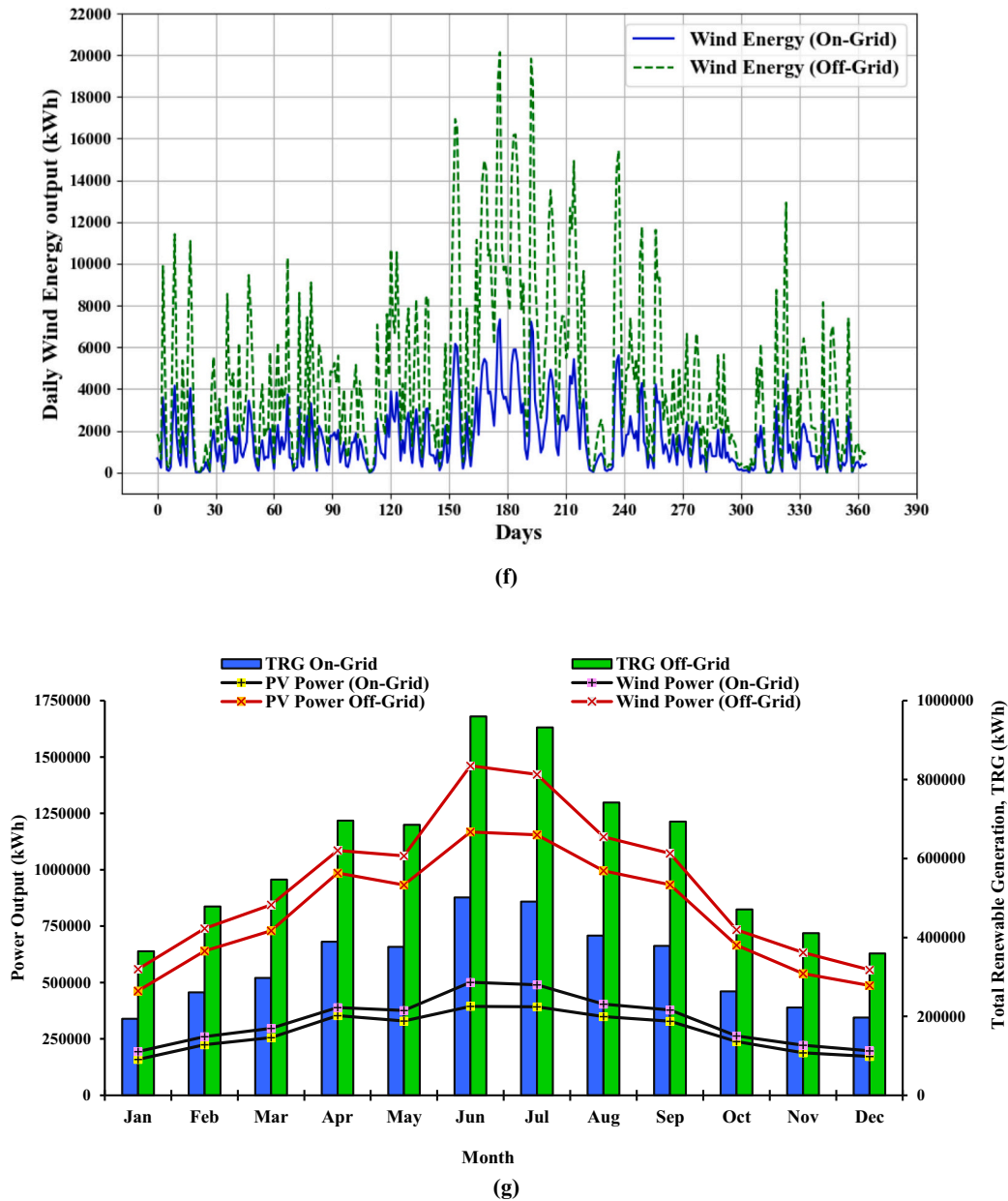


Fig. 6. (continued).

reaching 18,000 to 20,000 kWh. This indicates a need for greater wind energy generation in the off-grid system to meet load demands effectively.

The distributed power supply comparison in Fig. 6(g) supports the previous analysis of hourly renewable power dynamics over the year. The off-grid and on-grid systems peaked in June and July in total power generation with nearly 959.80 MWh and 501.24 MWh, respectively. Both systems exhibit the lowest power outputs in January and December, where wind power ranges from 18% to 26.30%, and PV power ranges from 73.70% to 82% of total monthly generation. The strategic distribution of generated power over the year and maintaining a reliable power supply are crucial in renewable energy networks.

Fig. 6(h) presents the daily fuel consumption scenario of the reformer over the yearly operation. The off-grid system required less fuel as the reformer supported as the backup hydrogen supplier for January and December only. The reformer was not activated for three months continuously from June to August due to the high level of renewable

energy penetration during this part of the year. As presented by figs. 35 and 36, during this period, the on-grid system produced the highest 9414.15 kg in June 8497.97 kg in July, and 7992.67 kg of H_2 in August, relieving the load sharing stress on the reformer. However, the highest generation month for the off-grid system was February, when the electrolyzer produced 9503.43 kg of H_2 (Fig. 6(i-j)).

The SOC of the hydrogen tank in both on-grid and off-grid HRES shows distinct performances. In the on-grid HRES (Fig. 6(k)), the SOC starts low, then gradually fluctuates before sharply increasing to about 1200 kg. The mid-trajectory dip indicates the peak SOC is briefly sustained, followed by rapid depletion, highlighting an effective load-sharing mechanism where grid electricity meets hydrogen demand without relying heavily on storage. In contrast, the off-grid HRES (Fig. 6(l)) shows a steady increase in SOC, reaching around 1500 kg and remaining high for a period before dropping significantly due to insufficient renewable generation. This indicates reliance on stored hydrogen for long durations without using the reformer. However, as time

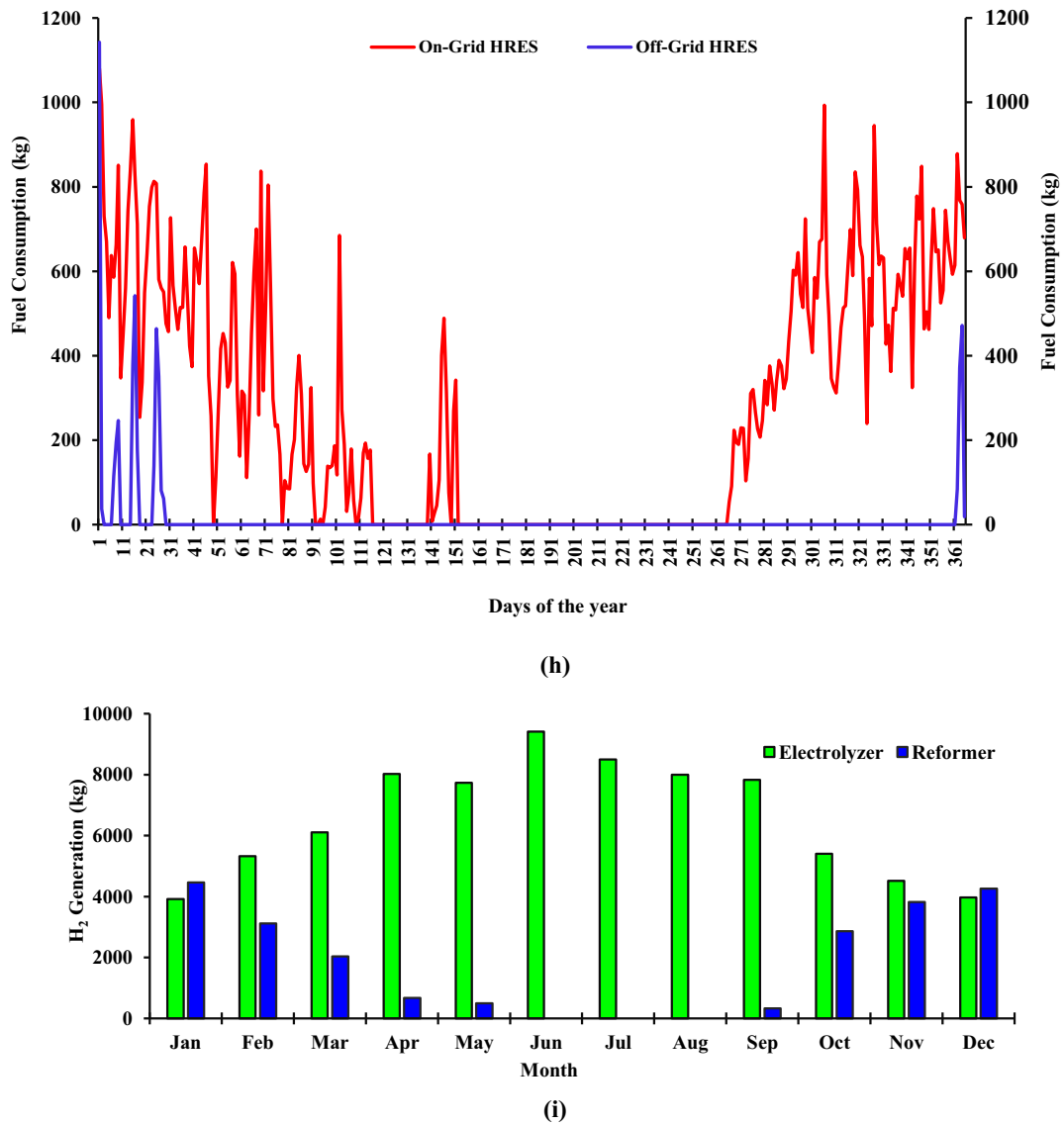


Fig. 6. (continued).

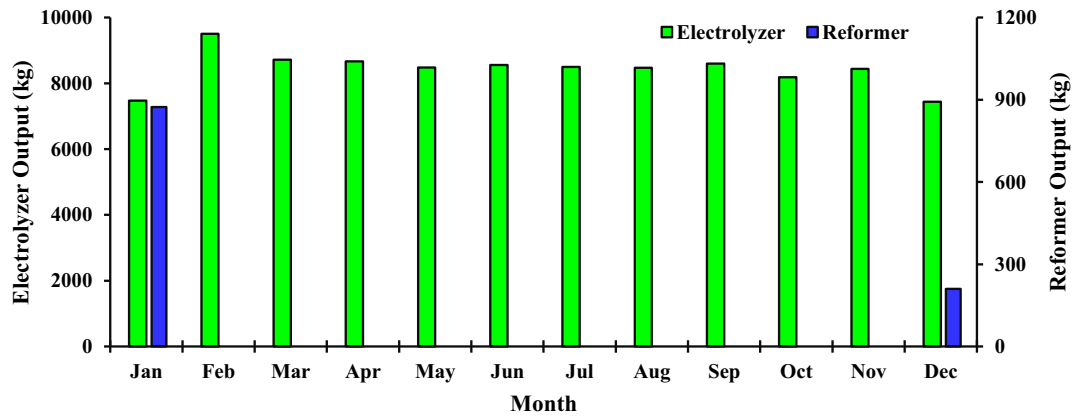
progresses, the SOC declines sharply, reflecting increased reliance on the reformer for hydrogen supply due to the absence of grid backup. In summary, the on-grid system demonstrates a balanced hydrogen utilization approach, while the off-grid system maintains SOC longer but has a sudden reliance on the reformer, resulting in less efficient load distribution.

4.12. Power dynamics visualization

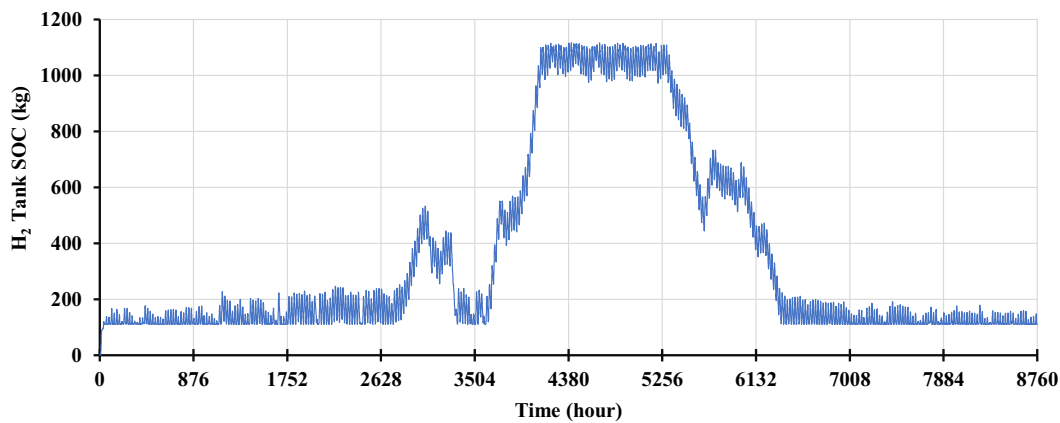
The proposed HRES has a seasonal energy share that relies on solar PV and wind power availability. PV generation is the primary energy source year-round, peaking in June (394,324 kWh), followed by July (392,885 kWh) and May (329,289 kWh). Although wind power generation is relatively low, it contributes significantly in June (106,916 kWh) and July (97,772 kWh). Electric demand remains consistent at about 14,250 kWh monthly. The electrolyzer demand peaks in high-generation months, reaching 436,373 kWh in June for adequate hydrogen production, while summer reliance on the reformer is minimal. In contrast, winter sees increased reformer consumption, reaching 26,560 kWh in December, underscoring its role in stabilizing energy supply when renewables fall short (Fig. 5(m)).

4.13. Comparison with literature

The current study applied a unique strategy by a trade-off at the cost of electricity (LCOE) to deal with the high cost of hydrogen production (LCOH) with renewable integrated systems. Renewable-integrated hydrogen production systems entail a relatively high hydrogen cost, as recently documented by Roy et al. [43], where they found the optimized LCOH value of 6.0264 \$/kg of hydrogen. However, the LCOE value was comparatively lower, at 0.33 \$/kWh. Similarly, Barhoumi et al. [44] achieved an LCOH value of 5.5 €/kg (~6.43\$/kg), slightly higher than the 3.94 \$/kg LCOH value obtained by Al-Orabi et al. [45] with an LCOE of 0.353 \$/kWh. Hussam et al. [25] did a previous study on the Shagaya renewable power plant, resulting in an LCOE of 0.539 \$/kWh and an LCOH of 6.85 \$/kg. Researchers in this study found that the high cost of LCOH is mainly due to the high cost of renewable integration, and that hydrogen production depends solely on electrolyzers, which require large amounts of energy to produce hydrogen. The present study achieved an LCOE of 1.21 \$/kWh and an LCOH of 0.87 \$/kg for the on-grid system. The balance between LCOE and the hydrogen production from reformers and electrolyzers significantly lowered costs in grid-connected systems. However, while renewable generation costs decrease, reliance on electrolyzers leads to high system sizing and



(j)



(k)

Fig. 6. (continued).

economic pressures, increasing overall hydrogen production costs. For the off-grid system, the study found an LCOH of 7.11 \$/kg and an LCOE of 2.36 \$/kWh, reflecting the high costs of green hydrogen production, as shown in Fig. 7.

5. Conclusions

This study investigated the integration of steam methane reforming with solar-wind renewable energy systems to reduce hydrogen production cost while maintaining a reliable electricity supply under on-grid and off-grid operating conditions. A multi-objective optimization framework was developed to evaluate the system operation, component sizing, and performance trade-offs using NSGA-II and a fuzzy decision-making approach.

The key outcomes of this research are summarized as follows:

- The integration of SMR with renewable energy enabled effective load sharing between electrolysis and reforming pathways, resulting in LCOH of 0.87 \$/kg for the on-grid configuration at the Shagaya Renewable Power Plant. This value is substantially lower than those typically reported for a fully electrolysis-based hydrogen system under similar conditions.
- On-grid system operation significantly improved system performance by reducing energy losses and supporting flexible operation under variable renewable generation. The optimized on-grid system

achieves high energy utilization, limited unmet electrical and hydrogen demand, and substantially lower life-cycle emissions than conventional fossil-based power systems.

- Fully off-grid operation enabled complete renewable penetration but required considerably larger generation and storage capacities, resulting in higher capital cost and increased conversion losses. The LCOE and LCOH for the off-grid HRES results of 2.36 \$/kWh and 7.11 \$/kg, respectively. These results highlight the economic and operational challenges associated with standalone renewable hydrogen systems in the absence of grid support.
- Comparative analysis shows that a hybrid configuration combining renewable electricity, SMR, and grid interaction offers a practical balance between cost, efficiency, and emissions of arid regions with high renewable potential.

The study provides a practical framework for evaluating off-grid hybrid energy systems by integrating economic, reliability, and environmental criteria key factors for sustainable deployment in remote regions of Kuwait. It offers clear guidance for system design, technology choice, and policy measures that reduce emissions while ensuring a reliable supply. Sensitivity analysis highlights the parameters that most affect cost and environmental performance, improving planning under uncertainty. As the approach is adaptable to different locations, it can support developers, policymakers, and sustainability-focused industries in advancing decentralized renewable energy solutions aligned with

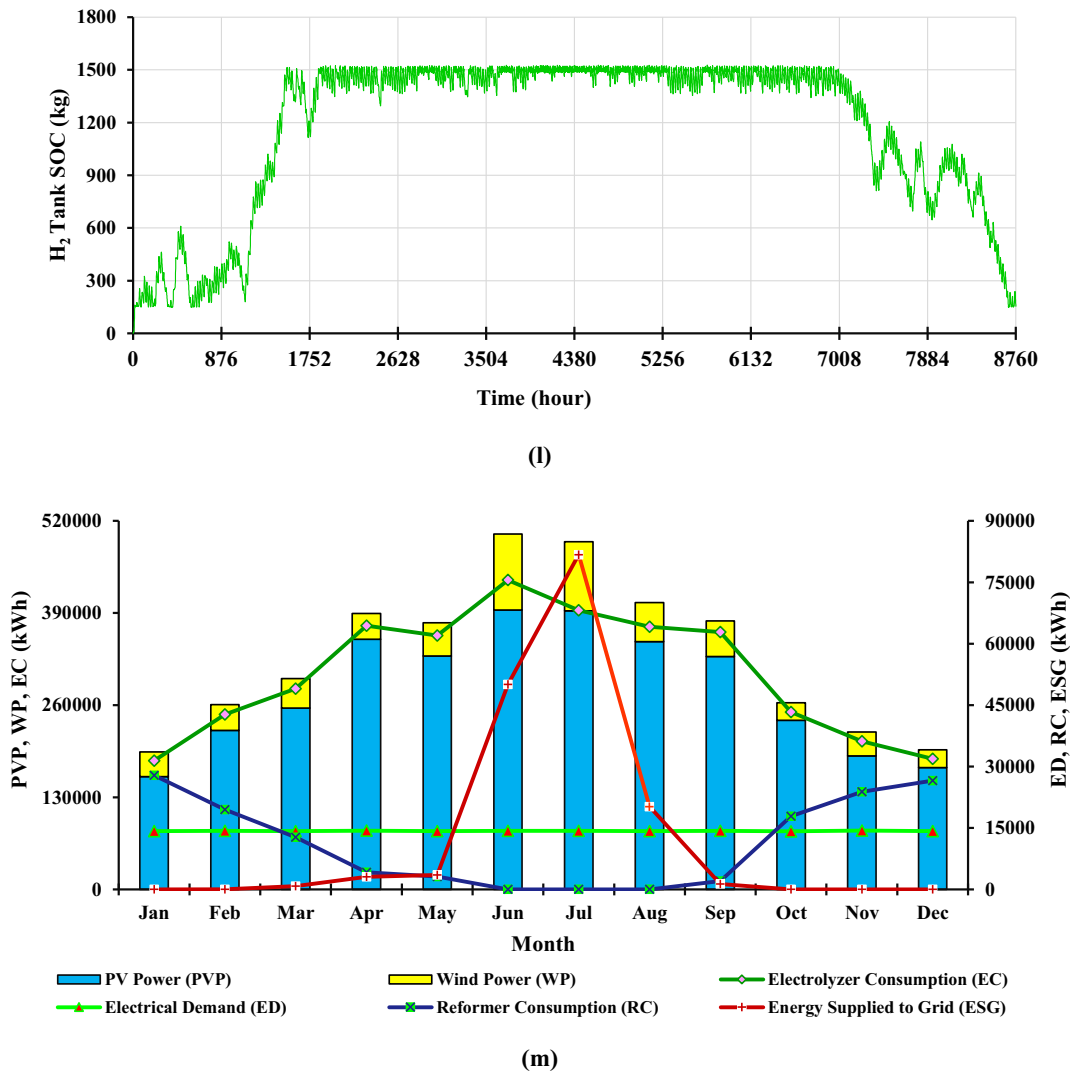


Fig. 6. (continued).

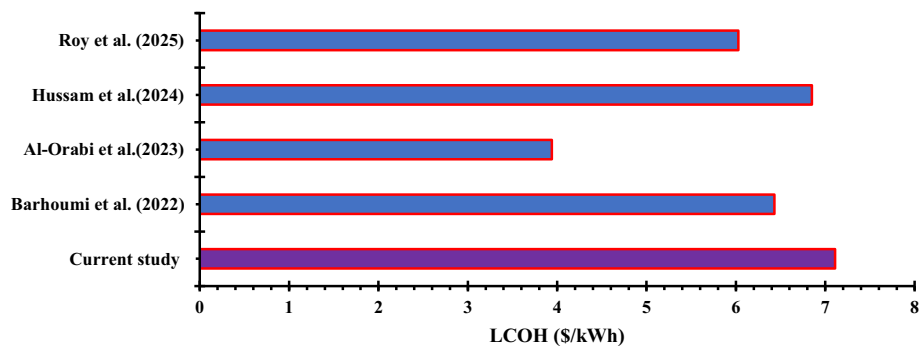


Fig. 7. Comparison of LCOH with relevant literature for off-grid green hydrogen production. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

environmental and development goals.

Future work will focus on improving off-grid system performance through advanced storage technologies and enhanced thermal integration, and on exploring carbon capture retrofitting for SMRs. These extensions aim to reduce emissions further and improve the scalability of integrated thermal-energy systems for hydrogen and power production. Future work may focus on improving off-grid performance through advanced storage and thermal integration, incorporating carbon capture

within the SMR framework, examining grid outages, import limits, and dynamic pricing, and refining socio-economic assessment methods for job creation and HDI evaluation. The present study is primarily based on numerical simulations, and direct validation against experimental data or published results under identical operating conditions has not been conducted. Future research should focus on providing deeper thermodynamic and physical insight into the observed parametric trends, including detailed analysis of heat transfer characteristics, system

irreversibility, and power distribution mechanisms.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

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Appendix A. Appendix

Table A1

Techno-economic specifications of HRES components.

HRES elements	Specifications/parameters	Value	Economical information	Value
Solar PV module [46,47]	Model	SPR-E20–327	Initial expenditure	1000 \$/kW
	Maximum power, R_{pv}	327 W	Replacement Cost	1000 \$/kW
	Solar efficiency, η_{pv}	21.4%	O&M expense	20\$/kW/yr
	Nominal voltage, V_{mpp}	54.7 V		
	Nominal current, I_{mpp}	5.98 A		
	Thermal coefficient of power, α_p	−0.35%/°C		
	Derating ratio, f_{pv}	88%		
	Lifespan	25 yrs		
Wind Turbine [25]	Model	XANT 330	Initial expenditure	2000 \$/kW
	Rated Capacity, R_{WT}	330 kW	O&M expense	500 \$/year
	Minimum wind speed, V_{cut-in}	3 m/s	Replacement Cost	2000 \$/kW
	Nominal wind speed, V_{rated}	12.5 m/s		
	Maximum wind speed, $V_{cut-out}$	24 m/s		
	Lifespan	20 years		
Reformer [48]	Model	Hy.Gen 50	Nominal Cost	2750 \$/kg/h
	Nominal Flow (H_2)	Max 52 Nm ³ /h	O&M Cost	0.01 \$/kg
	Purity Range	99.5%–99.9%	Replacement Cost	2750 \$/kg/h
	Pressure Range	1.5–7.5 bar(g)		
	Ambient Temp. Range	−20 to +40 °C		
Inverter [25]	Lifespan	25 years		
	Model	ABB MGS100	Capital Cost	500 \$/kW
	Efficiency	95%	Replacement Cost	500 \$/kW
	Rated Capacity	1 kW	O&M Cost	1 \$/year
	Lifespan	15 years		
Fuel Cell [25]	Model	PEMFC	Capital Cost	3000 \$/kW
	Efficiency	50%	Replacement Cost	2500 \$/kW
	Rated Capacity	1 kW	O&M Cost	10 \$/year
	Operational Life	50,000 h		
Hydrogen Tank [25]	Maximum Capacity	10 kg	Capital Cost	100 \$/kg
	Lifespan	25 years	Replacement Cost	100 \$/kg
			O&M Cost	1 \$/year
Battery [25]	Model	Li-ion	Capital Cost	550 \$/kWh
	Efficiency	90%	Replacement Cost	550 \$/kWh
	Rated Capacity	1 kWh	O&M Cost	0.01 \$/h
	Lifespan	15 years		
Electrolyzer [25]	Model	Generic PEM	Capital Cost	500 \$/kW
	Efficiency	85%	Replacement Cost	400 \$/kW
	Rated Capacity	1 kW	O&M Cost	10 \$/year
	Lifespan	15 years		

Appendix B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.applthermaleng.2026.131233>.

Data availability

No data was used for the research described in the article.

References

- [1] H. Musibau, K.L. Gold, Z. Abdurashed, H.A. Muili, Poland's net-zero pathways: moderating role of carbon tax and renewable energy on electricity generation through a novel multivariate quantile-on-quantile regression approach, *J. Environ. Manag.* 380 (2025) 124848, <https://doi.org/10.1016/j.jenvman.2025.124848>.
- [2] World Energy Outlook 2024. <https://www.iea.org/reports/world-energy-outlook-2024/executive-summary>, 2025. (Accessed 25 December 2025).
- [3] P. Malik, M. Awasthi, S. Sinha, A techno-economic investigation of grid integrated hybrid renewable energy systems, *Sustain. Energy Techn. and Assess.* 51 (2022) 101976, <https://doi.org/10.1016/j.seta.2022.101976>.
- [4] M.S. Mohtasim, B.K. Das, U.K. Paul, M.G. Kibria, M.S. Hossain, Hybrid renewable multi-generation system optimization: attaining sustainable development goals, *Renew. Sust. Energ. Rev.* 212 (2025) 115415, <https://doi.org/10.1016/j.rser.2025.115415>.
- [5] C. Ceylan, Y. Devrim, Green hydrogen based off-grid and on-grid hybrid energy systems, *Int. J. Hydrog. Energy* 48 (99) (2023) 39084–39096, <https://doi.org/10.1016/j.ijhydene.2023.02.031>.

- [6] A. Jaman, et al., Techno-economic analysis of sustainable hybrid solar-wind-biogas using municipal solid waste-based grid independent power plant with dual mode energy storage strategy, *Energy* 307 (2024) 132777, <https://doi.org/10.1016/j.energy.2024.132777>.
- [7] B. Akarsu, M. Serdar Genç, Optimization of electricity and hydrogen production with hybrid renewable energy systems, *Fuel* 324 (2022) 124465, <https://doi.org/10.1016/j.fuel.2022.124465>.
- [8] W.K. Hussam, A. Jaman, R. Mibarki, R.A. Mahmud, G.J. Sheard, Techno-economic and environmental evaluation of integrated microgrid systems for electrification and hydrogen production, *J. Phys. Conf. Ser.* 2968 (1) (2025) 012006, <https://doi.org/10.1088/1742-6596/2968/1/012006>.
- [9] M.M. Mishref, M. Tanaka, Techno-economic and environmental analysis of heat sources for steam methane reforming in microgrids, *Int. J. Hydrog. Energy* 53 (2024) 1387–1395, <https://doi.org/10.1016/j.ijhydene.2023.11.355>.
- [10] Y. Mao, X. Li, J. Liu, M. Yu, M.K. Kim, K. Yang, Multi-objective optimization of integrated energy systems in natural gas industrial zones: enhancing performance through variable hydrogen blending ratios, *Appl. Therm. Eng.* 268 (2025) 125942, <https://doi.org/10.1016/j.applthermaleng.2025.125942>.
- [11] T.-W. Lim, D.-H. Hwang, Y.-S. Choi, Design and optimization of a steam methane reformer for ship-based hydrogen production on LNG-fueled ship, *Appl. Therm. Eng.* 243 (2024) 122588, <https://doi.org/10.1016/j.applthermaleng.2024.122588>.
- [12] G. Steensma, et al., Shagaya renewable energy park project, in: AIP Conference Proceedings vol. 2126, 2019, p. 040003, <https://doi.org/10.1063/1.5117583>, no. 1.
- [13] J. He, N. Han, M. Xia, T. Sun, H. Ghaebi, Multi-objective optimization and exergoeconomic analysis of a multi-generation system based on biogas-steam reforming, *Int. J. Hydrog. Energy* 48 (55) (2023) 21161–21175, <https://doi.org/10.1016/j.ijhydene.2022.12.093>.
- [14] B. Farhang, H. Ghaebi, N. Javani, Techno-economic modeling of a novel poly-generation system based on biogas for power, hydrogen, freshwater, and ammonia production, *J. Clean. Prod.* 417 (2023) 137907, <https://doi.org/10.1016/j.jclepro.2023.137907>.
- [15] H. Song, Y. Liu, H. Bian, M. Shen, X. Lin, Energy, environment, and economic analyses on a novel hydrogen production method by electrified steam methane reforming with renewable energy accommodation, *Energy Convers. Manag.* 258 (2022) 115513, <https://doi.org/10.1016/j.enconman.2022.115513>.
- [16] A.M. Maghfuri, M. Kuku, Optimized hydrogen production through machine learning: comparative analysis of electrolyzer technologies using hybrid renewable energy, *Appl. Therm. Eng.* 276 (2025) 126923, <https://doi.org/10.1016/j.applthermaleng.2025.126923>.
- [17] T. Sathish, Sustainable hydrogen production by integrating solar PV electrolyser and solar evacuated tube collector with hybrid nanoparticles enhanced PCM, *Appl. Therm. Eng.* 257 (2024) 124317, <https://doi.org/10.1016/j.applthermaleng.2024.124317>.
- [18] R. Kumar, H.K. Channi, A PV-biomass off-grid hybrid renewable energy system (HRES) for rural electrification: design, optimization and techno-economic-environmental analysis, *J. Clean. Prod.* 349 (2022) 131347, <https://doi.org/10.1016/j.jclepro.2022.131347>.
- [19] L. Al-Ghussain, A.D. Ahmad, A.M. Abubaker, M.A. Hassan, Exploring the feasibility of green hydrogen production using excess energy from a country-scale 100% solar-wind renewable energy system, *Int. J. Hydrog. Energy* 47 (51) (2022) 21613–21633, <https://doi.org/10.1016/j.ijhydene.2022.04.289>.
- [20] M. Nasser, T.F. Megahed, S. Ookawara, H. Hassan, Techno-economic assessment of clean hydrogen production and storage using hybrid renewable energy system of PV/wind under different climatic conditions, *Sustain. Energy Techn. and Assess.* 52 (2022) 102195, <https://doi.org/10.1016/j.seta.2022.102195>.
- [21] R. Hassan, B.K. Das, M. Hasan, Integrated off-grid hybrid renewable energy system optimization based on economic, environmental, and social indicators for sustainable development, *Energy* 250 (2022) 123823, <https://doi.org/10.1016/j.energy.2022.123823>.
- [22] F.Q. Al-Enezi, J.K. Sykulski, N.A. Ahmed, Visibility and potential of solar energy on horizontal surface at Kuwait area, *Energy Procedia* 12 (2011) 862–872, <https://doi.org/10.1016/j.egypro.2011.10.114>.
- [23] W. Al-Nassar, S. Alhajraf, A. Al-Enizi, L. Al-Awadhi, Potential wind power generation in the State of Kuwait, *Renew. Energy* 30 (14) (2005) 2149–2161, <https://doi.org/10.1016/j.renene.2005.01.002>.
- [24] W.K. Al-Nassar, S. Neelamani, T.S. William, Economic feasibility of wind and photovoltaic energy in Kuwait, in: *E3S Web of Conferences* vol. 280, EDP Sciences, 2021, p. 05016.
- [25] W.K. Hussam, E.M. Barhoumi, M. Abdul-Niby, G.J. Sheard, Techno-economic analysis and optimization of hydrogen production from renewable hybrid energy systems: Shagaya renewable power plant-Kuwait, *Int. J. Hydrog. Energy* 58 (2024) 56–68, <https://doi.org/10.1016/j.ijhydene.2024.01.153>.
- [26] K. Deb, A. Pratap, S. Agarwal, T. Meyarivan, A fast and elitist multiobjective genetic algorithm: NSGA-II, *IEEE Trans. Evol. Comput.* 6 (2) (2002) 182–197, <https://doi.org/10.1109/4235.996017>.
- [27] R.E. Bellman, L.A. Zadeh, Decision-making in a fuzzy environment, *Manag. Sci.* 17 (4) (1970) B-141–B-164.
- [28] NASA Database, NASA Prediction Of Worldwide Energy Resources (POWER). <https://power.larc.nasa.gov/data-access-viewer/>, 2025. (Accessed 20 December 2025).
- [29] L. Gagnon, C. Bélanger, Y. Uchiyama, Life-cycle assessment of electricity generation options: the status of research in year 2001, *Energy Policy* 30 (14) (2002) 1267–1278, [https://doi.org/10.1016/S0301-4215\(02\)00088-5](https://doi.org/10.1016/S0301-4215(02)00088-5).
- [30] Y.A. Katsigiannis, P.S. Georgilakis, E.S. Karapidakis, Multiobjective genetic algorithm solution to the optimum economic and environmental performance problem of small autonomous hybrid power systems with renewables, *IET Renew. Power Gener.* 4 (5) (2010) 404–419, <https://doi.org/10.1049/iet-rpg.2009.0076>.
- [31] P.L. Spath, M.K. Mann, Life Cycle Assessment of Hydrogen Production Via Natural Gas Steam Reforming, National Renewable Energy Lab., Golden, CO (US), 2000.
- [32] P. Afanasev, T. Alekhina, A. Mukhametdinova, E. Popov, A. Cheremisin, Exploring the potential of natural gas reservoirs for underground hydrogen generation, in: *SPE Gas & Oil Technology Showcase and Conference*, SPE, 2024 p. D021S018R001.
- [33] Y. Gan, C. Ng, A. Elgowainy, J. Marcinkoski, Considering embodied greenhouse emissions of nuclear and renewable power plants for electrolytic hydrogen and its use for synthetic ammonia, methanol, Fischer–Tropsch fuel production, *Environ. Sci. Technol.* 58 (42) (2024) 18654–18662, <https://doi.org/10.1021/acs.est.3c06769>.
- [34] K. Bareiß, C. de la Rua, M. Möckl, T. Hamacher, Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems, *Appl. Energy* 237 (2019) 862–872, <https://doi.org/10.1016/j.apenergy.2019.01.001>.
- [35] S. Alkheder, A. Almusalam, Forecasting of carbon dioxide emissions from power plants in Kuwait using United States Environmental Protection Agency, Intergovernmental panel on climate change, and machine learning methods, *Renew. Energy* 191 (2022) 819–827, <https://doi.org/10.1016/j.renene.2022.04.023>.
- [36] J.W. Chong, M.M. Hanafiah, A review of life cycle assessment for fuel cell technologies: advancing clean energy and climate solutions, *Energy Rep.* 13 (2025) 6548–6565, <https://doi.org/10.1016/j.egy.2025.05.081>.
- [37] M. Gutsch, J. Leker, Global warming potential of lithium-ion battery energy storage systems: a review, *J. Energy Storage* 52 (2022) 105030, <https://doi.org/10.1016/j.est.2022.105030>.
- [38] C. Mokhtara, B. Negrou, N. Settou, B. Settou, M.M. Samy, Design optimization of off-grid hybrid renewable energy systems considering the effects of building energy performance and climate change: case study of Algeria, *Energy* 219 (2021) 119605, <https://doi.org/10.1016/j.energy.2020.119605>.
- [39] M.A. Vaziri Rad, A. Kasaeian, O. Mahian, A. Toopshekan, Technical and economic evaluation of excess electricity level management beyond the optimum storage capacity for off-grid renewable systems, *J. Energy Storage* 87 (2024) 111385, <https://doi.org/10.1016/j.est.2024.111385>.
- [40] A. Razmjoo, L. Gakenia Kaigutha, M.A. Vaziri Rad, M. Marzband, A. Davarpanah, M. Denai, A technical analysis investigating energy sustainability utilizing reliable renewable energy sources to reduce CO₂ emissions in a high potential area, *Renew. Energy* 164 (2021) 46–57, <https://doi.org/10.1016/j.renene.2020.09.042>.
- [41] M. Sharifzadeh, R.K.T. Hien, N. Shah, China's roadmap to low-carbon electricity and water: disentangling greenhouse gas (GHG) emissions from electricity-water nexus via renewable wind and solar power generation, and carbon capture and storage, *Appl. Energy* 235 (2019) 31–42, <https://doi.org/10.1016/j.apenergy.2018.10.087>.
- [42] A.K.S. Maisanam, A. Biswas, K.K. Sharma, Integrated socio-environmental and techno-economic factors for designing and sizing of a sustainable hybrid renewable energy system, *Energy Convers. Manag.* 247 (2021) 114709, <https://doi.org/10.1016/j.enconman.2021.114709>.
- [43] T.K. Roy, M.A. Mahmud, A.M.T. Oo, Techno-economic feasibility of stand-alone hybrid energy systems for a remote Australian community: optimization and sensitivity analysis, *Renew. Energy* 241 (2025) 122286, <https://doi.org/10.1016/j.renene.2024.122286>.
- [44] E.M. Barhoumi, P.C. Okonkwo, I. Ben Belgacem, M. Zghaibeh, I. Tlili, Optimal sizing of photovoltaic systems based green hydrogen refueling stations case study Oman, *Int. J. Hydrog. Energy* 47 (75) (2022) 31964–31973, <https://doi.org/10.1016/j.ijhydene.2022.07.140>.
- [45] A.M. Al-Orabi, M.G. Osman, B.E. Sedhom, Evaluation of green hydrogen production using solar, wind, and hybrid technologies under various technical and financial scenarios for multi-sites in Egypt, *Int. J. Hydrog. Energy* 48 (98) (2023) 38535–38556, <https://doi.org/10.1016/j.ijhydene.2023.06.218>.
- [46] A. Jaman, R. Al Mahmud, B.K. Das, M.S.H.K. Tushar, Optimizing an integrated hybrid energy system with hydrogen-based storage to develop an off-grid green community for sustainable development in Bangladesh, *Int. J. Hydrog. Energy* 97 (2025) 766–786, <https://doi.org/10.1016/j.ijhydene.2024.11.454>.
- [47] SunPower, Monocrystalline Solar Cell for Highly Efficient Power Generation. <https://www.enersage.com/equipment/solar-panels/sunpower/spr-e20-327-ce9611fa/>, 2025. (Accessed 10 May 2025).
- [48] HyGear, HYGEAR HyGEN on-site Hydrogen Generation (Reformer). https://hygear.com/wp-content/uploads/2015/10/HYGEAR_HyGEN_Hydrogen-Generation.pdf, 2025. (Accessed 5 May 2025).