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Research Article

Sustainable Integration of Green Hydrogen in Renewable Energy Systems for Residential and EV Applications

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The surge in interest surrounding renewable energy stems from concerns regarding pollution and the finite supply of nonrenewable resources. Solar PV and wind hybrid renewable energy systems (HRES) are increasingly recognized as practical and cost-effective solutions, particularly in remote areas. However, the intermittent nature of solar and wind power presents a challenge. To address this, incorporating a hydrogen source into the system has been proposed. This study focuses on modelling and sizing a hybrid energy system tailored for remote areas, accommodating both home and electric vehicle loads. The simulation is conducted for Siliguri, West Bengal, India, with the goal of optimizing productivity, minimizing expenses, and considering economic factors using HOMER Pro software. The integration of green hydrogen-based power generation with photovoltaic and wind HRES emerges as an effective solution. Solar power, in particular, showcases promising opportunities for the electrolysis process and HRES systems. The presented work facilitates the modelling of a green hydrogen-based green energy system, taking into account capacity, cost, and emission constraints. Various case studies are conducted to enhance system efficiency and reduce the costs of energy (COE). In this paper, three cases of grid-connected and three cases of off-grid or grid-disconnected systems are considered for highlighting the benefits of hydrogen energy incorporation in both types of systems. This research contributes to sustainable energy solutions, advancing a greener and more efficient energy landscape, especially in addressing the recent development in load combinations of home and electric vehicle loads in both grid-connected as well as grid-disconnected system.

1. Introduction

1.1. Motivations. The escalating concerns over pollution and the finite supply of nonrenewable resources have fuelled significant growth in renewable energy utilization. Photovoltaic and wind HRES are gaining recognition as practical and cost-effective solutions, particularly in remote areas. Despite their advantages, the variable or irregular nature of solar and wind power remains a challenge, prompting innovative solutions to address intermittency issues. This study, conducted in Siliguri, West Bengal, India, utilizes HOMER Pro software to model and size a HRES tailored for remote areas, accommodating home and electric vehicle loads. A key proposition involves integrating a hydrogen source into the system through electrolysis, introducing green hydrogen-based power generation to enhance overall efficiency. The focus on solar power, specifically the electrolysis process and HRES systems, underscores the potential of these technologies. The research contributes significantly to sustainable energy solutions, aiming to optimize productivity, minimize expenses, and consider economic factors. Through various case studies, the work is aimed at enhancing the efficiency of the proposed system and mitigating the costs of energy, addressing evolving load combinations, particularly those associated with home and electric vehicle loads. This endeavour strives to advance a greener and more efficient energy landscape, aligning with the global imperative for sustainable energy solutions.

1.2. Related Work. Researchers and engineers have contributed significantly to address the challenges of HRES, particularly those incorporating hydrogen. Notable studies include Recioui and Dekhandji's proposal of an optimization methodology using HOMER for sizing HRES based on hydrogen. Ghosh et al. presented a ten-year operational experience investigation of a hydrogen-based green energy supply network. Other works encompass comprehensive reviews of PV-wind hybrid systems, comparisons of software tools for optimization, and investigations into the economical cum technological exploration of solar energy networks.

Recioui and Dekhandji [1] present an optimization methodology utilizing HOMER to size a hydrogen-based HRES. The goal is to minimize the overall system cost by selecting optimal configurations for components, including hydrogen storage, photovoltaic panels, wind turbines, and fuel cells. Ghosh et al. [2] conduct a ten-year operational experience analysis of a hydrogen-based green power supply network. Their focus lies on assessing the system's reliability, efficiency, and environmental impact.

Sawle et al. [3] conduct a thorough examination of PV-wind hybrid networks, covering technical, economic, and environmental aspects. Kavadias and Triantafyllou [4] perform a review and comparison of software tools for optimizing HRES. Hatata and Lafi [5] propose a clonal selection algorithm for optimizing the sizing of a HRES.

Authors of [6] investigate the economical cum technological analysis and enhancement of solar energy network for generation of power and production of hydrogen in the Mazyouna area. Kotian et al. [7] plan the assessment of a HRES for Ramea Island, Newfoundland, combining wind, solar, and diesel generators. Rahman et al. [8] direct a technoeconomic analysis of a hybrid PV/fuel cell/wind system for EV charging stations.

Rehman et al. [9] recommend an optimal design and model predictive control of stand-alone HRES for residential demand-side management, utilizing solar, wind, and battery storage. Nallolla and Perumal [10] propose the optimum design of a hybrid off-grid green energy network for remote or rural locations, considering solar, wind, and biomass. Nair et al. [11] advise an optimal sizing methodology for PV-BESS-based microgrids in rural electrification.

Parida and Bohre [12] plan an optimization model for a grid-connected HRES with EV to minimize NPC and emissions. Marais et al. [13] conduct a technoeconomic feasibility analysis of a grid-interactive PV system for residential loads in South Africa. Lin et al. [14] use HOMER Software to optimize the design of a HRES in the Philippines, aiming to minimize NPC and LCOE.

Ishraque and Ali [15] implement a design methodology for a hybrid microgrid using renewable resources, aiming to minimize NPC and LCOE while maintaining reliability. Atilola et al. [16] propose an optimal sizing methodology for an off-grid PV system in Nigeria, considering cost, CO2 emissions, and system reliability. Devkota et al. [17] employ a case study of a HRES for grid extension in Nepal, aiming to minimize NPC while meeting load demand and grid requirements.

Maleki and Askarzadeh [18] compare different AI techniques for sizing a stand-alone PV/wind/hydrogen hybrid system to minimize NPC while ensuring reliability. Sopian et al. [19] scrutinize the performance of a PV/wind/hydrogen hybrid system for hydrogen generation. Panahandeh et al. [20] simulate a PV/wind/hydrogen hybrid system with hydrogen storage for rural electrification in Morocco to minimize NPC.

Ngouleu et al. [21] propose the use of a self-sufficient photovoltaic/wind hybrid system in remote areas of Cameroon, emphasizing the incorporation of battery storage and hydrogen technology. Smaoui et al. [22] focus on determining the ideal configuration for a stand-alone hybrid system comprising solar photovoltaics, wind energy, and hydrogen, specifically tailored to power a desalination unit. Torreglosa et al. [23] investigate an energy dispatching strategy tailored for an off-grid hybrid system consisting of wind turbines, solar photovoltaics, hydrogen technology, and batteries. Mills and Al-Hallaj [24] model a hydrogen-based hybrid system for remote power applications. Kaviani et al. [25] examine a multiobjective optimization model for a stand-alone wind/PV system considering component outages. Notton et al. [26] analyze a hybrid system installed in Corsica, France, to optimize performance. Fetanat and Khorasaninejad [27] explore an optimization approach for sizing hybrid solar-PV-wind energy systems.

Macedo and Peyerl [28] evaluate the economic feasibility of wind and solar PV hybrid systems for hydrogen production in the Brazilian electric power sector. Yazdanpanah [29] suggests a model for optimizing the sizing of a hybrid photovoltaic/wind power generation system. Kaabeche et al. [30] apply an optimization approach to a grid-independent hybrid photovoltaic/wind power production system. Ghofrani and Hosseini [31] provide a comprehensive overview of optimization techniques for HRES.

Bhandari et al. [32] review various optimization techniques for designing HRES. Ardakani et al. [33] suggest the design of an optimal HRES considering reliability indices. Zahboune et al. [34] introduce a methodology for the optimal design of HRES in autonomous applications.

Bernal-Agustin and Dufo-Lopez [35] present a review of simulation and optimization techniques for stand-alone HRES, focusing on the use of software tools. Erdinc and Uzunoglu [36] provide an overview of different approaches to optimizing the design of HRES.

Karmaker et al. [37] evaluate the feasibility and design of a hybrid renewable energy-based EV charging station in Bangladesh. Abd El-Sattar et al. [38] design an optimal HRES for a remote area in Egypt, considering genetic algorithm optimization. Bohre et al. [39, 40] study the impacts of different utility tariffs on a grid-connected hybrid microgrid. Muna and Kuo [41] evaluate the viability and technoeconomic efficiency of an EV charging system powered by a HRES. In their work, Mahmoud et al. [42] delve into the integration of wind-driven PMSG (permanent magnet synchronous generators) with a power grid, offering a comprehensive exploration of current perspectives and future possibilities within wind engineering. Mahmoud's research takes a novel approach to improving wind-side converter current control loops by incorporating support from a wild horse optimizer, thereby enhancing the dynamic performance of wind generation systems based on PMSG [43].

The study by Mahmoud et al. applies the whale optimization algorithm in FOPI controllers for STATCOM and UPQC, presenting effective solutions to mitigate harmonics and address voltage instability in contemporary distribution power grids [44]. Ibrahim et al. introduce a multiport converter utility interface featuring a high-frequency link to connect clean energy sources, such as PV, wind, fuel cells, and batteries, to the power system, utilizing the HHA algorithm [45]. Mahmoud et al. assess the dynamic performance of wind energy conversion systems using PMSG and doubly fed induction generators, employing the manta ray foraging optimizer to address issues related to MPPT (maximum power point tracking), pitch control, and fault ride-through capability [46]. Awad et al. contribute to advancements in green technology by designing and analyzing photovoltaic/wind operations at MPPT for hydrogen generation using a proton-exchange membrane electrolyzer [47]. A research on providing more resilience for integration of green energy, i.e., nuclear energy to conventional grid is proposed in [48] using PSO (particle swarm optimization). A multiarea system is simulated in [49] using TLBO (teaching learning-based optimization) which provides better resilience in generation control during case of disturbances on power network. An improved reconfigured power network has been proposed in [50, 51] where authors have utilized PSO for suitable sizing of solar PV and STATCOM in such a manner that power losses can be reduced and voltage profile can be improved. Authors of [52] have proposed wind power integration in multiarea hybrid power system using firefly optimization for enhanced robustness considering different climatic conditions. Three distinct cases are considered for studying the impact of hydrogen energy integration in rural area power network for improvement in overall system efficiency that is given in [53]. In [53], it has been observed that a system with hydrogen energy has better performance as compared to other two cases with no hydrogen energy in the grid-connected system.

1.3. Contributions. Researchers have provided valuable contributions towards optimizing and designing HRES to enhance reliability, economic feasibility, and sustainability. Studies such as Rahman et al.'s technoeconomic analysis of a hybrid PV/wind/fuel cell system for electric vehicle charging stations, and Nallolla and Perumal's optimization methodology for a hybrid off-grid green energy network, showcase efforts to tailor solutions for specific applications. The literature also delves into diverse areas, including grid-connected HRES, microgrids for rural electrification, and stand-alone systems for desalination and electric vehicle charging stations. Moreover, optimization techniques, economic feasibility assessments, and sizing methodologies have been explored to enhance the overall performance of HRES.

The study integrates photovoltaic and wind hybrid systems (HRES) with a hydrogen source to address challenges in solar and wind power intermittency, showcasing adaptability to remote areas. Designed for home and electric vehicle loads, the hybrid system proves versatile and contributes to enhanced energy accessibility. The use of HOMER Pro software enhances robustness by allowing optimization for productivity, cost, and economic factors, ensuring comprehensive real-world resilience.

The incorporation of green hydrogen-based power generation strengthens the system's robustness, providing a reliable solution to renewable resource intermittency. The study's focus on capacity, cost, and emission constraints further reinforces the environmental sustainability and economic viability of the proposed system. Case studies in Siliguri, West Bengal, showcase efficiency enhancements and cost reductions, emphasizing the system's adaptability to diverse operational conditions crucial for successful renewable energy implementation. This research significantly contributes to advancing sustainable energy solutions, particularly in addressing evolving load combinations such as those associated with home and electric vehicle loads.

In this paper, the benefit of incorporating green hydrogen system in grid-connected as well off-grid system is proposed.

2. Hybrid Renewable System Motivations and Advantages

The evaluation of a nation's economic and social progress is significantly influenced by its energy landscape. Currently, around 80% of the global energy supply is derived from fossil fuels. However, there is a growing acknowledgment of the potential of green sources of energy such as solar PV, geothermal, wind, and hydro due to their abundant and sustainable nature. The contemporary world faces various challenges, including global warming, harmful pollutant emissions, and the depletion of fossil fuels. Consequently, the exploration of energy from renewable sources emerges as a promising alternative, driven by its profound social and economic benefits. Despite the intermittent and variable nature of renewable sources, they offer numerous advantages over traditional fuels. The positive impacts of integrating hybrid renewable sources into conventional energy grids outweigh the challenges. HRES, which combine sources like solar PV and wind with more reliable ones such as biomass, hydro, geothermal, and hydrogen, provide economic, social, and technical advantages. These systems enhance reliability, result in cost savings, contribute to environmental protection, and improve grid stability. The numerous benefits associated with hybrid renewable energy systems make them a compelling choice for a shift towards a future of energy that is both sustainable and resilient. The motivation for adopting such systems includes the pursuit of improved reliability, cost-effectiveness, environmental conservation, and enhanced grid stability [38–41]:

(i) Enhanced reliability and energy availability: By combining multiple renewable sources, hybrid systems can provide a more consistent and reliable energy supply. When one source is not producing energy due to weather conditions, others may compensate, ensuring a steady power output

(ii) Reduced variability: Intermittent sources like solar and wind can experience fluctuations in energy production. Combining them with more stable sources such as biomass, hydro, or geothermal can help smooth out these fluctuations, reducing grid instability and the need for backup power

(iii) Energy storage integration: Many hybrid systems incorporate energy storage solutions like batteries. This allows the retention of surplus energy produced during periods of increased generation and its release when demand is high or production is low, increasing system efficiency and grid stability

(iv) Cost savings: Hybrid systems can often be more cost-effective than relying solely on a single renewable energy source. They can optimize energy production based on resource availability, potentially lowering the overall cost of energy generation

(v) Environmental benefits: By utilizing renewable energy sources, hybrid systems contribute to reduced greenhouse gas emissions and decreased reliance on fossil fuels, leading to improved air quality and a smaller carbon footprint

(vi) Grid support: Hybrid systems can provide grid stability by offering ancillary services like frequency regulation and voltage control. This helps improve the overall performance and reliability of the electrical grid

(vii) Energy independence: By diversifying energy sources, hybrid systems can reduce dependence on external energy suppliers, increasing energy security and reducing vulnerability to supply disruptions

(viii) Scalability: Hybrid systems are scalable and can be tailored to meet varying energy demands, making them suitable for a wide range of applications, from residential homes to large industrial facilities

(ix) Job creation: The deployment, installation, and maintenance of HRES can create jobs in manufacturing, construction, and maintenance, contributing to local economic development

(x) Technological advancements: The development and deployment of hybrid systems drive innovation and research in the renewable energy sector, leading to advancements in energy conversion and storage technologies

(xi) Resilience: Hybrid systems with energy storage can provide backup power during grid outages or emergencies, enhancing energy resilience for critical infrastructure and homes

(xii) Regulatory and policy support: Many governments offer incentives, subsidies, and favourable policies to promote the adoption of hybrid renewable energy systems, making them more financially attractive for individuals and businesses

(xiii) Climate change mitigation: Reducing reliance on fossil fuels through the adoption of hybrid systems is a crucial step in mitigating climate change by lowering carbon emissions

(xiv) Energy access: In areas with limited access to reliable electricity, hybrid renewable energy systems can provide a sustainable and affordable energy source, improving living conditions and enabling economic development

(xv) Community benefits: Hybrid systems can provide localized energy solutions for communities, reducing transmission losses and enhancing the resilience of local power generation

(xvi) Rural electrification: In remote locations where grid access is limited or unreliable, HRES offer an economically viable and sustainable approach to fulfilling energy requirements

3. Modelling of System Components

The modelling of different components of hybrid renewable system is discussed in this section like PV, wind, battery electrolyzer, fuel cell, H_2 tank, converter, diesel generator, home load, EV load, and grid systems.

3.1. Solar PV System. The output of the solar PV system depends on the solar radiation intensity and its availability. The generic type PV system is considered in this work with the HOMER Optimizer. The optimization process helps in determining the appropriate sizing of the PV module, as well as other components such as batteries, wind turbines, and diesel generators, if applicable, to meet the energy demands while considering the solar radiation availability. The solar system equation for output power is expressed in

$$P_{\mathrm{PV}}(t)=\begin{cases} P_R\left(\dfrac{{R_{\mathrm{ff}}}^2}{R_s R_C}\right), & 0\le R_{\mathrm{ff}}<R_C \\ P_R\left(\dfrac{R_{\mathrm{ff}}}{R_{\mathrm{ss}}}\right), & R_C<R_{\mathrm{ff}}<R_{\mathrm{ss}} \\ P_R, & R_s\le R_{\mathrm{ff}} \end{cases}, \quad (1)$$

where R_{ff} is the factor of radiation, P_R is the rated PV panel power, R_{ss} is the solar radiation standard $1000(\mathrm{W/m^2})$, R_C is the certain radiation $[150(\mathrm{W/m^2})]$, and $P_{\mathrm{PV}}(t)$ is the PV system power production at t instant.

3.2. Wind Turbine. When incorporating a wind turbine, it is essential to consider capital, O&M costs, and replacement costs.

The output power of turbine is given by

$$P_{\mathrm{Wind}}(t)=\begin{cases} 0, & W_{\mathrm{ss}}\le C_i \text{ or } W_{\mathrm{ss}}\ge C_o \\ P_W\left(\dfrac{W_{\mathrm{ss}}-C_i}{N_{\mathrm{ss}}-C_i}\right), & C_i<W_{\mathrm{ss}}<C_o \\ P_W, & N_{\mathrm{ss}}\le W_{\mathrm{ss}}<C_o \end{cases}, \quad (2)$$

where P_{Wind} is the turbine power production at t instant, P_W is the wind generator-rated power, W_{ss} is the speed of wind, N_{ss} is the wind turbine speed (nominal), C_o is the cutout speed, and C_i is the cut-in value of speed.

3.3. Battery. When considering the integration of a LI ASM generic battery, it is important to examine capacity and lifespan in conjunction with capital costs, O&M costs, and replacement costs.

Battery capacity is expressed as [53]

$$C_{\text{Bat}} = \frac{A_{dd} \times P_l}{\eta_{\text{In}} \cdot \eta_{\text{Battery}} \cdot D_{\text{Od}}}, \quad (3)$$

where A_{dd} is the day of autonomy, P_l is the total power demand (home + EV), η_{In} is the efficiency of inverter, η_{Battery} is the efficiency in battery, and D_{Od} is the battery depth discharging.

The power of battery is given by

$$P_{\text{Battery}}(t) = P_{\text{PV}}(t) + P_{\text{Wind}}(t) + P_{\text{fc}}(t) - P_{\text{EV}}(t) - \frac{P_{\text{Home}}(t)}{\eta_{\text{In}}}, \quad (4)$$

where $P_{\text{PV}}(t)$ is the PV system power production at t instant, $P_{\text{WIND}}(t)$ is the turbine power production at t instant, and $P_{\text{fc}}(t)$ is the fuel cell power production at t instant.

The state of charge ($\text{SOC}(t)$) is given by

$$\text{SOC}(t) = \begin{cases} \text{SOC}(t-1)(1-\delta) + \left((P_{\text{PV}}(t) + P_{\text{Wind}}(t)) + P_{\text{fc}}(t) - P_{\text{EV}}(t) - \dfrac{P_{\text{Home}}(t)}{\eta_{\text{In}}} \right) \times \eta_{\text{Battery}} \\ \text{if } (P_{\text{PV}}(t) + P_{\text{Wind}}(t) + P_{\text{fc}}(t)) > P_l(t) \\ \text{SOC}(t-1)(1-\delta) + \left(\left(P_{\text{EV}}(t) + \dfrac{P_{\text{Home}}(t)}{\eta_{\text{In}}} \right) - (P_{\text{PV}}(t) + P_{\text{Wind}}(t) + P_{\text{fc}}(t)) \right) \times \eta_{\text{Battery}} \\ \text{if } (P_{\text{PV}}(t) + P_{\text{Wind}}(t) + P_{\text{fc}}(t)) < P_l(t) \end{cases}, \quad (5)$$

where δ is the battery self-discharge rate.

3.4. Converter. In both the case of rectifier and inverter, efficiency is being considered, along with other parameters that are initially predefined, such as capital cost, replacement cost, and inverter lifespan.

The total value of efficiency is given by eq. (6) and eq. (7) [53]:

For the case of inverter,

$$\eta_{\text{inv}} = \frac{P_{\text{ac}_{\text{output}}}}{P_{\text{dc}_{\text{input}}}}. \quad (6)$$

For the case of rectifier,

$$\eta_{\text{rect}} = \frac{P_{\text{dc}_{\text{output}}}}{P_{\text{ac}_{\text{input}}}}, \quad (7)$$

where η_{inv} is the efficiency of inverter, $P_{\text{ac}_{\text{out}}}$ is the inverter power output (AC), $P_{\text{dc}_{\text{input}}}$ is the inverter power input (DC), η_{rect} is the efficiency of rectifier, $P_{\text{dc}_{\text{output}}}$ is the rectifier output power (DC), and $P_{\text{ac}_{\text{input}}}$ is the rectifier input power (AC).

3.5. Green Hydrogen Energy. Green hydrogen energy is devoid of carbon emissions, produced through the electrolysis of water, and commonly employed in fuel cells for energy generation. The main components of green hydrogen energy system are fuel cell (FC), electrolyzer, and H_2 tank.

The electrolyzer-transmitted power to the hydrogen tank and surplus power can be given by

$$P_{\text{T-elz}} = P_{\text{elz-surplus}}(t) * \text{eff}_{\text{elz}}, \quad (8)$$

$$P_{\text{elz-surplus}}(t) = P_{p-v}(t) - P_{\text{inver}}(t). \quad (9)$$

The hydrogen energy stored in the tank at step time t can be expressed as

$$\epsilon_{\text{h2}}(t) = \epsilon_{\text{h2}}(t-1) + P_{\text{T-elz}}{}^{*} \Delta t. \quad (10)$$

The fuel cell power production P_{fc} can be expressed as

$$P_{\text{fc}} = P_{\text{t-fc}}{}^{*} \text{eff}_{\text{fc}}. \quad (11)$$

3.6. Grid. The power-balance equation serves as a fundamental tool for load management, allowing for a comprehensive analysis of load demand while considering the presence or absence of hybrid renewable energy systems. It enables system operators and researchers to make informed decisions and implement measures to ensure a reliable and sustainable power supply. Equation of power balancing to calculate mainly the load demand is given by eq. (12) and eq. (13):

Without HRES:

$$P_{\text{Grid}} = P_{\text{EV}} + P_{\text{Home}} + P_{\text{Loss}} + P_{\text{Battery}}. \quad (12)$$

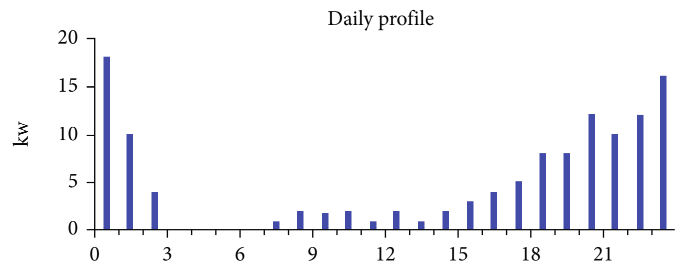

Figure 1: Daily EV load profile.

With HRES:

$$P_{\text{Grid}} = P_{\text{EV}} + P_{\text{Home}} + P_{\text{Loss}} - P_{\text{Wind}} - P_{\text{PV}} \pm P_{\text{Battery}}, \quad (13)$$

where P_{Grid} is the output power (grid), P_{EV} is the power produced (EV), P_{Home} is the output power (home load), P_{PV} is the total power produced (PV), P_{Loss} is the power loss, P_{Wind} is the total wind turbine power production, and P_{Battery} is the output power of battery (+ve charging, −ve discharging).

3.7. EV Load. Electric vehicle (EV) load refers to the electrical demand or power consumption associated with charging electric vehicles. The modelling of EV load is crucial for utilities, grid operators, and researchers to understand, predict, and manage the impact of electric vehicle charging on the electrical grid. A graph has been provided in Figure 1 for 24-hour variations of EV load requirement. The EV load can be mathematically modelled as [53]

$$P(t) = P_{\max} \times f(t), \quad (14)$$

where $P(t)$ is the power demand at time t. $P_{\max}$ is the maximum power rating of the charging station. $f(t)$ is a function that describes the charging profile over time.

3.8. Home/Residential Load. The home load, also known as residential load or household load, refers to the electrical demand or power consumption of a residential building or household. Mathematical modelling of residential load is essential for various purposes, including load forecasting, energy management, and grid planning. A seasonal and daily profile for residential load is given in Figure 2. The modelling of home load involves creating mathematical equations or representations that describe the relationship between various factors influencing electricity consumption in a residential setting. The mathematical modelling for residential load can be expressed as

$$P_{\text{Load}}^{\text{Home}}(t) = P_{\text{Load}}^{\text{Base}} + \Sigma(a_i \times X_i(t)), \quad (15)$$

where $P_{\text{Load}}^{\text{Home}}(t)$ is the home load power demand at time t, $P_{\text{Load}}^{\text{Base}}$ is the base load, a_i is the coefficients that weigh the impact of different factors $X_i(t)$ on the load, and $X_i(t)$ represents various factors that influence the load (e.g., time of day, weather, and appliance usage).

4. Operational Method and Proposed System Cases

The proposed hybrid renewable system including home and EV loads strives to achieve the optimal arrangement of various components for minimum cost and sustainable operation. The components such as the PV array, wind, and hydrogen FC are utilized to fulfill the load demand including battery storage. The primary objective is to fulfill the load demand through the available energy from different renewables like PV array, wind, and hydrogen FC; and if surplus energy is available after fulfilling the load, then, it is utilized for battery charging as well as to sell out the grid utility. The battery power connected to the grid is employed to meet the entire load demand in cases where the available green resources are insufficient to satisfy the combined load requirements for home and EV loads. It is possible that the battery and renewables both do not have the capacity to satisfy the demanded power at any instance; then, the grid will supply the load demand. In any emergency due to natural hazards or power cut from all sources, then, it will be fulfilled by the diesel generator, and the consumers' demand is secured in emergency cases. The flow of power from different resources to the user or different loads is controlled by the cycle charging power dispatch strategy to achieve optimized performances of the hybrid system. In the power dispatch strategy, a grid or generator is utilized to supply just enough power to satisfy loads with lesser capacity to secure the consumer from power interruptions.

Securing consumers and suppliers in a HRES involves ensuring reliable and efficient energy production, distribution, and consumption while minimizing risks and uncertainties. In a well-designed and well-managed hybrid renewable energy system, the security of both consumers and suppliers is enhanced by a combination of technology, regulation, and good practices that ensure reliable and sustainable energy production and distribution. Here are some key strategies and considerations for securing consumers and suppliers in such systems:

(1) Reliable energy supply with diversified energy sources: Hybrid renewable systems typically combine multiple energy sources, such as wind turbines, solar PV panels, and energy storage. This diversification helps ensure a more reliable energy supply, as one source can compensate for the intermittency of another

(2) Battery energy storage: battery systems: Implementing energy storage networks, such as lithium-

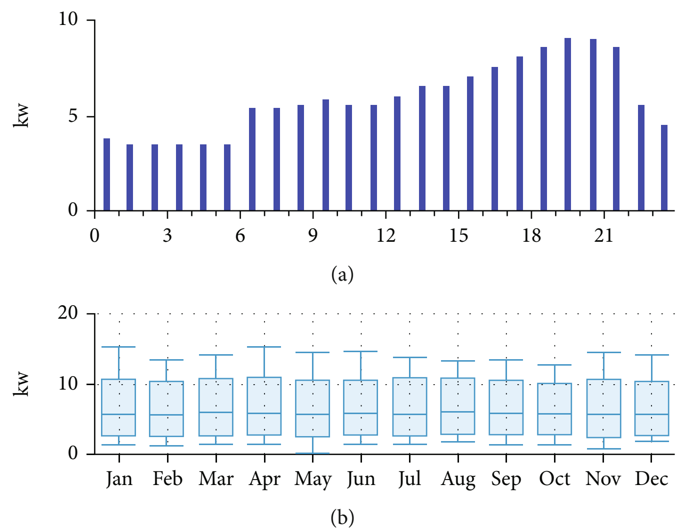

FIGURE 2: Home load: (a) daily profile and (b) seasonal profile.

ion batteries, can store excess energy during periods of higher generation and start dissipating it when production is low. This stabilizes the energy supply and ensures that consumers have access to electricity even when renewable sources are not producing

(3) Grid integration: Connecting the hybrid system to the electrical grid allows consumers to draw power from the grid when renewable generation is insufficient. It also enables the system to export excess energy to the grid, providing a source of revenue for suppliers

(4) Advanced control and monitoring with smart grid technologies: Utilizing smart grid technologies allows for live monitoring and control of energy production and utilization by end users. This enables better management of supply-demand imbalances

(5) Demand-side management with consumer engagement: Educating and engaging consumers in energy-efficient practices can help balance energy supply and demand. Incentives like time-of-use pricing can encourage consumers to shift their energy usage to times when renewable generation is high

(6) Backup generator systems: In the case of prolonged renewable energy resource scarcity or system failures, backup generators (e.g., diesel generators) can provide a reliable energy source for critical loads

(7) Financial mechanisms through power purchase agreements (PPAs): PPAs can provide revenue certainty for renewable energy suppliers, ensuring a steady income stream. Consumers can also benefit from long-term contracts that stabilize energy costs

(8) Regulatory support and government incentives: Governments can provide incentives such as tax credits, subsidies, and renewable energy certificates (RECs) to encourage the development and use of green sources of energy, which can benefit both consumers and suppliers

(9) Risk management and weather forecasting: Advanced weather forecasting technology can help suppliers anticipate changes in renewable energy generation, allowing for better planning and risk management

(10) Cybersecurity: Implement robust cybersecurity measures to protect the energy system from potential threats and vulnerabilities, ensuring the security of both consumers and suppliers

(11) Resilience planning: Develop resilience plans that outline how the system will respond to extreme weather events or other disruptions to ensure uninterrupted energy supply

(12) Community engagement: Engage with local communities to address concerns and ensure that the interests of consumers and suppliers are aligned with the goals of the hybrid renewable system

In this analysis, six different cases have been considered to evaluate the system configuration and identify the most cost-efficient solution with minimal emissions. These cases are represented as follows:

(i) Case 1 (base case of grid-connected system): This case involves only grid connectivity, where the energy supply is solely dependent on the traditional power grid

(ii) Case 2 (all renewable connect case with hydrogen): In this case, all renewable sources, such as solar and wind, are connected to the system, and hydrogen is included as an additional energy storage medium. This configuration allows excess

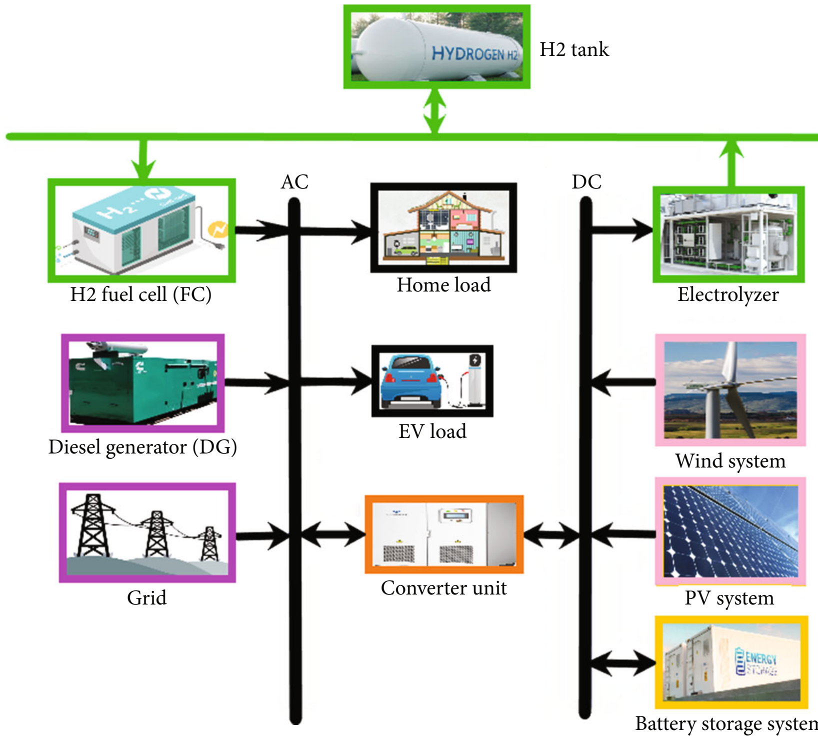

Figure 3: Grid-connected hybrid system with different system components.

renewable energy to be stored as hydrogen and used during periods of low energy production

(iii) Case 3 (all renewable connect case without hydrogen): Similar to case 2, all renewable sources are connected to the system, but hydrogen storage is excluded. The system relies solely on the renewable sources for power supply

(iv) Case 3: This case is similar to case 2, but with the absence of grid connectivity. The system operates independently, utilizing renewable sources and hydrogen storage

(v) Case 5: This case is the same as case 4, but with different operational strategies or configurations to optimize the system's performance without grid connectivity

(vi) Case 6 (base case of off-grid system): This case is similar to case 5, but with further adjustments to enhance the system's efficiency and performance

To establish the most favourable scenario, the analysis evaluates critical factors including the COE, NPC, and the environmental impact associated with emissions. The objective is to pinpoint the system configuration that achieves the optimal balance between cost-effectiveness and emission reduction. Beyond the primary load, which consumes 140.90 kWh of energy daily with a peak demand of 15.38 kW, an electric vehicle (EV) load is factored in. The EV load consumes 11.26 kWh of energy per day with a peak demand of 2.52 kW. The hybrid system, encompassing home load, EV load, and various energy sources, is depicted in Figure 3. To elucidate the proposed methodology, a detailed flowchart is presented in Figure 4. This flowchart delineates the step-by-step approach employed in the analysis, encompassing system modelling, sizing, optimization, and the evaluation of different scenarios. Through a systematic assessment of diverse configurations, considering different loads and energy sources, the analysis is aimed at pinpointing the most suitable and cost-efficient system configuration. Aspects such as grid connectivity, renewable sources, hydrogen storage, and operational strategies are factored in to identify the optimal solution that meets energy demands while minimizing costs and emissions. HOMER Pro adopts a multicriteria optimization approach, weighing various economic and technical factors. These factors include minimizing the levelized cost of energy, total net present cost, and total annualized cost and enhancing reliability. Consequently, the economic, social, and technical parameters for the proposed HRES are outlined as follows.

4.1. Net Present Cost. The total net present cost (NPC) of these systems refers to the overall sum of current system cost elements, encompassing initial expenses, replacement costs, operation and maintenance expenditures, emission penalties, fuel outlays, and costs associated with power procurement from the grid throughout the project's lifespan. The total net present cost (NPC) of a system serves as a fundamental economic parameter, crucial for ranking

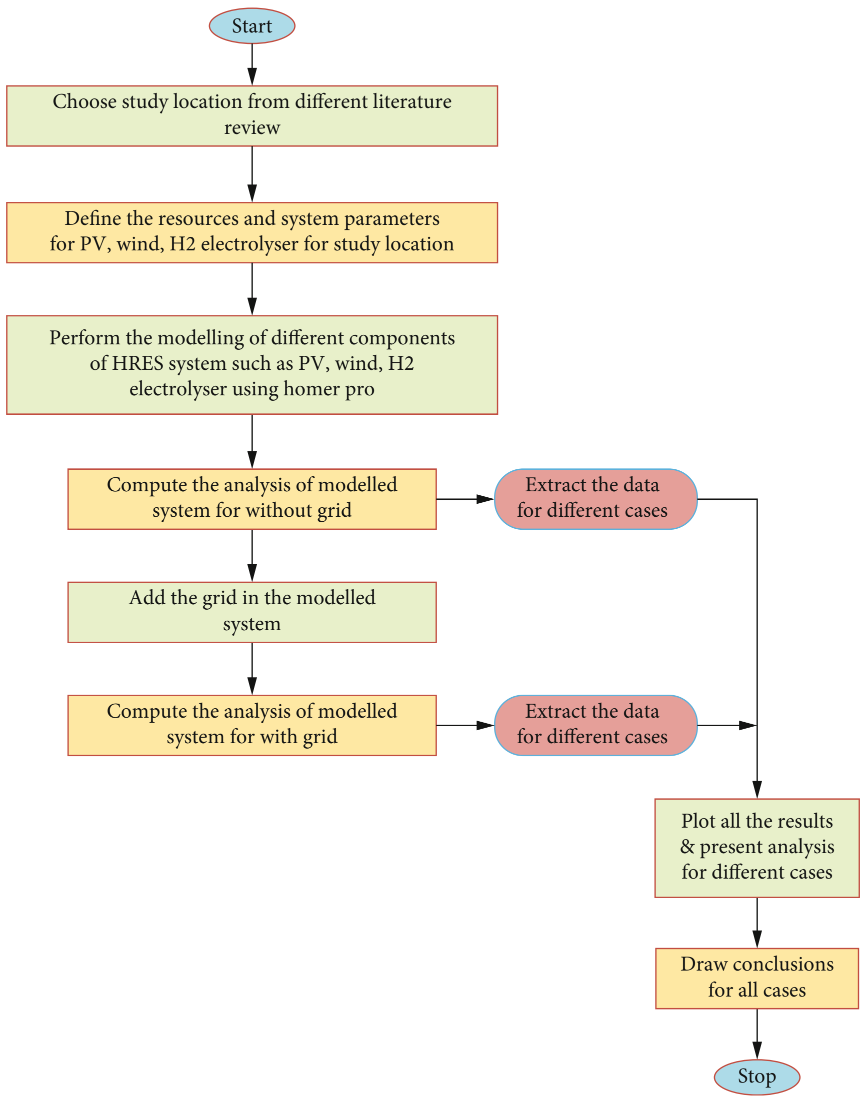

FIGURE 4: Flowchart for the proposed methodology.

various system configurations. This parameter is instrumental in estimating both the levelized cost of energy and the total annualized cost.

4.2. Levelized Cost of Energy. The levelized cost of energy (LCOE), often denoted as COE, is a pivotal and significant metric for conducting cost-effective analyses of distribution grids or networks in the context of renewable energy sources. The LCOE, or the average cost of energy, can be defined as [9, 10]

$$\mathrm{LCOE} = \frac{C_{\mathrm{TNPC}}}{\sum_{H=1}^{H=8760} P_{\mathrm{demand}}} \times \mathrm{CRF}, \tag{16}$$

where P_{demand} is the hourly power consumed (kWh), C_{TNPC} is the net present cost, and capital recovery factor is denoted as CRF, which is determined by

$$\mathrm{CRF} = \frac{r(1+r)^n}{(1+r)^n - 1}, \tag{17}$$

where r is the actual rate of interest and n is the project lifetime of system.

The entire process relies on the availability of solar radiation, with a focus on a generic PV flat plate. Sizing is conducted through the HOMER Optimizer, allowing researchers to evaluate diverse scenarios, input parameters, and system configurations. This approach facilitates the identification of the most efficient and cost-effective solution tailored to the specific location and energy requirements. Through optimization, researchers can determine the appropriate sizing not only for the PV module but also for other components like batteries, wind turbines, and diesel generators, if applicable. This ensures that the system can meet energy demands while accounting for solar radiation availability. The incorporation of solar irradiance information, the utilization of a generic PV flat plate, and the application

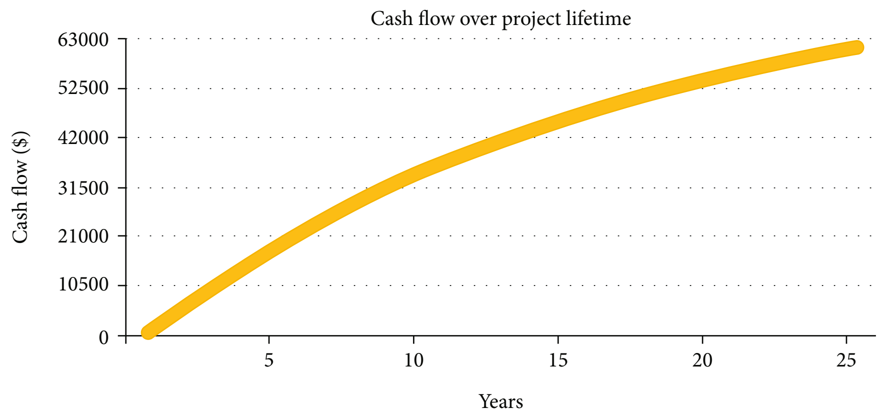

Figure 5: Cash flow for case 1.

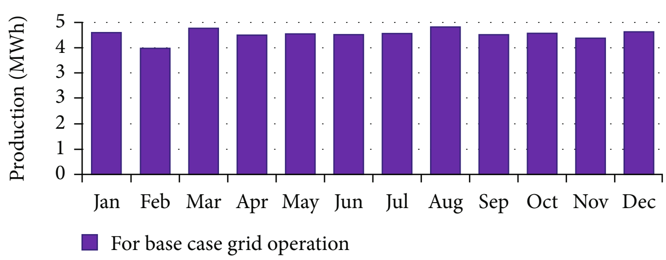

Figure 6: Consumed electric energy of grid for case 1.

of the HOMER Optimizer jointly play a crucial role in evaluating and optimizing the performance and feasibility of the hybrid renewable energy network under investigation.

5. Results and Discussion

The primary aim or goal of conducting these case studies is to ascertain the minimum energy cost needed to sustain the system. This investigation is carried out through the utilization of HOMER Pro version 3.14.2, leveraging its optimizer functionality to identify optimal solutions across diverse scenarios. The analysis encompasses six distinct scenarios, with the base case featuring the grid as the sole component. By comparing and evaluating against the base case, the optimal configuration is determined. Subsequently, a comprehensive and detailed examination of each of the six hybrid system cases is provided as follows. Case 1, case 2, and case 3 are grid-connected cases, and case 4, case 5, and case 6 are off-grid or grid-disconnected cases. Case 1 is the base case of grid-connected system, and case 6 is the base case for off-grid system.

5.1. Case 1: Only Grid to Supply the Electrical Load. This is the base case; the energy system relies solely on the traditional power grid without any renewable energy sources or additional storage options. The operating costs for energy amount to $4721 per year. The microgrid associated with this case has a daily requirement of 152 kWh of energy and a peak load of 17 kW. Throughout the year, the microgrid purchases a total of 55538 kWh of energy from the grid, while no energy is sold back to the grid. Therefore, the net energy purchased from the grid is 55538 kWh. To provide a visual representation of the project's financial performance, the cumulative cash flow over the lifetime of the project is depicted in Figure 5. This figure illustrates the inflows and outflows of cash over time, taking into account factors such as initial investment, operating costs, revenue generation, and other financial parameters associated with the energy system. Figure 6 showcases the electric consumption of the grid over a period of 12 months. It provides insights into the pattern of grid electricity usage, including variations in consumption throughout different months of the year. To facilitate a comparative analysis of the different cases considered, they are presented in Tables 1 and 2. These tables likely outline key metrics, such as cost, energy generation, energy consumption, emissions, or other relevant parameters, for each case. By comparing the values across the different cases, it becomes possible to assess and evaluate the pros and cons of each system setup and pinpoint the most advantageous choices based on factors such as cost, efficiency, and environmental effect. It holds significance to note that while the provided information gives an overview of the base case, further details regarding the specific comparative study in Table 3, as well as the exact content of Figures 3 and 4, are necessary to provide a more comprehensive analysis of case 1.

5.2. Case 2: PV Panels, Wind Turbine, Hydrogen, Diesel Generator, Fuel Cell Generator, Battery, Converter, and Grid, to Serve the Electrical Load. In this specific case, the microgrid system comprises several components, including PV panels, a wind turbine, hydrogen storage, a diesel generator, a fuel cell generator, a battery, a converter, and grid connectivity. Together, these components cater to the electrical load of the microgrid. The daily energy requirement

Table 1: Emissions for different cases of the system.

Parameters	System case values (kg/year)					
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
CO2	35100	21100	21105	7247	5,581	51745
CO	0	0	0	49.3	38.0	352
Unburned hydrocarbons	0	0	0	1.99	1.54	14.2
Particulate matter	0	0	0	0.197	0.152	1.41
SO2	152	91.5	91.5	17.8	13.7	127
NOX	74.4	44.7	44.7	3.94	3.04	28.2

Table 2: Comparison of economics for different cases of the system.

Parameters	System cases					
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Net present cost	$61,027	$56,443	$45,930	$216,611	$196,320	$319,913
CAPEX	$0.00	$47,071	$37,092	$116,122	$112,863	$8,000
OPEX	$4,721	$724.99	$683.64	$7,773	$6,456	$24,128
LCOE (per kWh)	$0.0850	$0.0510	$0.0413	$0.302	$0.273	$0.446
CO2 emitted (kg/yr)	35,100	21,100	21,105	7,247	5,581	51,745
Fuel consumption (L/yr)	0	0	0	2,993	2,134	19,783
IRR (%)	N/A	6.82	9.83	15.3	17.2	N/A
Discounted payback (yr)	N/A	23.9	13.0	7.30	6.56	N/A
Simple payback (yr)	N/A	11.7	8.90	6.07	5.46	N/A

Table 3: Different parameters of energy evaluated for case 1.

Month	Energy procured (kWh)	Energy sold (kWh)	Net energy procured (kWh)	Peak load (kW)	Energy cost	Total charge
January	4,677	0	4,677	17.2	$397.53	$397.53
February	4,139	0	4,139	15.0	$351.86	$351.86
March	4,838	0	4,838	15.3	$411.25	$411.25
April	4,592	0	4,592	17.3	$390.29	$390.29
May	4,631	0	4,631	15.6	$393.62	$393.62
June	4,612	0	4,612	15.8	$392.01	$392.01
July	4,673	0	4,673	15.2	$397.17	$397.17
August	4,882	0	4,882	14.5	$414.96	$414.96
September	4,616	0	4,616	14.5	$392.33	$392.33
October	4,655	0	4,655	14.3	$395.65	$395.65
November	4,504	0	4,504	15.7	$382.82	$382.82
December	4,720	0	4,720	15.4	$401.20	$401.20
Annual	55,538	0	55,538	17.3	$4,721	$4,721

for this microgrid is 236 kWh, with a peak load of 33 kW, and the current operating cost for energy is $4,721 per year. To enhance system efficiency and reduce operating costs, proposed upgrades involve adding 34 kW of PV capacity, increasing the generator capacity by 30 kW, incorporating a 1.0 kWh battery, and installing 1.0 kW of wind generation capacity. These upgrades are expected to significantly decrease the operating cost to $724.99 per year. Additionally, the investment is projected to have a payback period of 11.7 years, an IRR (internal rate of return) of 6.82%, and a return on investment of 5.02%. The net present value of the system is estimated to be $4,584, with a capital investment of $47,071. Annualized savings from the system are projected to be $3,996. The generic PV system in this case has a nominal capacity of 34.4 kW, generating an annual production of 58,133 kWh, with a capital cost of $24,075 and a maintenance cost and LCOE of $0.0350 per kWh. The generic wind turbine system has a rated capacity of 1.00 kW, generating 64.3 kWh per year, with a capital cost of $1,500, operating for 2,533 hours per year, and a maintenance cost of $10.0 per year, and an expected lifetime of 25 years. The two generators in the system include one using stored hydrogen and another using diesel as fuel, both with operational lifetimes of 1,000 years. The hydrogen generator has a rated capacity

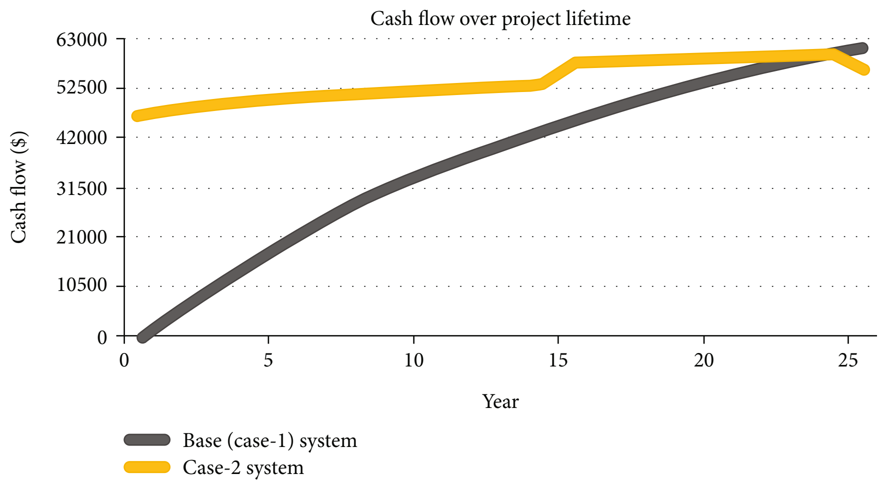

Figure 7: Cash flow for case 2.

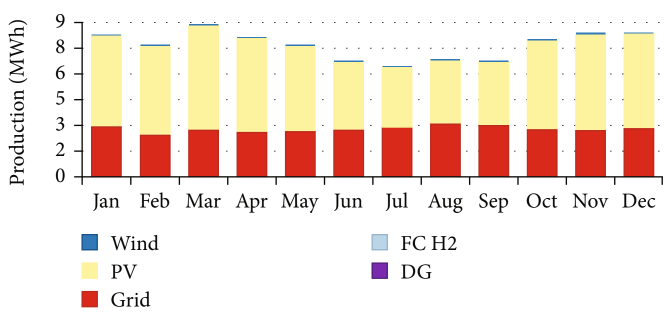

Figure 8: Consumed electric energy of grid and PV for case 2.

of 20.0 kW, and the diesel generator has a rated capacity of 10.0 kW, with capital costs of $8,000 and $4,000, respectively. The generic lithium-ion storage system has a nominal capacity of 1.00 kWh, with a maintenance cost of $10.0 per year and a capital cost of $500, an autonomy of 0.126 hours, and an expected lifetime of 15.0 years. The system converter has a capacity of 23.3 kW, operating for 5,257 hours per year, with an energy output of 52,189 kWh per year and losses of 2,747 kWh per year. The generic electrolyzer in the system has a rated capacity of 10.0 kW, producing 10.0 kg of hydrogen per year, with an initial capital investment of $2,000, operating for 75.0 hours per year, and operating expenses of $100 per year. The hydrogen tank has a storage capacity of 20.0 kg, equivalent to an energy storage capacity of 667 kWh, starting the year with 10 kg, ending with 20.0 kg, and having a tank autonomy of 105 hours. The cash flow over the project's lifetime is illustrated in Figure 7, depicting the inflows and outflows of cash throughout the project's duration, considering factors such as initial investment, operating costs, and revenue generation. Figure 8 presents the electrical consumption of the grid and PV, offering a visual representation of energy consumption patterns over a 12-month period. To facilitate a comparative analysis, Tables 1 and 2 provide a comprehensive comparison of various metrics across different cases, encompassing costs, energy generation, consumption, and other relevant parameters for each configuration. It is essential to note that additional details about the specific content of Tables 1, 2, and 4, as well as the precise information displayed in Figures 7 and 8, are required for a more in-depth analysis.

5.3. Case 3: Photovoltaic Panels, a Wind Turbine, a Diesel Generator, a Battery, a Converter, and Grid Connectivity, without Including Hydrogen Components Such as the Electrolyzer, Hydrogen Fuel Cell, and Hydrogen Tank, Collectively Function to Meet the Electrical Load. In this particular case, the microgrid system is composed of PV panels, a wind turbine, a diesel generator, a battery, a converter, and grid connectivity. Notably, this system does not include hydrogen components such as an electrolyzer, hydrogen fuel cell, and hydrogen tank. The purpose of this system is to serve the electrical load of the microgrid. The daily energy requirement for this microgrid is 236 kWh, with a peak load of 24 kW. The generic PV system integrated into this microgrid has a nominal capacity of 34.3 kW, generating an annual production of 58,018 kWh. The capital cost of the PV system is $24,028, and it incurs a maintenance cost of $172 per year. The specific yield of the PV system is 1,690 kWh/kW, and the LCOE is $0.0350 per kWh. The PV penetration in the microgrid is 104%. The power output of the generic wind turbine system, rated at 1.00 kW, is 64.3 kWh per year. It operates for 2,533 hours per year, and the capital cost of the wind turbine is $1,500. The maintenance cost for the wind turbine is $10.0 per year, and its

Table 4: Different parameters of energy evaluated for case 2.

Month	Energy procured (kWh)	Energy sold (kWh)	Net energy procured (kWh)	Peak load (kW)	Energy cost	Total charge
January	2,911	2,547	364	17.2	$30.95	$30.95
February	2,425	2,857	-432	15.0	-$12.96	-$12.96
March	2,750	3,272	-523	15.3	-$15.68	-$15.68
April	2,617	3,027	-410	17.3	-$12.29	-$12.29
May	2,659	2,656	3.65	15.6	$0.310	$0.310
June	2,754	1,832	923	15.8	$78.43	$78.43
July	2,912	1,497	1,415	15.2	$120.28	$120.28
August	3,088	1,643	1,444	14.5	$122.76	$122.76
September	2,990	1,764	1,226	14.5	$104.22	$104.22
October	2,774	2,819	-45.3	14.3	-$1.36	-$1.36
November	2,677	3,125	-448	15.7	-$13.45	-$13.45
December	2,829	2,998	-169	15.4	-$5.08	-$5.08
Annual	33,386	30,037	3,348	17.3	$396.13	$396.13

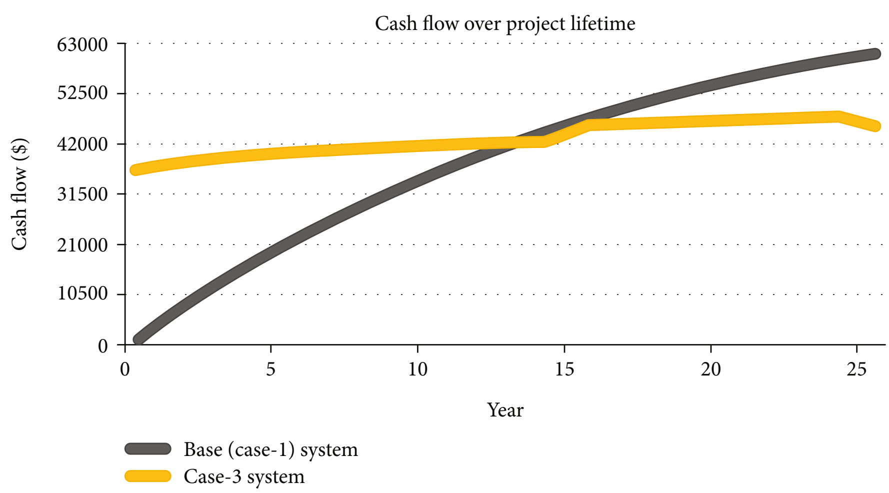

Figure 9: Cash flow for case 3.

expected lifetime is 25 years. The capacity of the generic generator system, which utilizes diesel as fuel, is 10.0 kW. It has an operational life of 1,000 years, and the generator fuel price is $1.00 per liter. The capital cost for this generator is $4,000, and it incurs a marginal generation cost of $0.253 per kWh and a fixed generation cost of $0.547 per hour. The generic lithium-ion battery in the system has an expected lifetime of 15.0 years and an autonomy of 0.126 hours. The capital cost for the 1 kWh battery is $500.0, and it incurs a maintenance cost of $10.0 per year. The system converter has a capacity of 23.5 kW and operates for 5,257 hours per year. Its mean output is 6.01 kW, with a minimum output of 0 kW and a maximum output of 23.5 kW. The converter has an energy output of 52,640 kWh per year and an energy input of 55,411 kWh per year, resulting in losses of 2,771 kWh per year. The capacity factor of the converter is 25.5%. The microgrid purchases 33,395 kWh of energy annually from the grid, while selling 30,498 kWh of energy back to the grid. These figures indicate the energy flow between the microgrid and the grid. To visualize the financial performance of the project, the cumulative cash flow over the project's lifetime is presented in Figure 9. This cash flow diagram represents the inflows and outflows of cash throughout the project's duration, accounting for various factors such as initial investment, operating costs, and revenue generation. Tables 1, 2, 5 furnish a comparative analysis of key metrics across different cases, enabling a comprehensive analysis of the system configurations. Additionally, Figure 10 displays the electric consumption of the grid and PV for case 3, highlighting the energy consumption patterns over a 12-month period. It holds significance to note that further details regarding the specific content of Tables 1, 2, 5, as well as the exact information depicted in Figures 9 and 10, are required to provide a more detailed analysis.

5.4. Case 4: Photovoltaic Panels, a Wind Turbine, Hydrogen, a Diesel Generator, a Fuel Cell Generator, a Battery, and a Converter, Excluding the Grid. In case 4, the microgrid is tailored to meet its electricity demands with a 20 kW generator. The current energy operating costs stand at $24,128 per year. The investment in this system yields a simple payback period of 6.07 years, an IRR of 15.3%, an ROI of 11.2%,

Table 5: Different parameters of energy evaluated for case 3.

Month	Energy procured (kWh)	Energy sold (kWh)	Net energy procured (kWh)	Peak load (kW)	Energy cost	Demand charge	Total charge
January	2,911	2,902	9.51	17.2	$0.809	$0.00	$0.809
February	2,425	2,873	-448	15.0	-$13.44	$0.00	-$13.44
March	2,751	3,294	-543	15.3	-$16.29	$0.00	-$16.29
April	2,618	3,041	-423	17.3	-$12.69	$0.00	-$12.69
May	2,660	2,659	1.12	15.6	$0.0951	$0.00	$0.0951
June	2,755	1,831	924	15.8	$78.53	$0.00	$78.53
July	2,913	1,499	1,414	15.2	$120.22	$0.00	$120.22
August	3,089	1,646	1,443	14.5	$122.67	$0.00	$122.67
September	2,991	1,768	1,223	14.5	$103.98	$0.00	$103.98
October	2,774	2,830	-55.5	14.3	-$1.67	$0.00	-$1.67
November	2,677	3,141	-464	15.7	-$13.91	$0.00	-$13.91
December	2,830	3,015	-185	15.4	-$5.55	$0.00	-$5.55
Annual	33,395	30,498	2,897	17.3	$362.76	$0.00	$362.76

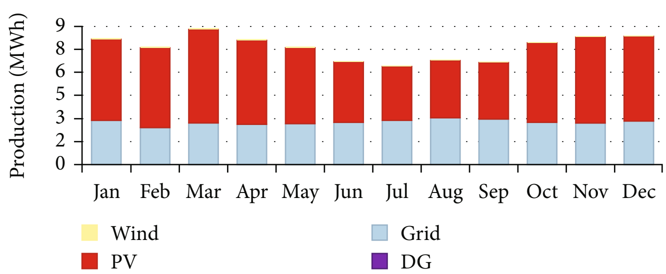

Figure 10: Consumed electric energy of grid and PV for case 3.

and an NPV (net present value) of $103,302. The total capital investment is $108,122, and annualized savings amount to $16,355. The microgrid has a daily energy requirement of 179 kWh and a peak load of 21 kW. The generic PV system integrated into the microgrid has a nominal capacity of 41.4 kW, generating an annual output of 69,960 kWh. With a capital cost of $28,985 and an additional maintenance cost of $207 per year, the PV system has a specific yield of 1,690 kWh/kW and an LCOE of $0.0350 per kWh, reaching a penetration of 126%. The generic wind turbine system, rated at 1.00 kW, produces 64.3 kWh per year, operates for 2,533 hours annually, and has a lifetime of 25.0 years. Its capital cost is $1,500, with an annual maintenance cost of $10.0. The generic generator system utilizing stored hydrogen as fuel generates 1,642 kWh per year, with an operational life of 45.9 years and a generator fuel price of $3.00 per kg. It has a capital cost of $8,000 and an annual maintenance cost of $654. The generator operates for 327 hours annually, with a fixed generation cost of $2.53 per hour. The generator system using diesel as fuel produces 7,915 kWh per year, with an operational life of 43.7 years and a fuel price of $1.00 per liter. Its capital cost is $8,000, and the annual maintenance cost is $549. The generator operates for 1,372 hours annually, with a marginal generation cost of $0.253 per kWh and a fixed generation cost of $1.09 per hour. The generic lithium-ion storage system has a nominal capacity of 127 kWh, an annual throughput of 28,823 kWh, and an expected lifetime of 13.2 years. The capital cost is $63,500, with an annual maintenance cost of $1,270, losses of 3,034 kWh per year, and an autonomy of 16.0 hours. The system converter, with a capacity of 13.8 kW, operates for 7,984 hours per year, producing 46,607 kWh per year with losses of 2,453 kWh per year and a capacity factor of 38.7%. The generic electrolyzer has a rated capacity of 10.0 kW, producing 213 kg of hydrogen annually, with a capital cost of $2,000, operating expenses of $100, and operating for 1,291 hours per year. The hydrogen tank has a storage capacity of 20.0 kg, equivalent to 667 kWh, starting the year with 10.0 kg and ending with 0.443 kg, with an autonomy of 105 hours. To visualize the project's financial performance, Figure 11 depicts the cumulative cash flow over the project's lifetime, illustrating inflows and outflows over time. It can be observed from Figure 11 that NPC got reduced when compared to case 6 which is the base case of off-grid system. Figure 12 presents a graphical representation of electric consumption for case 4, displaying energy consumption patterns over a 12-month period.

5.5. Case 5: Photovoltaic Panels, a Wind Turbine, a Converter, a Battery, and a Diesel Generator Are Integrated to Meet the Electrical Load, Excluding Hydrogen Components like the Electrolyzer, Hydrogen Fuel Cell, and Hydrogen Tank. Under case 5, the system consists of a PV,

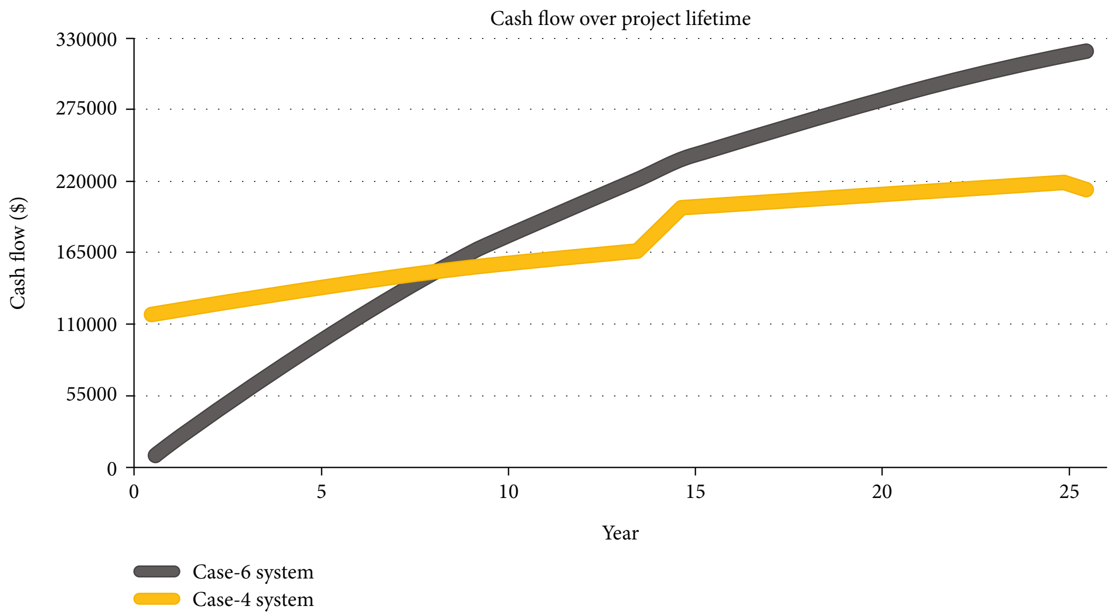

FIGURE 11: Cash flow for case 4.

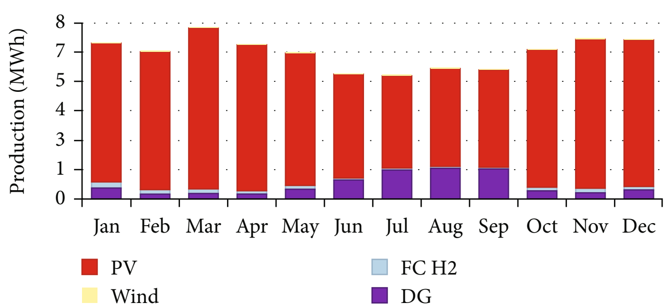

FIGURE 12: Consumed electric energy of PV, wind, DG, and FC H_2 system for case 4.

wind turbine, converter, battery, and diesel generator. The hydrogen components are not included. The system satisfies its electric needs through a 20 kW generator capacity, while the current energy operating costs amount to $24,128 per year. The investment in this system exhibits a payback period of 5.46 years and an IRR of 17.2%. The NPV is $123,594, with a capital investment of $104,863. The ROI stands at 12.8%, and the annualized savings total $17,672. The microgrid in question has a daily energy requirement of 152 kWh and a peak load of 17 kW. The generic flat plate PV system has a nominal capacity of 51.0 kW, resulting in an annual energy production of 86,168 kWh. The capital cost of the PV system is $35,700, with an additional maintenance cost of $255 per year. The specific yield of the PV system is 1,690 kWh/kW, and the LCOE amounts to $0.0350 per kWh. The PV penetration within the microgrid reaches 155%. The power output from the generic wind turbine system, rated at 1.00 kW, amounts to 64.3 kWh per year. The wind turbine operates for 2,533 hours per year, and its expected lifetime is 25 years. The maintenance cost of the wind turbine is $10.0, and the capital cost is $1,500. The power output from the generic generator system, rated at 20.0 kW and utilizing diesel as fuel, reaches 6,073 kWh per year. The operational life of this generator system is 56.2 years, with a generator fuel price of $1.00 per liter. The capital cost of the generator system is $8,000, and the annual maintenance cost amounts to $427. The fuel consumption of the generator totals 2,134 liters, with 1,067 hours of operation per year. The electrical production of the generator matches the aforementioned energy output, and the marginal generation cost is $0.253 per kWh. The fixed generation cost is $1.09 per hour. The nominal capacity of the generic storage system within the microgrid is 127 kWh, with an annual throughput of 29,939 kWh. The capital costs for the storage system are $63,500, and the maintenance cost is $1,270 per year. The system experiences losses of 3,152 kWh per year and has an autonomy of 16.0 hours. The system converter in the microgrid possesses a capacity of 13.9 kW and operates for 8,211 hours per year. The mean output of the converter is 5.70 kW, with a maximum output of 12.6 kW. The energy output of the converter reaches 49,920 kWh per year, while the energy input amounts to 52,548 kWh per year. The converter incurs losses of 2,627 kWh per year, resulting in a capacity factor of 41.1%. To visualize the financial performance of the project, Figure 13 displays the comparative cumulative cash flow

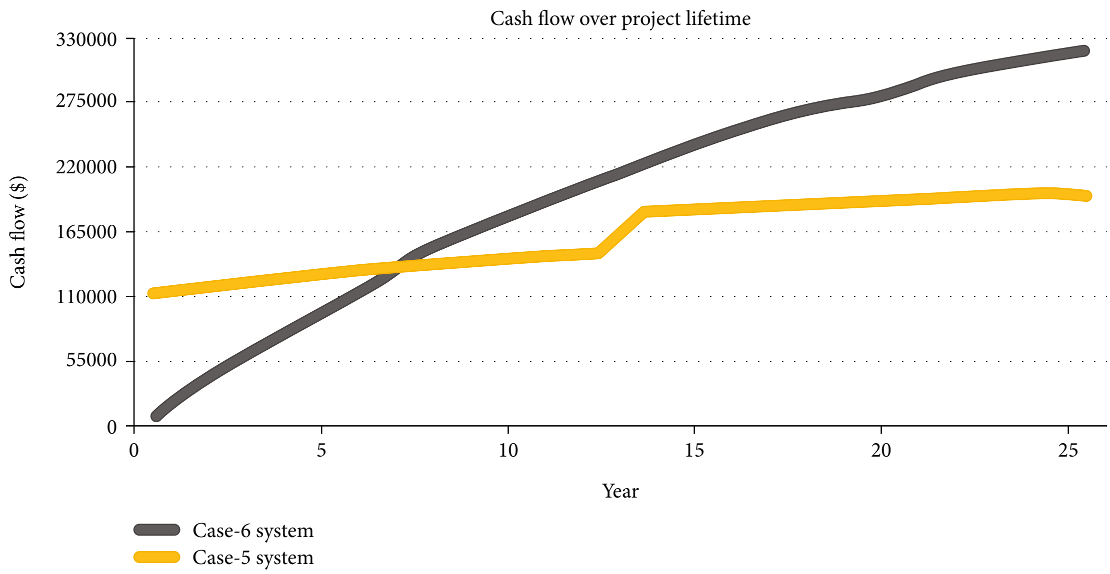

FIGURE 13: Cash flow for case 5.

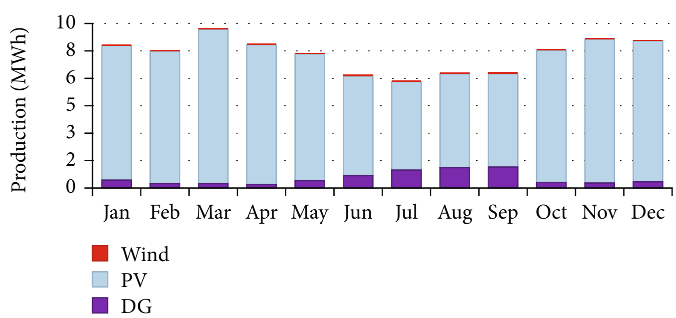

FIGURE 14: Consumed electric energy of DG, PV, and wind for case 5.

over the project's lifetime. It can be observed that case 5 is better than case 6 (base case of off-grid system). This diagram presents the inflows and outflows of cash throughout the project's duration, considering factors such as the initial investment, operating costs, and savings. Tables 1 and 2 furnish a comparative analysis of pertinent parameters across different cases, enabling a comprehensive analysis of the system configurations. Additionally, Figure 14 showcases the electric consumption for case 5, illustrating the patterns of energy consumption over a 12-month period.

5.6. Case 6: No Grid and No Other Components, except Only Diesel Generator, Which Serves the Electrical Load. In this specific case, the microgrid system solely comprises a diesel generator, with no grid or other components involved. Case 6 is the base case of off-grid system. The electrical load is served exclusively by the diesel generator. To meet the electrical energy requirements of the system, a generator capacity of 20 kW is necessary, while the annual operating cost for energy amounts to $24,128. This microgrid has a daily energy demand of 152 kWh and a peak load of 17 kW. The power output from the generic diesel generator system, utilizing diesel as fuel, is 58,805 kWh per year. The operational life of the system is 6.85 years, with a capital cost of $8,000. The diesel generator consumes 19,783 liters of diesel fuel and can operate for up to 8,760 hours per year. The generator fuel price is $1.00 per liter, and the maintenance cost of the system is $3,504 per year. The fixed generation cost amounts to $1.09 per year, while the marginal generation cost is $0.253 per kWh. The mean electrical output of the system is 6.71 kW, with a capacity factor of 33.6%. The system's minimum and maximum electrical outputs are 5.00 kW and 17.3 kW, respectively. The mean electrical efficiency of the system is calculated to be 30.2%. To gain insights into the financial performance of the project for case 6, Figure 15 illustrates the cumulative cash flow over the project's lifetime. This figure provides an overview of the inflows and outflows of cash throughout the project's duration, including factors such as initial investment, operating costs, and potential savings. For a comprehensive comparison of different cases, Tables 1 and 2 present a comparative study of relevant parameters. These tables enable a detailed analysis and evaluation of the system configurations and their respective performance. Furthermore, Figure 16 showcases the electric consumption for case 6, displaying the pattern of energy consumption over a specific 12-month period.

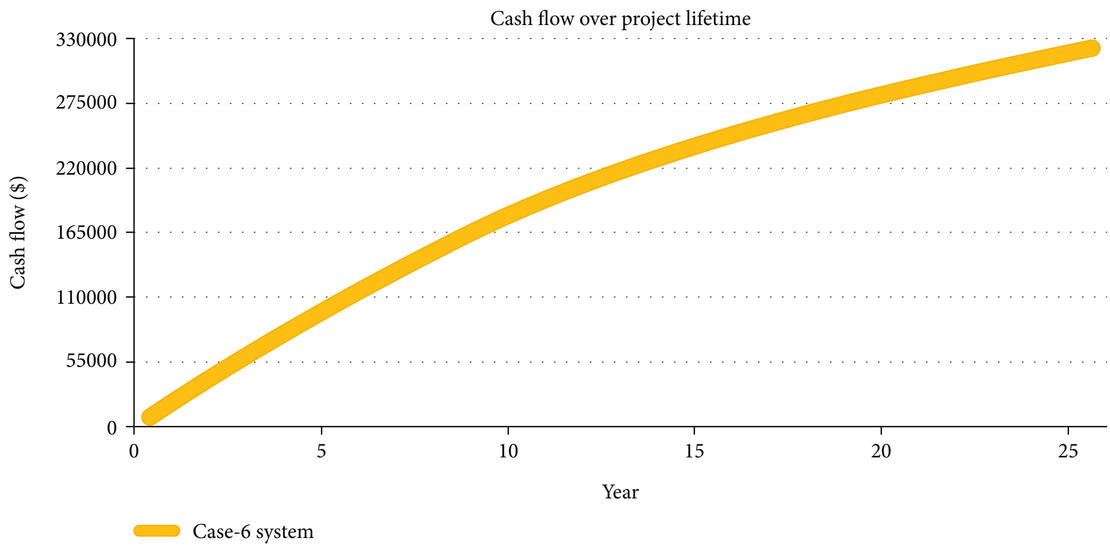

Figure 15: Cash flow for case 6.

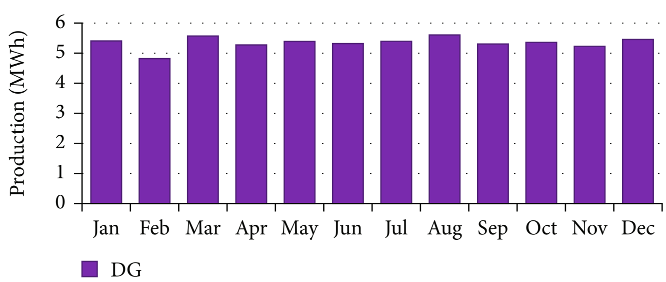

Figure 16: Consumed electric energy of DG for case 6.

Table 2 provides a comprehensive financial analysis across the six cases examined in the paper, emphasizing the advantages of integrating hydrogen energy in both grid and off-grid systems. In the grid-connected system, case 2, featuring hydrogen energy, outperforms the base case (case 1). Similarly, in the off-grid system, case 4 with hydrogen energy demonstrates superior performance compared to the off-grid base case (case 6). Notably, while case 3 and case 5 show better financial values than cases 1 and 6, respectively, in Table 2, the intermittent nature of solar PV and wind suggests that case 2 and case 4, incorporating green hydrogen systems, offer a more reliable solution.

5.7. Critical and Robustness Analysis. The HRES presented in the study exhibits notable robustness in addressing key challenges associated with renewable energy adoption, particularly in remote areas. The system's ability to integrate photovoltaic and wind technologies with a hydrogen source signifies a forward-thinking solution to the intermittency of solar and wind power, a common challenge in remote regions. The proposed model, simulated using HOMER Pro software, demonstrates a robust approach to optimizing productivity, minimizing expenses, and considering economic factors. The incorporation of green hydrogen-based power generation into the HRES stands out as a resilient solution. By leveraging solar power for the electrolysis process, the system showcases adaptability to the irregular nature of renewable resources available on earth. This highlights the robustness of the system in providing a continuous and reliable power supply, especially tailored for remote areas where traditional energy sources may be inaccessible.

Various case studies conducted for Siliguri, West Bengal, India, contribute to the system's robustness by enhancing efficiency and reducing the costs of energy. The positive effects of adopting hydrogen resources, as demonstrated in case 2, reveal a substantial decrease in the NPC, COE, and pollutant emissions. The economic viability of the system is evident, with the NPC reduced from $61,027 to $56,443 and the COE decreasing from $0.085 per kWh to $0.051 per kWh. Furthermore, the significant reduction in operating costs from $4,721 per year to $725 per year underscores the financial robustness of the proposed HRES. The consideration of disconnected systems, though showing higher NPC, COE, and operating costs compared to connected systems, introduces a nuanced perspective. The lower pollutant emissions in disconnected systems highlight their potential environmental benefits, emphasizing a robust trade-off between economic and ecological factors.

The overall robustness of the system is further accentuated by the broader context provided in the latter part of the study. The encouragement for researchers to delve into the technoeconomic aspects of HRES, utilizing advanced methodologies, indicates a commitment to continuous improvement and innovation. The recognition of HRES as gradually becoming mainstream technologies capable of contributing to both environmental sustainability and socioeconomic development reinforces the robustness of these solutions on a larger scale. In conclusion, the HRES outlined in this research exhibits robustness in addressing the challenges of green energy adoption in remote locations. The integration of green hydrogen, supported by advanced simulations and economic analyses, positions the system as a resilient and sustainable solution. The positive impacts demonstrated in case 2 underscore the system's economic viability, while the broader considerations for disconnected systems and the encouragement for further research contribute to the overall robustness of the proposed HRES.

6. Conclusion

The growing energy demand due to increased automation and minimized human effort in the current era has prompted the exploration of new and alternative energy sources, driven by technological advancements. Solar PV, hydrogen, wind, and hybrid systems have emerged as promising options for power production, particularly in remote or rural locations, commonly referred to as hinterlands. These systems offer vast potential and are expected to find widespread applications. One significant area of focus is the production and utilization of hydrogen as a clean energy resource. Hydrogen has the advantage of storing energy for future use and can be utilized in various applications. By replacing conventional energy sources with hydrogen fuel, it becomes possible to minimize pollution and reduce the environmental impact associated with energy production and consumption. Additionally, anaerobic digesters can produce carbon dioxide, which can be harnessed for synthesizing methane using hydrogen. Methane serves as a clean and cost-effective fuel which is suitable for heating purposes and in fuel cell vehicles. Utilizing methane helps mitigate environmental concerns by reducing emissions and contributing to a cleaner energy landscape. In the present study, 6 distinct cases have been considered where case 1, case 2, and case 3 cases are grid-connected system and case 4, case 5, and case 6 are off-grid or grid-disconnected system. This study underscores the favourable outcomes associated with the incorporation of hydrogen resources in grid-connected systems, particularly exemplified in case 2. The results reveal noteworthy reductions in NPC, COE, and pollutant emissions. The NPC experiences a decline from $61,027 to $56,443, while the COE drops from $0.085 per kWh to $0.051 per kWh. Additionally, operational costs witness a significant decrease from $4,721 per year to $725 per year. When contrasting grid-disconnected systems, it is evident that NPC, COE, and operational costs are generally higher, albeit with the noteworthy observation of lower pollutant emissions, signifying potential environmental advantages.

Examining the off-grid scenario, particularly in case 4 featuring hydrogen energy, a substantial reduction is observed in NPC, COE, and pollutant emissions compared to the off-grid base case (case 6). The NPC decreases from $319,913 to $216,611, and the COE from $0.446 per kWh to $0.302 per kWh. Moreover, operational costs for case 4 with integrated hydrogen energy in the off-grid power network plummet from $24,128 per year to $7,773 per year. Conversely, cases 3 and 5, lacking hydrogen integration, demonstrate lower NPC, COE, and emissions than cases 2 and 4. However, the intermittent nature of solar and wind power in 24-hour cycles underscores their limitations. The availability of renewable energy resources presents opportunities to replace carbon-intensive energy sources and substantially curb emissions of greenhouse gas. Furthermore, the integration of renewable energy sources leads to stable energy costs, job creation, and economic advantages. Researchers are encouraged to focus on the technoeconomic aspects of HRES, employing advanced methodologies for further analysis. HRES are gradually becoming mainstream technologies, capable of alleviating the burden on both the economy and the environment. As their deployment increases, the potential benefits extend beyond environmental sustainability, contributing to overall socioeconomic development.

Data Availability

All data generated or analyzed during this study are included in this published article.

Conflicts of Interest

On behalf of all authors, the corresponding authors state that there is no conflict of interest.

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