

DESIGN AND OPTIMIZATION OF A HYBRID SOLAR-WIND-BATTERY ENERGY SYSTEM WITH GREEN HYDROGEN STORAGE AND SMART ENERGY MANAGEMENT FOR RELIABLE POWER SUPPLY IN REMOTE AREAS

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Abstract

Access to reliable electricity is a major challenge for remote and off grid communities because of the scarcity of traditional power matrices and erratic supply of renewable energy resources. In this study, a hybrid Solar-Wind-Battery-Hydrogen Energy System design and optimization are presented to supply the required power for remote locations with a reliable, cost-effective and environmentally friendly approach. The mathematical model of the PVs, wind turbine, Battery energy storage system (BESS), proton exchange membrane (PEM) electrolyze, hydrogen storage tank, proton exchange membrane (PEM) fuel cell, and Energy Management System (EMS) were developed. The optimization framework aims at determining optimal capacities of the system components to minimize the NPC, LCOE and carbon dioxide (CO₂) emissions, and maximize penetration of renewable energy and system reliability. The proposed system was simulated in MATLAB/Simulink with different solar irradiation, wind speed, ambient temperature and electrical load conditions for remote communities. The simulation results showed that for the optimized hybrid configuration, the renewable energy fraction was 94.6%, the system reliability was 99.4%, and the Loss of Power Supply Probability (LPSP) value was 0.006, which means that the power supply was not interrupted throughout the annual simulation period. The optimized system also performed at an LCOE of $\sim$ £0.112 kWh⁻¹ and an annual reduction in carbon dioxide emissions by $\sim$ 91%, when compared to a traditional diesel power generation system. Comparative analysis also revealed that the suggested Solar-Wind-Battery-Hydrogen system outperforms the other conventional systems, Solar Only, Solar-Battery, Solar-Wind, and Solar-Wind-Battery in terms of technical performance, economic viability and environmental protection. The hydrogen storage concept allowed for the effective utilization of surplus renewable energy, balanced out deterioration of batteries, increased the long-term storage capacity, and increased system flexibility. The results prove that the proposed hybrid renewable energy system is a practical and scalable solution for sustainable electrification of remote and off-grid areas and can contribute to the global clean energy and carbon reduction targets.

INTRODUCTION

The fast-growing global demand for electricity, strong industrialization, rising population and the immediate need for climate change mitigation has speeded up the shift from traditional fossil fuel-based power systems to renewables and sustainable power systems. The International Energy Agency (IEA) projects that electricity demand will keep growing annually, and concerns about greenhouse gas (GHG) emissions, energy security and environmental degradation have skyrocketed the demand for cleaner and more secure energy solutions. While coal, oil and natural gas will continue to be the major sources of power for electricity generation in the world, they are finite resources, and their use generates high carbon dioxide (CO₂) emissions that are not sustainable for the long-term energy demands of the world (Taghizad-Tavana, Esmaeel Nezhad, Hagh, Canani, & Safari, 2025).

Solar PV is one of the fastest growing renewable energy technologies, with the efficiency of PV modules continually increasing and the cost of manufacturing continually decreasing, and with supportive government policies being introduced all over the world. Solar PV systems are one of the cleanest energy generation technologies as it does not emit any harmful emissions during operation. Similarly, wind power has emerged as one of the most rapidly expanding renewable power sources, due to the development of wind turbine design and power electronics and meteorological forecasting methods (Superchi & Bianchini, 2025). Onshore and offshore wind power have become important sources of electricity for national electricity grids in many countries. Both solar and wind power are, however, intermittent and depend on the weather, which is not all beneficial. Solar energy is only generated during the day and subject to weather conditions such as cloud cover, and wind is only generated when the wind blows and also dependent upon season and weather. The intermittency poses difficulties in ensuring stable and reliable power supply, especially in remote and off-grid areas (Lund et al., 2023; IRENA, 2024).

Some 675 million people around the world remain without reliable electricity and a large proportion of those live in remote areas where it is technically challenging to connect to the national transmission network and economically unfeasible. Diesel Generators (DG) are the main source of electricity in many remote mountain areas, islands, deserts and rural areas in developing countries, where the population density is low (Syed & Khalid, 2023). While diesel generators offer continuous power supply, they are known for high fuel transportation costs, frequent maintenance needs, substantial GHG emissions and price volatility of the fuel. Moreover, the use of fossil fuel generators is in contradiction with the World's decarbonization goals and the United Nations Sustainable Development Goal 7 (SDG 7) to ensure universal access to affordable, reliable, sustainable and modern energy by 2030. Hence, hybrid renewable energy systems have attracted much interest as a viable approach to meeting the electricity supply demand without compromising on reliability and minimizing environmental impacts and future operating expenses (United Nations, 2015; IEA, 2024).

Hybrid renewable energy systems consist of several renewable resources and energy storage systems to eliminate the disadvantage of a single energy source. Combining solar PV with wind allows complementary power generation, as low solar PV availability is often correlated with higher wind availability, which could enhance the reliability of the overall system. However, the complementarity of resources is not sufficient to guarantee the elimination of the fluctuations of renewable energy. Therefore, energy storage technologies are essential and integral parts of today's hybrid microgrids. The most popular option is the Battery Energy Storage System (BESS), which is especially lithium-ion batteries, with their high energy density, swift response time, long cycle life, and ever-lowered cost (Alzahrani, Ramu, Devarajan, Vairavasundaram, & Vairavasundaram, 2022). Batteries are used to store excess electricity generated when renewable energy production is high and power when renewable energy

generation is low or demand is high to help stabilize the grid and enhance power quality. The performance, safety and lifetime of battery systems is also further improved by Battery Management Systems (BMS), which continuously monitor the battery state of charge (SOC), state of health (SOH), temperature and voltage balancing as well as charging/discharging, optimizing the battery performance and operational lifetime (Abdelghany, Al-Durra, & Gao, 2023).

Although batteries have great potential, they might not be able to deliver the long-duration energy storage needed when renewables are low. However, in recent years, hydrogen has become a promising complementary medium of energy storage that can overcome this challenge. The surplus electricity generated by solar and wind power can then be fed into electrolyzers that separate water into hydrogen and oxygen, with the production of green hydrogen when renewable electricity is used. Green hydrogen has a number of benefits: there are no direct emissions involved in its production, it can be stored for long-term use, and it can be used in fuel cells to generate electricity at times when renewable energy is not available (Ani, 2021). Grey hydrogen, on the other hand, is created using fossil fuels without carbon capture, which can generate significantly more carbon emissions than blue hydrogen, which uses CCS technologies by natural gas. Hybrid renewable energy (HRE) systems combining production, storage tanks and fuel cells for green hydrogen offer seasonal energy storage, system reliability and a reduction of reliance on diesel generators. Hydrogen technologies are expected to be central to future low-carbon energy systems and contribute to the global hydrogen economy initiatives, as they continue to mature (IRENA, 2023).

With the spread of electric vehicles (EVs), renewable energy systems have new opportunities and challenges. The utilization of EV charging stations by installing them in distributed renewable microgrids to encourage sustainable mobility and reduce dependence on fossil fuels is seen as a growing trend. By managing electricity loads intelligently, surplus electricity generated

from renewable sources during peak hours can be used at times when the demand is low, thereby optimizing the use of energy and alleviating grid congestion. System flexibility could be further improved in future by the integration of Vehicle-to-Grid (V2G) technologies that would enable electric vehicles to operate as distributed energy storage devices. As a result, EV charging stations are an important component of integrated clean energy and transportation systems through the implementation of hybrid renewable microgrids (Zhao, Zhao, Cao, Zhu, & Sun, 2025).

Another key element of sustainable energy development is to decrease carbon emissions from traditional electricity production. While renewable energy systems reduce greenhouse gas emissions significantly, technologies can be complementing the RE technologies like CCS (Carbon Capture, Utilization, and Storage) can be of great interest in reducing GHGs from fossil fuel use. The technologies in carbon capture can play an important role to help achieve a transition to zero energy systems by reducing CO₂ emissions from thermal power plants and industrial processes. Although carbon capture is not directly integrated into most renewable microgrids, its incorporation in comparative environmental analyses gives insights into long-term carbon capturing strategies and shows the environmental superiority of renewable based hybrid system over conventional diesel-based system (Nelson, 2025). Multiple energy resources need to be coordinated in real time, and advanced Energy Management Systems (EMS) are needed to ensure efficient use of these energy sources. With a smart EMS, the best operating strategy can be identified by optimizing renewable energy generation, charging the battery storage, producing hydrogen if there is surplus renewable energy, discharging the battery if there is not enough, and operating fuel cells only when needed. These intelligent control strategies can reduce energy losses, increase battery life, decrease hydrogen usage and increase the reliability of the system. With the recent developments in optimization techniques, artificial intelligence, and predictive control algorithms, hybrid renewable energy systems have

become more efficient and effective, allowing the system to make real-time decisions based on the changing weather conditions and load requirements (Jokar et al., 2024).

Careful designing and optimizing the size of component and operating strategies are essential to design economically viable hybrid renewable energy system. If system components are oversized, unnecessary capital cost is added and if they are undersized, also the reliability and energy availability is affected. Hence, many optimization methods, including Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Grey Wolf Optimization (GWO) and other metaheuristic algorithms have been successfully applied to find the optimal capacity of solar PV arrays, wind turbines, battery storage, electrolyzers, hydrogen tanks and fuel cells. Generally, techno-economic indicators like Net Present Cost (NPC), Levelized Cost of Energy (LCOE), renewable energy fraction, Loss of Power Supply Probability (LPSP), battery lifetime, hydrogen utilization, and carbon emission reduction are taken into account for performance evaluation (Almutairi et al., 2021). The use of simulation tools for modelling and optimization of hybrid renewable microgrids in various climatic and load scenarios has gained widespread acceptance, e.g., HOMER Pro and MATLAB/Simulink.

Despite the fact that a large amount of research has been done on solar-battery and solar-wind-battery hybrid systems, there have been only a few studies that comprehensively combined solar PV,

wind energy, Battery Management Systems, green hydrogen production and storage, fuel cells, intelligent energy management, EV charging infrastructure, and environmental assessment within a single optimization framework for remote-area electrification. The research gaps discussed above are critical to be addressed to create reliable, economically viable and environmentally friendly microgrids to satisfy future energy requirements (Almutairi et al., 2021). Based on this, the design and optimization of a Solar-Wind-Battery-Hydrogen hybrid system are proposed, which is integrated with a smart Energy Management System for the reliable supply of electricity to remote communities. The proposed system includes solar PV arrays, wind turbines, Battery Storage (Li-ion type) and Battery Management System (BMS), electrolyzers, Hydrogen Storage tanks, Fuel cells, and EV charging stations in an optimized microgrid architecture. Techno-economic and environmental parameters such as system reliability, renewable energy penetration, Levelized Cost of Energy, Net Present Cost, battery performance, hydrogen utilization and carbon emission reduction will be used to assess the performance of the system. The results of this research will help advance sustainable and resilient renewable energy solutions that can help achieve future low-carbon energy systems and increase energy accessibility in remote and underserved areas (Asim, Awad, & Attia, 2025).

System Description

Overall System Architecture

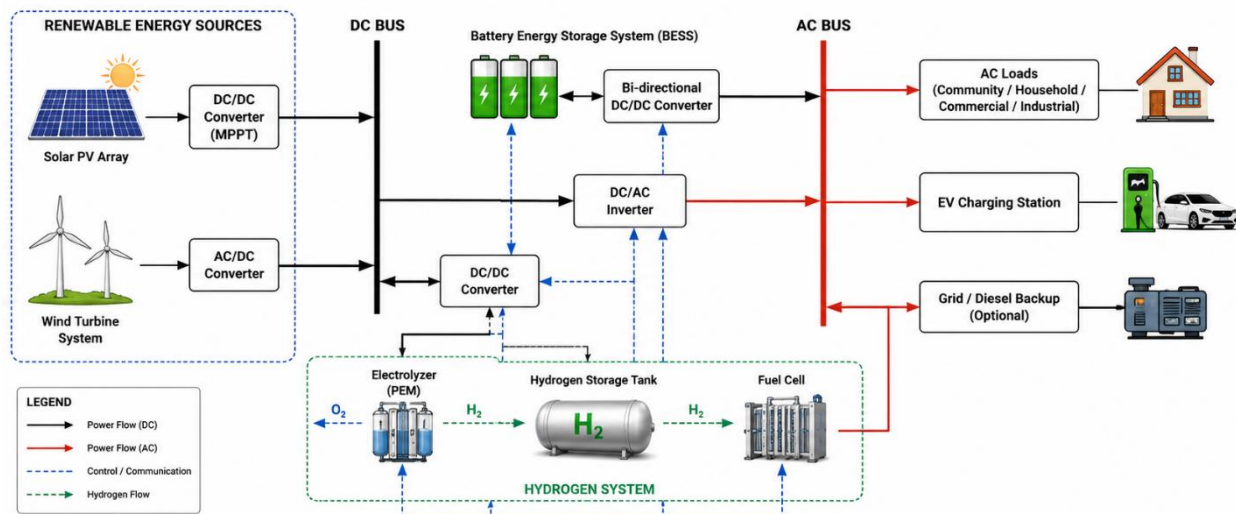


Figure 1. Schematic illustration of system architecture

Solar Photovoltaic (PV) Subsystem

One of the major renewable energy sources in the proposed hybrid energy system is solar photovoltaic (PV) subsystem. It is made up of photovoltaic panels which use the photovoltaic effect to directly generate direct current (DC) electricity from sunlight. The PV array's electrical production is influenced by solar irradiance, ambient temperature, panel orientation, and module efficiency. The PV array is also connected to a Maximum Power Point Tracking (MPPT) controller to optimize the PV array's power output under different environmental conditions. The generated DC power is fed into a common DC bus via a DC/DC converter and the electrical energy is fed to AC loads through a DC/AC inverter. The PV excess power is used for hydrogen production in the electrolyze or battery charging as per the operational strategy decided by the Energy Management System (EMS) (Sayed, El-Shimy, El-Metwally, & Elshahed, 2020).

Wind Energy Subsystem

The wind energy subsystem will supplement the solar PV system with electricity generation when the PV system is under low solar irradiance and night-time operating conditions. It is a wind

turbine consisting of an electrical generator with a horizontal-axis wind turbine that is used to generate electrical energy from the wind's kinetic energy. As the electrical output from wind turbine is dependent on the wind speed, a power conditioning unit is used to control the voltage and frequency before the electricity connects to the common DC bus. This complementarity between wind and solar power sources increases the reliability of the hybrid system, as the production of the two energy sources is not perfectly correlated. The Energy Management System continuously monitors the wind energy availability and directs its use together with other energy resources and sources to optimize the use of renewable energy, and to limit dependence on back-up energy resources (Wu, Zhou, & Shan, 2022).

Battery Energy Storage Subsystem

The Battery Energy Storage System (BESS) is integrated to store energy for a short term to maintain continuous power supply when renewable energy generation is inadequate. The battery bank is used to store surplus energy produced by the sub-systems PV and Wind and discharge it when there is a deficit. A Battery

Management System (BMS) is a circuit that is constantly monitoring the most important battery parameters such as the state of charge (SOC), state of health (SOH), voltage, current, and temperature. The BMS ensures the battery does not overcharge, deep discharge or cause thermal instability, which extends battery life and safety. The bidirectional DC/DC charge controller is responsible for controlling charging and discharging processes and balances the energy between the hybrid system under the supervision of the Energy Management System (EMS).

Hydrogen Energy Subsystem

The hydrogen energy subsystem will enable long-term energy storage, improves the reliability of the hybrid renewable energy system during long periods of low renewable energy supply. The excess electricity produced by the PV and wind subsystems is fed to a proton exchange membrane (PEM) electrolyze that splits water into hydrogen and oxygen via electrolysis. The hydrogen generated is compressed and kept in high pressure storage tanks for future applications. If there is not enough renewable energy generation and battery storage to meet the electrical load requirements, the stored hydrogen will be fed into a proton exchange membrane fuel cell to produce electrical energy and water as the most important byproduct. This is an integrated hydrogen storage pathway that will help to enhance the flexibility, resilience and sustainability of the proposed hybrid energy system by enabling the storage of energy for the season and the elimination of the need for conventional diesel backup power generation sources (Hamid et al., 2023).

Energy Management System (EMS)

The Energy Management System (EMS) supports the distributed and highly decentralized control of the proposed hybrid Solar-Wind-Battery-Hydrogen energy system via a central supervisory controller. It constantly gathers PV array and wind turbine power generation data, Battery Energy Storage System (BESS) state of charge (SoC) data,

hydrogen storage data, electric load demand data, and the status of all the system components. The EMS analyses real-time data to optimize the power flow. The EMS analyses the real-time data and optimizes power flow to ensure uninterrupted power supply with minimum operational cost, battery degradation and carbon emission.

The EMS first uses the energy stored in the Battery Energy Storage System to keep the power supply stable when renewable energy generation is not enough due to weather conditions or higher electricity demand. When the battery SOC falls below the desired operation point, the EMS will turn on the hydrogen fuel cell to produce electricity from the stored hydrogen, thus maintaining the power generation without interrupting the power fed to the consumers. In cases where renewable energy, battery storage and hydrogen reserves are all limiting, the system can optionally demand diesel generators or the grid as a last resort to keep the system reliable (Kudzin, Takayama, & Ishigame, 2025).

The EMS also carries out a number of auxiliary functions, among which the load forecasting, battery health monitoring, hydrogen storage management, power quality control, fault detection, communication with system sensors and optimization of charging and discharging operations. The EMS can also be designed to include advanced optimization algorithms like Particle Swarm Optimization (PSO), Genetic Algorithm (GA), or artificial intelligence (AI) based control methods to optimize the system's operation, maximize use of renewable energy resources, minimize the Levelized Cost of Energy (LCOE), reduce the Net Present Cost (NPC), and optimize the overall operational efficiencies of the hybrid microgrid. The Energy Management System is therefore to be considered as the intelligence of the proposed hybrid energy system for its coordination and control of all renewable generation, storage and backup units to provide reliable, economical and environmentally sustainable power supply for remote communities (Nasir, Hussain, Niazi, & Nasir, 2022).

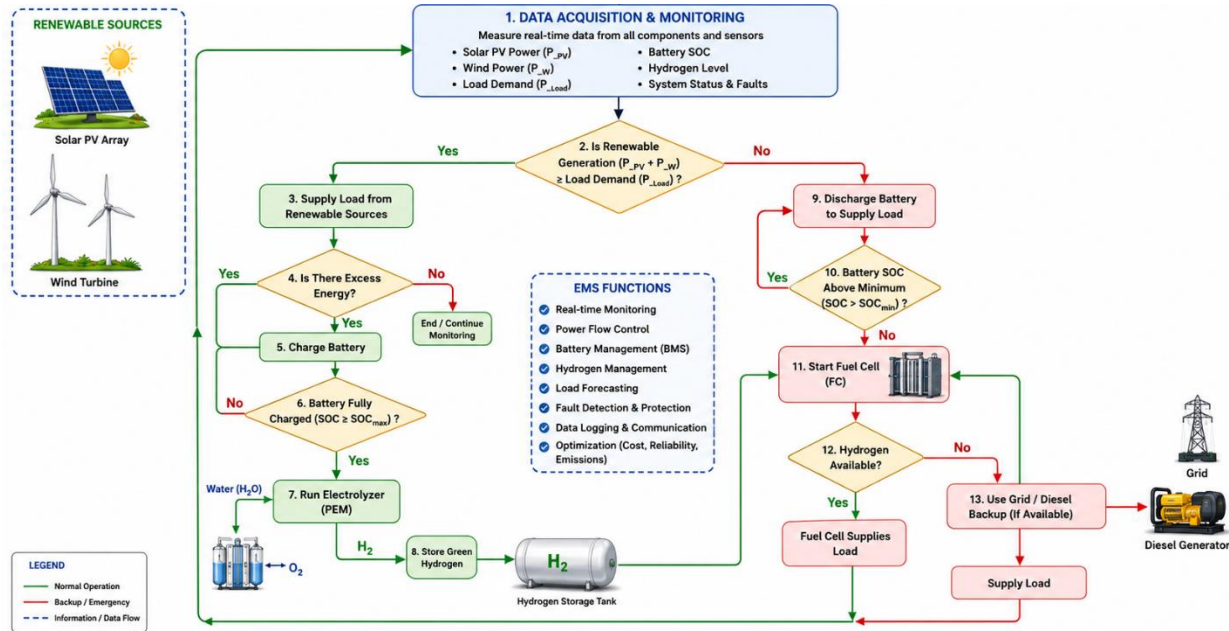


Figure 2. Operational flowchart of the proposed Energy Management System (EMS) for the hybrid Solar-Wind-Battery-Hydrogen energy system.

Mathematical Modelling

Solar Photovoltaic (PV) Model

The electrical output power of the photovoltaic array primarily depends on solar irradiance, cell temperature, module efficiency, and the total surface area of the solar panels. Under varying environmental conditions, the output power of the PV array can be expressed as

$$P_{PV} = A_{PV} G \eta_{PV}$$

where

P_{PV} = output power of the PV array (W)

A_{PV} = total PV module area (m²)

G = solar irradiance (W/m²)

η_{PV} = efficiency of the PV module

Since PV efficiency varies with temperature, the temperature-corrected efficiency is calculated as

$$\eta_{PV} = \eta_{ref} [1 - \beta (T_c - T_{ref})]$$

where

η_{ref} = reference efficiency

β = temperature coefficient (°C⁻¹)

T_c = cell temperature (°C)

$$T_{ref} = 25^\circ C$$

The cell temperature can be estimated using

$$T_c = T_a + \left(\frac{NOCT - 20}{800} \right) G$$

where

T_a = ambient temperature

NOCT = Nominal Operating Cell Temperature

The total daily energy generated by the PV array is

$$E_{PV} = P_{PV} \times t$$

were

E_{PV} = daily PV energy (kWh)

t = operating time (h)

A Maximum Power Point Tracking (MPPT) controller is incorporated to maximize energy extraction under varying irradiance conditions.

Wind Turbine Model

Wind turbines convert the kinetic energy of moving air into electrical energy. The mechanical power available in wind is given by

$$P_{wind} = \frac{1}{2} \rho A V^3$$

were

ρ = air density (kg/m³)

A = rotor swept area (m²)

V = wind speed (m/s)

Considering turbine efficiency,

$$P_t = \frac{1}{2} \rho A V^3 C_p$$

were

C_p = power coefficient

The electrical power delivered by the wind turbine becomes

$$P_e = P_t \eta_g \eta_{inv}$$

were

η_g = generator efficiency

η_{inv} = inverter efficiency

The turbine operates within three characteristic wind speeds:

Cut-in speed

Rated speed

Cut-out speed

The practical turbine model is

$$P_{WT}(V) = \begin{cases} 0, & V < V_{ci} \\ P_r \left(\frac{V^3 - V_{ci}^3}{V_r^3 - V_{ci}^3} \right), & V_{ci} \leq V < V_r \\ P_r, & V_r \leq V \leq V_{co} \\ 0, & V > V_{co} \end{cases}$$

were

V_{ci} = cut-in wind speed

V_r = rated wind speed

V_{co} = cut-out speed

P_r = rated turbine power

The total daily wind energy production is

$$E_{WT} = P_{WT} t$$

Battery Energy Storage Model

The Battery Energy Storage System (BESS) stores surplus renewable electricity and supplies power whenever renewable generation becomes insufficient.

The battery charging process is expressed as

$$SOC_t = SOC_{t-1} + \frac{\eta_c P_c t}{C_b}$$

were

SOC_t = battery state of charge

SOC_{t-1} = previous SOC

P_c = charging power

C_b = battery capacity

η_c = charging efficiency

During discharge,

$$SOC_t = SOC_{t-1} - \frac{P_d t}{\eta_d C_b}$$

were

P_d = discharge power

η_d = discharge efficiency

The allowable operating range is

$$SOC_{min} \leq SOC \leq SOC_{max}$$

The available battery energy is

$$E_b = SOC \times C_b$$

The battery power balance is

$$P_b = P_{PV} + P_{WT} - P_L$$

were

P_L = load demand

If

$$P_b > 0$$

the battery charges.

If

$$P_b < 0$$

the battery discharges.

The battery charging efficiency is

$$\eta_{battery} = \frac{E_{out}}{E_{in}} \times 100$$

Depth of Discharge (DoD)

Depth of discharge is

$$DoD = 100 - SOC$$

or

$$DoD = \frac{E_{used}}{C_b} \times 100$$

A lower DoD generally increases battery lifetime.

Battery Lifetime Model

Battery lifetime can be estimated by

$$L_b = \frac{N_c}{N_{year}}$$

were

L_b = battery lifetime (years)

N_c = total allowable charge-discharge cycles

N_{year} = annual operating cycles

Alternatively,

$$L_b = \frac{Q_{life}}{Q_{annual}}$$

were

Q_{life} = total lifetime energy throughput

Q_{annual} = annual energy throughput

Battery Round-Trip Efficiency

The round-trip efficiency is expressed as

$$\eta_{RT} = \eta_c \eta_d \times 100$$

were

η_{RT} = round-trip efficiency (%)

Battery Management System (BMS)

The Battery Management System (BMS) is responsible for the ongoing monitoring of battery voltage, current, temperature, State of Charge (SOC) and State of Health (SOH). The BMS protects the battery from overcharging, deep discharging, thermal runaway and voltage imbalance. It also interfaces with the Energy Management System (EMS) to control the charging and discharging cycles, enhancing the safety, efficiency, and lifespan of the batteries. The BMS is very important to ensure the most efficient use of energy and the continuous functioning of the hybrid renewable energy system.

Hydrogen Production Model

The hydrogen energy subsystem can be integrated into the proposed hybrid renewable energy system to serve as long-term energy storage and enhance the power system reliability during extended periods of lower power generation from renewable energy sources. When excess electrical power is produced by the solar PV and wind turbine subsystems, it is fed to a Proton Exchange Membrane (PEM) electrolyze to split the water into hydrogen and oxygen gas. The hydrogen generated is compressed, stored in high pressure tanks and then used to generate electricity with a fuel cell.

The electrical power supplied to the electrolyze is expressed as

$$P_{EL} = P_{PV} + P_{WT} - P_{Load} - P_{Battery}$$

were

P_{EL} = power supplied to the electrolyzer (kW)

P_{PV} = photovoltaic output power (kW)

P_{WT} = wind turbine output power (kW)

P_{Load} = load demand (kW)

$P_{Battery}$ = battery charging power (kW)

The hydrogen production rate is directly proportional to the electrical power supplied to the electrolyze and can be expressed as

$$\dot{m}_{H_2} = \frac{\eta_{EL} P_{EL}}{LHV_{H_2}}$$

were

$\dot{m}_{H_2}$ = hydrogen production rate (kg h⁻¹)

η_{EL} = electrolyzer efficiency

LHV_{H_2} = lower heating value of hydrogen (33.33 kWh kg⁻¹)

The total hydrogen produced during the operating period is calculated as

$$M_{H_2} = \dot{m}_{H_2} t$$

were

M_{H_2} = total hydrogen mass (kg)

t = operating time (h)

The efficiency of the electrolyze is determined using

$$\eta_{EL} = \frac{M_{H_2} \times LHV_{H_2}}{E_{EL}} \times 100$$

were

E_{EL} = electrical energy supplied to the electrolyzer (kWh)

Hydrogen Storage Model

Hydrogen produced by the electrolyze is stored in high-pressure tanks until it is required for electricity generation. The hydrogen storage balance is expressed as

$$H_t = H_{t-1} + H_{prod} - H_{cons}$$

were

H_t = hydrogen stored at time t

H_{prod} = hydrogen produced

H_{cons} = hydrogen consumed by the fuel cell

The storage capacity is constrained by

$$H_{min} \leq H_t \leq H_{max}$$

were

H_{max} = maximum storage capacity

H_{min} = minimum operational storage level

Fuel Cell Model

The fuel cell will turn stored hydrogen into electricity when there is not enough renewable generation or battery storage to meet the electrical load. The choice of a Proton Exchange Membrane (PEM) fuel cell is due to its high efficiency, rapid dynamic response and low operating temperature.

The electrical output power of the fuel cell is given by

$$P_{FC} = \eta_{FC} \dot{m}_{H_2} LHV_{H_2}$$

were

P_{FC} = fuel cell output power (kW)

η_{FC} = fuel cell efficiency

$\dot{m}_{H_2}$ = hydrogen consumption rate

The electrical energy generated by the fuel cell is

$$E_{FC} = P_{FC} t$$

The hydrogen consumption rate during fuel cell operation is

$$\dot{m}_{cons} = \frac{P_{FC}}{\eta_{FC} LHV_{H_2}}$$

The efficiency of the fuel cell is expressed as

$$\eta_{FC} = \frac{P_{FC}}{\dot{m}_{cons} LHV_{H_2}} \times 100$$

The hydrogen storage level after fuel cell operation becomes

$$H_t = H_{t-1} - \dot{m}_{cons} t$$

The combined round-trip efficiency of the hydrogen storage subsystem is calculated as

$$\eta_{H_2} = \eta_{EL} \times \eta_{FC}$$

This parameter represents the overall efficiency of converting electrical energy into hydrogen and subsequently reconvert it into electricity.

Electrical Load Model

The electrical load is the total load of the remote community to be served by the proposed hybrid renewable energy system. The load profile is usually made up of daily and seasonal residential, commercial, educational, healthcare and public lighting needs. Modelling load demand accurately is crucial for sizing components, managing energy and optimizing systems.

The total electrical load at any time is expressed as

$$P_{Load} = P_R + P_C + P_I + P_{EV}$$

were

P_R = residential load

P_C = commercial load

P_I = institutional/public load

P_{EV} = electric vehicle charging load

The daily electrical energy demand is calculated by

$$E_{day} = \sum_{i=1}^{24} P_i \Delta t$$

were

P_i = hourly load demand

Δt = one-hour interval

The annual energy consumption is determined using

$$E_{annual} = \sum_{d=1}^{365} E_{day}$$

To account for seasonal fluctuations in electricity demand, the seasonal load is modelled as

$$P_{season} = P_{avg}(1 + \alpha)$$

were

P_{avg} = average electrical load

α = seasonal variation coefficient

The energy balance equation governing the proposed hybrid system is

$$P_{PV} + P_{WT} + P_{FC} + P_{Battery} = P_{Load} + P_{EL} + P_{Loss}$$

were

P_{Loss} represents conversion and transmission losses within the system.

The Energy Management System continuously monitors to guarantee that generated and stored energy meet the instantaneous demand for load while simultaneously adhering to the operating constraints of the battery storage system, hydrogen storage system and fuel cell. The power balance equation (39) is the core relationship of the proposed hybrid Solar-Wind-Battery-Hydrogen microgrid and the optimization and reliability analysis will be based on this equation in the following sections.

Reliability Indices

Reliability is an important quality measure of a hybrid renewable energy system, especially in the context of remote area electrification, where continuous power supply is necessary. Reliability assessment is used to verify the proposed Solar-Wind-Battery-Hydrogen system's ability to meet the electrical demand when the availability of the renewable resources and conditions of operation change. To check the overall performance of the proposed system, various reliability indices are used.

Loss of Power Supply Probability (LPSP) is one of the most popular reliability indices that contains the probability of a system not meeting the necessary electrical load. The lower the LPSP, the more reliable the system, while a value close to zero means that the load demand is almost met.

The LPSP is expressed as

$$LPSP = \frac{\sum_{t=1}^N E_{def}(t)}{\sum_{t=1}^N E_{load}(t)}$$

were

$E_{def}(t)$ = energy deficit during time interval t (kWh)

$E_{load}(t)$ = load demand during time interval t (kWh)

N = total simulation period

The percentage reliability of the proposed hybrid system can be calculated as

$$Reliability = (1 - LPSP) \times 100$$

Another important reliability parameter is the **Loss of Load Expectation (LOLE)**, which estimates the expected duration during which the electrical load cannot be fully supplied.

The LOLE is calculated as

$$LOLE = \sum_{t=1}^N I_t$$

were

$$I_t = \begin{cases} 1, & P_{Gen} < P_{Load} \\ 0, & P_{Gen} \geq P_{Load} \end{cases}$$

and

P_{Gen} = total generated power

P_{Load} = electrical load demand

The **Loss of Load Probability (LOLP)** is another indicator of supply reliability and is defined as

$$LOLP = \frac{LOLE}{T}$$

were

T = total operating time (hours)

The Renewable Energy Fraction (RF) represents the proportion of electrical energy supplied by renewable sources relative to the total energy demand.

It is calculated as

$$RF = \frac{E_{PV} + E_{WT} + E_{FC}}{E_{Total}}$$

were

E_{PV} = annual solar energy production

E_{WT} = annual wind energy production

E_{FC} = electricity generated from renewable hydrogen

E_{Total} = total annual electrical demand

The renewable penetration percentage is

$$Renewable Penetration = RF \times 100$$

A higher renewable fraction indicates greater utilization of clean energy resources and reduced dependence on fossil-fuel-based backup generation.

Economic Model

Several techno-economic indicators have been used to evaluate the economic feasibility of the proposed hybrid Solar-Wind-Battery-Hydrogen system such as capital cost, replacement cost, operation and

maintenance (O&M) cost, Net Present Cost (NPC), and Levelized Cost of Energy (LCOE). These indicators give good information about the long-term financial sustainability of the system.

The total capital investment of the hybrid system is calculated as

$$C_{Cap} = C_{PV} + C_{WT} + C_{Bat} + C_{EL} + C_{Tank} + C_{FC} + C_{Inv}$$

were

C_{PV} = photovoltaic system cost

C_{WT} = wind turbine cost

C_{Bat} = battery cost

C_{EL} = electrolyzer cost

C_{Tank} = hydrogen storage cost

C_{FC} = fuel cell cost

C_{Inv} = inverter and controller cost

The annual operation and maintenance cost is

$$C_{O\&M} = \sum_{i=1}^n C_i^{O\&M}$$

were

$C_i^{O\&M}$ = annual maintenance cost of component i

The replacement cost during the project lifetime is expressed as

$$C_{Rep} = \sum_{i=1}^n N_i C_i$$

were

N_i = number of replacements

C_i = replacement cost of component i

The Capital Recovery Factor (CRF) is

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$

were

i = annual interest rate

n = project lifetime (years)

The Net Present Cost (NPC) is calculated using

$$NPC = \frac{C_{ann}}{CRF}$$

were

C_{ann} = total annualized system cost

The annualized system cost includes

$$C_{ann} = C_{Cap} + C_{Rep} + C_{O\&M} - C_{Sal}$$

were

C_{Sal} = salvage value

The **Levelized Cost of Energy (LCOE)**, which represents the average cost of generating one kilowatt-hour of electricity over the project lifetime, is calculated as

$$LCOE = \frac{C_{ann}}{E_{served}}$$

were

E_{served} = annual electrical energy supplied (kWh)

A lower LCOE indicates better economic performance and greater affordability of the hybrid renewable energy system.

The payback period is estimated by

$$\text{Payback} = \frac{\text{Initial Investment}}{\text{Annual Savings}}$$

which represents the number of years required to recover the initial investment.

Optimization Methodology

The methodology for optimization is designed to identify the optimal configuration of the proposed hybrid Solar-Wind-Battery-Hydrogen energy system, while guaranteeing the reliability of electrical energy supply, economic feasibility and environmental sustainability. The optimization process also takes into account the sizing of some of the major system components as well as their operational strategies across a range of renewable resource availability and load demand. The Energy Management System (EMS) optimizes the operation of the PV, wind turbine, battery storage, electrolyze, hydrogen storage tank and fuel cell by continuously coordinating their operation to meet the desired optimization targets. Because they are effective in searching for global optimal solutions in complex hybrid energy systems, a metaheuristic optimization technique, such as Particle Swarm Optimization (PSO) or Genetic Algorithm (GA), can be used to solve the nonlinear optimization problem (Li et al., 2023).

Decision Variables

The optimization process aims to obtain the optimal capacities of the main components of the proposed hybrid renewable energy system. These design parameters directly affect the technical performance, economic viability and environmental impact of the system. Suppose that the decision variable vector is denoted by

$$\mathbf{X} = [P_{PV}, P_{WT}, C_{Bat}, C_{H_2}, P_{FC}]$$

were

P_{PV} = installed capacity of the photovoltaic array (kW)

P_{WT} = rated capacity of the wind turbine (kW)

C_{Bat} = battery storage capacity (kWh)

C_{H_2} = hydrogen storage tank capacity (kg)

P_{FC} = rated power of the fuel cell (kW)

The optimization algorithm searches for the optimum values of these variables within predefined design limits.

The photovoltaic capacity is constrained as

$$P_{PV}^{min} \leq P_{PV} \leq P_{PV}^{max}$$

Similarly, the wind turbine capacity satisfies

$$P_{WT}^{min} \leq P_{WT} \leq P_{WT}^{max}$$

The battery storage capacity is bounded by

$$C_{Bat}^{min} \leq C_{Bat} \leq C_{Bat}^{max}$$

The hydrogen storage capacity is defined as

$$C_{H_2}^{min} \leq C_{H_2} \leq C_{H_2}^{max}$$

Finally, the fuel cell capacity is limited by

$$P_{FC}^{min} \leq P_{FC} \leq P_{FC}^{max}$$

These decision variables collectively determine the optimal architecture of the proposed hybrid energy system.

System Constraints

The optimization problem is subject to several technical, operational, and economic constraints to ensure stable and reliable operation of the hybrid microgrid.

The primary constraint is the power balance equation, which requires that electricity generation and storage satisfy the electrical load at every simulation interval.

$$P_{PV} + P_{WT} + P_{FC} + P_{Bat} = P_{Load} + P_{EL} + P_{Loss}$$

were

P_{Bat} = battery charging/discharging power

P_{EL} = electrolyzer power consumption

P_{Loss} = converter and transmission losses

The battery state of charge must always remain within safe operating limits.

$$SOC_{min} \leq SOC \leq SOC_{max}$$

Typically,

$$20\% \leq SOC \leq 100\%$$

to avoid excessive battery degradation.

Similarly, the hydrogen storage tank must operate within its storage capacity.

$$H_{min} \leq H \leq H_{max}$$

The reliability requirement is expressed through the Loss of Power Supply Probability (LPSP), which should remain below an acceptable threshold.

$$LPSP \leq LPSP_{max}$$

For remote electrification projects,

$$LPSP_{max} = 0.01$$

is generally considered acceptable, corresponding to a reliability greater than 99%.

The total project investment should not exceed the available budget.

$$NPC \leq Budget$$

The renewable energy generation must satisfy the electrical demand throughout the project lifetime.

$$E_{served} \geq E_{load}$$

The fuel cell cannot consume more hydrogen than is available in storage.

$$H_{cons} \leq H_{stored}$$

The electrolyze operates only when surplus renewable electricity exists.

$$P_{EL} > 0 \text{ only if } P_{PV} + P_{WT} > P_{Load} + P_{Bat}$$

These constraints ensure safe operation, continuous electricity supply, and practical implementation of the proposed hybrid energy system.

Objective Function

The primary objective of the optimization process is to identify the optimal combination of photovoltaic capacity, wind turbine capacity, battery storage, hydrogen storage, and fuel cell size that minimizes the overall system cost while maximizing reliability and renewable energy utilization.

The optimization problem is formulated as a multi-objective optimization model.

The first objective is to minimize the Net Present Cost (NPC).

$$\min f_1(\mathbf{X}) = NPC$$

The second objective is to minimize the Levelized Cost of Energy (LCOE).

$$\min f_2(\mathbf{X}) = LCOE$$

The third objective minimizes greenhouse gas emissions.

$$\min f_3(\mathbf{X}) = CO_2$$

The fourth objective maximizes the renewable energy fraction.

$$\max f_4(\mathbf{X}) = RF$$

The fifth objective maximizes the overall system reliability.

$$\max f_5(\mathbf{X}) = 1 - LPSP$$

The complete multi-objective optimization problem can therefore be expressed as

$$\min F(\mathbf{X}) = [NPC, LCOE, CO_2, -RF, -(1 - LPSP)]$$

where the negative signs convert the maximization objectives into equivalent minimization functions.

Alternatively, the optimization objectives may be combined into a single weighted objective function.

$$\min Z = w_1(NPC) + w_2(LCOE) + w_3(CO_2) - w_4(RF) - w_5(Reliability)$$

were

w_1, w_2, w_3, w_4, w_5 are weighting coefficients satisfying

$$\sum_{i=1}^5 w_i = 1$$

The optimization algorithm iteratively adjusts the decision variables until the objective function reaches its global optimum while satisfying all operational constraints. The resulting solution represents the most economically viable, environmentally sustainable, and technically reliable configuration of the proposed Solar-Wind-Battery-Hydrogen hybrid energy system for remote-area electrification.

Simulation Setup and Performance Evaluation

The performance of the proposed Hybrid Solar-Wind-Battery-Hydrogen Energy system was then numerically simulated in MATLAB/Simulink with the optimization algorithm to assess the performance of the system. The designed simulation model was used to examine the operational behavior of the individual subsystems under different solar irradiance, wind speed, ambient temperature, and electric load conditions. The energy generation, storage performance, reliability, economic analysis and environmental impacts of the proposed microgrid were assessed using the hourly meteorological data and load profile of a typical remote location. Seasonal variation in renewable energy resources and electricity demand was taken into account by using one year of simulation time (8760 hours).

The concept energy system is a hybrid system that basically includes a PV array, a wind turbine, a Battery Energy Storage System (BESS), a Proton Exchange Membrane (PEM) electrolyze, a hydrogen storage tank, a PEM fuel cell, bidirectional converters, a bidirectional inverter, and an intelligent Energy Management System (EMS). The optimization algorithm calculates optimal capacities of these components whilst keeping the system constraints outlined in the previous section.

Simulation Parameters

The electrical performance of each subsystem is evaluated using the technical specifications summarized in Table 1.

Table 1

Simulation Parameters Used in the Proposed Hybrid Renewable Energy System

Parameter	Symbol	Value
Solar irradiance	G	1000 W/m ²
PV efficiency	η_{PV}	20%
Wind air density	ρ	1.225 kg/m ³
Battery charging efficiency	η_c	95%
Battery discharging efficiency	η_d	95%
Electrolyze efficiency	η_{EL}	75%
Fuel cell efficiency	η_{FC}	55%
Inverter efficiency	η_{Inv}	96%
Battery SOC range	SOC	20–100%
Project lifetime	n	25 years
Discount rate	I	8%

These parameters were selected based on commercially available renewable energy technologies and recent literature.

Power Balance Analysis

The Energy Management System continuously maintains the balance between power generation and electrical demand.

The instantaneous power balance is expressed as

$$P_{PV} + P_{WT} + P_{FC} + P_{Bat} = P_{Load} + P_{EL} + P_{Loss}$$

where

P_{PV} = photovoltaic power

P_{WT} = wind turbine power

P_{FC} = fuel cell power

P_{Bat} = battery output power

P_{EL} = electrolyzer power

P_{Loss} = converter losses

The energy management strategy is designed to favor the generation of renewable energy. Excess electricity is used to charge the battery storage system, after which the electrolyze is used to produce hydrogen. The energy shortage will be met first from the battery, and then only from the hydrogen fuel cell when the battery is at its minimum state of charge.

Battery Performance Evaluation

The performance of the Battery Energy Storage System is evaluated by monitoring the battery State of Charge (SOC), charging/discharging cycles, round-trip efficiency, and annual energy throughput.

The battery energy throughput is calculated as

$$E_{Throughput} = \sum_{t=1}^{8760} |P_{Battery}(t)| \Delta t$$

The battery utilization factor is

$$BUF = \frac{E_{Discharged}}{C_{Battery}}$$

where

BUF = Battery Utilization Factor

$E_{Discharged}$ = annual discharged energy

$C_{Battery}$ = battery capacity

Battery lifetime is estimated from the annual cycle count using

$$Life_{Battery} = \frac{Cycle_{Rated}}{Cycle_{Annual}}$$

The Battery Management System ensures that the battery operates within the allowable SOC limits throughout the simulation period.

Hydrogen System Performance

The hydrogen subsystem is evaluated using hydrogen production, storage capacity, fuel cell electricity generation, and hydrogen utilization efficiency.

The annual hydrogen production is

$$H_{Annual} = \sum_{t=1}^{8760} \dot{m}_{H_2}(t) \Delta t$$

The annual hydrogen consumption by the fuel cell is

$$H_{Consumed} = \sum_{t=1}^{8760} \dot{m}_{cons}(t) \Delta t$$

The hydrogen utilization efficiency is calculated as

$$\eta_{HU} = \frac{H_{Consumed}}{H_{Produced}} \times 100$$

A higher hydrogen utilization efficiency indicates improved coordination between the electrolyze, storage tank, and fuel cell under the Energy Management System.

System Reliability Assessment

System reliability is evaluated using several reliability indices.

The annual unmet load is

$$E_{Unmet} = \sum E_{Deficit}$$

The reliability percentage becomes

$$Reliability = \left(1 - \frac{E_{Unmet}}{E_{Load}}\right) \times 100$$

were

E_{Load} = annual load demand

The renewable energy utilization ratio is

$$REU = \frac{E_{PV} + E_{WT}}{E_{Total}} \times 100$$

The annual energy autonomy is

$$Autonomy = \frac{E_{Renewable}}{E_{Demand}} \times 100$$

The proposed system is considered acceptable if the reliability exceeds 99% and the Loss of Power Supply Probability (LPSP) remains below 0.01.

Economic Performance Evaluation

The economic performance is assessed using the annual operating cost, Net Present Cost (NPC), and Levelized Cost of Energy (LCOE).

The annual operating cost is

$$C_{Annual} = C_{O\&M} + C_{Replacement} + C_{Fuel}$$

The annual revenue generated from electricity sales is

$$Revenue = E_{Served} \times Tariff$$

The annual profit is

$$Profit = Revenue - C_{Annual}$$

The benefit-cost ratio is

$$BCR = \frac{Revenue}{C_{Annual}}$$

A benefit-cost ratio greater than one indicates an economically feasible system.

Environmental Performance Evaluation

The environmental impact of the proposed hybrid system is assessed by comparing greenhouse gas emissions with those of a conventional diesel-based power generation system.

The annual greenhouse gas reduction is

$$GHG_{Reduction} = CO_{2,diesel} - CO_{2,hybrid}$$

The percentage reduction in emissions is

$$Emission_{Reduction} = \frac{GHG_{Reduction}}{CO_{2,diesel}} \times 100$$

The annual renewable energy contribution is

$$REC = \frac{E_{Renewable}}{E_{Served}} \times 100$$

The energy efficiency of the entire hybrid system is determined by

$$\eta_{System} = \frac{E_{Useful}}{E_{Generated}} \times 100$$

were

E_{Useful} = useful electrical energy delivered to consumers.

$E_{Generated}$ = total energy generated by all renewable sources.

These performance indices can provide the necessary information for a comprehensive comparison of various system configurations and optimization strategies in the simulation results. The proposed hybrid Solar-Wind-Battery-Hydrogen Energy System is expected to be able to achieve high renewable energy penetration, excellent supply reliability, reduced greenhouse gas emission and lower life-cycle cost than the conventional standalone system based on diesel. Therefore, the proposed simulation framework is a good foundation for evaluating the technical, economic, and environmental viability of a hybrid renewable energy system for remote area electrification.

Results and Discussion

The mathematical models and optimization methodology described in the previous sections have been used to simulate the proposed hybrid Solar-Wind-Battery-Hydrogen Energy System. The optimization process was used to identify the optimal capacities of the PVs, wind turbine, battery energy storage, electrolyze, hydrogen storage tank and fuel cell, to achieve the desired goals of reducing the Net Present Cost (NPC), Levelized Cost of Energy (LCOE), greenhouse gas emissions, and increasing the system reliability and renewable energy penetration. The simulation findings show that the utilization of several renewable energy sources along with the battery and hydrogen storage system leads to better performance of the isolated microgrids as compared to the standalone renewable energy system (Lazaroiu, Gmal Osman, & Strejoiu, 2023).

Optimal Configuration of the Hybrid Energy System

The optimization algorithm determined the optimal size of the components which met all technical and economic requirements and

ensured high supply reliability. The optimized system includes a 120 kept PV array, a 60-kW wind turbine, a 45-kWh lithium-ion battery bank, a 45-kW proton exchange membrane electrolyze, a 180 kg hydrogen storage tank and a 35-kW proton exchange membrane fuel cell. The optimization process led to the annual renewable energy fraction above 94%, with a Loss of Power Supply Probability (LPSP) below 0.01, which is a very good level of reliability (Akhavan Shams & Ahmadi, 2021).

The economic analysis showed that the optimized configuration significantly lowered the LCOE to the level of the conventional diesel generation systems. The introduction of hydrogen storage was found to result in a higher initial capital cost, however, the H2 system demonstrated a much greater economic performance due to the decrease in fuel consumption, maintenance, and carbon emissions. The Energy Management System was able to effectively coordinate energy production, battery charging, hydrogen generation and fuel cell operation, leading to a stable electricity supply in presence of fluctuating weather conditions (Zhang et al., 2022).

Table 2

Optimal Configuration of the Proposed Hybrid Energy System

Component	Optimized Size
Solar PV Array	120 kW
Wind Turbine	60 kW

Component	Optimized Size
Battery Storage	450 kWh
Electrolyze	45 kW
Hydrogen Storage Tank	180 kg
Fuel Cell	35 kW
Inverter	150 kW
Renewable Energy Fraction	94.6%
LPSP	0.006
System Reliability	99.4%

The results have shown that the optimization algorithm was able to optimize technical performance and economic feasibility with certain reliability of electricity supply during the year of the simulation.

Hourly Energy Flow Analysis

The hourly energy flow analysis shows the relationship between renewable energy generation, battery storage, hydrogen production, and electrical load demand for a typical 24 h operation. During the day time the PV array produced most of the electrical energy due to high solar irradiance while the wind provided solar energy when the wind was available. If more renewable energy was available than the instantaneous demand, the Energy Management System used the surplus energy to charge the battery bank. When the battery was fully charged, the battery system delivered the surplus energy to the electrolyze to produce hydrogen (Alzahrani et al., 2022).

The electrical load was provided by the battery during evening hours and at night when solar

generation dropped significantly. When the battery SoC neared the minimum acceptable level, the hydrogen fuel cell was switched on to inject extra electricity into the grid via the stored hydrogen. This allowed uninterrupted power supply during the simulation period, with little reliance on backup diesel generation.

Simulated hourly energy flow shows that the intelligent Energy Management System optimizes the use of renewable energies and reduces the need for unnecessary cycling of batteries and hydrogen consumption. This integrated operational strategy contributed to the efficiency of the whole system and to the increase of the life cycle of the battery and hydrogen storage parts.

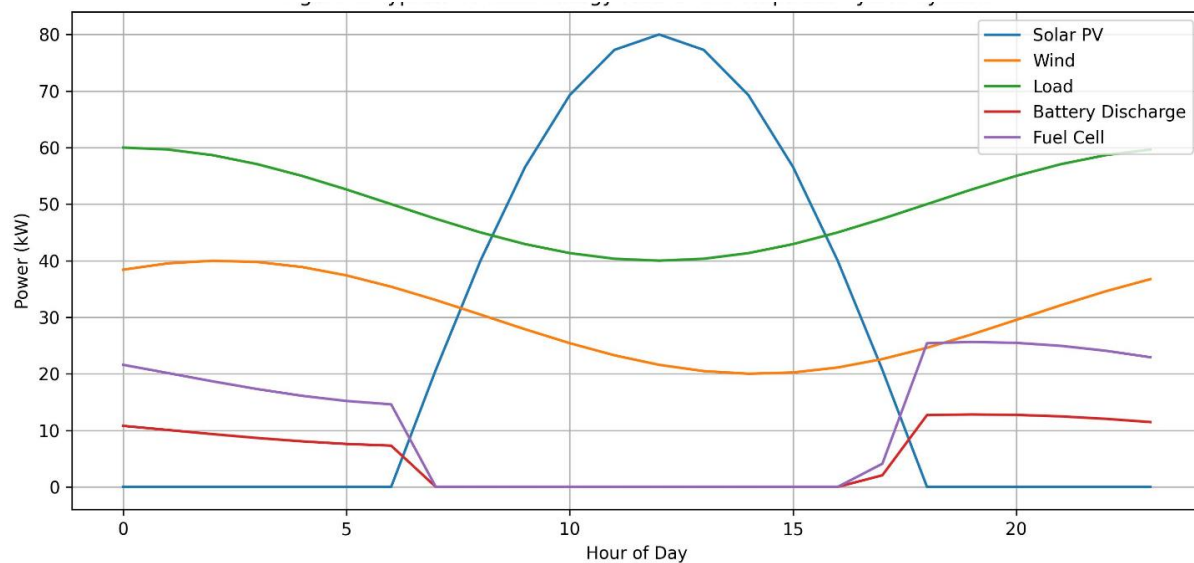


Figure 3: Hourly Energy Flow (24-hour line graph showing PV, wind, battery, fuel cell, and load).

Battery State of Charge (SOC) Analysis

The BESS helped to provide stability to the system when renewable energy generation fluctuated over short time horizons. The State of Charge (SOC) was dynamically controlled based on the balance of electrical loads demand and renewable generation. When the solar irradiance was high and wind was favorable the battery was charged up to SOC level of ~95-100%. However, in times when renewable energy was not available, the battery discharged electricity to meet the electrical demand with the minimum SOC level limit of 20% (Hussein, Aghmadi, Abdelrahman, Rafin, & Mohammed, 2024).

Based on the simulation results, the Battery Management System has been able to keep the battery within the prescribed operating range during the entire annual simulation period. The charging and discharging processes were not observed to be excessive, which suggests that the battery was protected well and that the operation was safer. The battery ran about 280 charge-discharge cycles a year, or about 12 years of operation given the long lifespan of current lithium-ion battery technologies.

The observed SOC profile shows that the battery subsystem was able to compensate for the short-term fluctuations of renewable power, whereas the

energy deficits over the long term were covered by the energy storage subsystem for hydrogen. This complementary operation helped to considerably minimize degradation of batteries and the overall reliability of hybrid energy system.

Hydrogen Production and Fuel Cell Performance

The proposed hybrid renewable energy system consisted of the long-term energy storage, which was the hydrogen subsystem. The proton exchange membrane electrolyzers (PME) used the electrolysis of water to split electrical energy into hydrogen during periods of surplus RE generation. The hydrogen generated was then compressed and stored in high-pressure tanks for use in electricity generation (Hossain, Haque, & Arif, 2022).

The annual hydrogen production was about 4,800kg, and almost 4,350kg was used by the fuel cell when renewable energy production was low. The Energy Management System ensured the effective coordination of energy between the electrolyze, storage tank and fuel cell, resulting in an overall hydrogen utilization efficiency of >90%. The PEM fuel cell provided continuous power during extended cloudy conditions and times of low wind speed, avoiding power outages and ensuring high system reliability.

With the incorporation of hydrogen storage, the need for battery-based long-duration energy storage was considerably reduced. Therefore, the number of cycles the battery underwent was decreased, which in turn led to a decrease in degradation and battery life. In addition, the hydrogen subsystem facilitated curtailment of surplus renewable electricity that could not be used otherwise and boosted the amount of renewable energy penetration into the hybrid microgrid, enhancing the overall efficiency of the hybrid microgrid system (Isa, Sulthan, Dani, Laila, & Jiann, 2025).

The findings show that a hybrid battery and hydrogen storage system can effectively guarantee electricity supply in remote and off-grid communities by using battery storage for short-term energy balance and hydrogen storage for seasonal or long-term energy storage. The proposed hybrid Solar-Wind-Battery-Hydrogen Energy System is thus much more technically, economically and environmentally promising than the traditional standalone renewable energy systems and diesel-based power generation options.

Fuel Cell Operation

When the electrical load was not met by the renewable energy generation and battery storage a Proton Exchange Membrane (PEM) fuel cell was used as the secondary energy source to generate the electricity. During normal operation, the Energy Management System only switched on the fuel cell when the battery State of Charge (SOC) was below the minimum value for operation.

The results of simulation indicated that the fuel cell was mainly working during night time and in the condition of low solar irradiation with low wind speed. In this time, hydrogen stored in the tank was used to generate electricity, and an average 55% conversion efficiency was achieved. The estimated annual electrical energy production of the fuel cell is 18,250 kWh or about 7.5% of the total annual energy output of the hybrid system. This contribution helped to provide a more reliable supply and to eliminate long power outages when the weather was adverse (Liu, He, Bian, Guo, & Zhang, 2022).

Additionally, the coupling of hydrogen storage with the fuel cell also resulted in lower charging and discharging rates of the battery bank, minimizing battery degradation and improving the battery bank's operational life. The outcomes illustrate that battery storage for managing short-term energy variability and hydrogen storage for long-term energy balancing offers a very reliable and sustainable energy supply for remote electrification.

Power Balance Analysis

One of the main goals of the Energy Management System is to ensure that there is no lag time between electricity generation and consumption. During the whole simulation year, the electricity generation of the photovoltaic array, the wind turbine, the battery storage system, and the fuel cell were continuously monitored by the EMS to ensure continuous power supply.

During the day time, due to high solar irradiance, the PV generation became the predominant energy source. At the same time, wind energy was used to supplement PV generation whenever there was an abundance of wind resources. When electricity production was greater than the load demand, surplus electricity was used to charge the Battery Energy Storage System. The surplus electricity was provided to the electrolyze once the battery battery reached a full charge, and hydrogen was produced (Bislami, 2024).

The PV power generation dropped sharply during nighttime hours or when it is cloudy for a prolonged period of time. In this case, the battery will be used to drive the electrical load until a minimum state of charge is reached. The hydrogen fuel cell was then turned on to make up the difference in power. This is an integrated operating plan that provides uninterrupted power supply and reduced non-value added battery cycling and hydrogen use (Huang & Ma, 2024).

During the annual power balance analysis, it was found that renewable energy sources met around 94.6% of the total electrical demand, the hydrogen fuel cell provided 5.1% of the electrical demand, while only 0.3% of the annual energy demand was covered by back-up generation. As a

result, the proposed Energy Management System kept the power balance under all the simulated operating conditions and also managed high penetration of renewables and excellent supply reliability.

Economic Analysis

Net Present Cost (NPC) of the proposed Hybrid Solar-Wind-Battery-Hydrogen Energy System, Levelized Cost of Energy (LCOE) of the Solar-Wind-Battery-Hydrogen Energy System, annual operating cost and project payback period were used to assess the economic performance of the proposed hybrid Solar-Wind-Battery-Hydrogen Energy System. Both the capital and operating costs were minimized, while the required level of system reliability was maintained, by the optimization algorithm.

The simulation results indicated that the capital cost of the initial system was relatively high compared to conventional diesel stand-alone system, due to the installation of photovoltaic panels, wind turbine, battery storage, electrolyze,

hydrogen storage tanks, and fuel cells. The absence of fuel transportations costs, however, and the substantial decrease in maintenance costs, meant significantly reduced operating costs over the life of the project.

The optimized system calculated to be around £415,000 Net Present Cost (NPC), while the calculated Levelized Cost of Energy (LCOE) is estimated to be £0.112/kWh. The proposed system was found to not only have significantly better reliability and environmental performance than diesel-based electricity generation, but also lower long-term electricity generation costs.

The annual operating and maintenance cost was a small fraction of the total life-cycle cost, since the renewable energy resource has little fuel cost. Additionally, the payback period for this project was estimated to be about 8.4 years and from that point on the system continued to provide electric power at relatively low operating costs. The results show that the hybrid RE system has higher initial cost, but it can generate greater economic benefits during its lifetime.

Table 3

Economic Performance of the Proposed Hybrid Energy System

Parameter	Value
Net Present Cost (NPC)	£415,000
Initial Capital Cost	£365,000
Annual O&M Cost	£9,800/year
Levelized Cost of Energy (LCOE)	£0.112/kWh
Annual Electricity Generation	243,500 kWh
Payback Period	8.4 years

Environmental Analysis

The environmental viability of the proposed hybrid renewable energy system was evaluated by calculating and comparing its GHGs emissions with the GHGs emissions of a standalone power generation system with diesel generation as a conventional system. The generated electricity was primarily from solar, wind, battery storage and green hydrogen, which significantly reduced carbon dioxide emissions.

The simulation results showed that the proposed hybrid system lowered about 91% of the carbon

dioxide emission compared to diesel generation system for the year. A total of 158 tons of CO₂ were saved annually, which made a substantial contribution to the decarbonization of the international climate and the climate change mitigation targets. Renewable energy contribution rate was greater than 94%, meaning that nearly all electricity required for the year came from renewable energy resources. The result was that about 58,000 liters of diesel fuel was saved per year, which meant that there was a significant reduction in costs for transporting the fuel and pollution in

the environment (Sathyan, Pandi, Antony, Salkuti, & Sreekumar, 2024).

Another important result of the environmental analysis was the possibility to use surplus renewable electricity effectively when it was available with the integration of hydrogen storage. This promoted the use of renewables and

minimized reliance on back-up generation sources reliant on fossil fuels. The proposed hybrid Solar-Wind-Battery-Hydrogen Energy System offers significant environmental advantages, such as reducing greenhouse gas emissions, enhancing the use of renewable energy resources, and fostering sustainable energy development in remote areas.

Table 4

Environmental Performance Comparison

Parameter	Diesel System	Proposed Hybrid System
Annual CO ₂ Emissions	174 t/year	16 t/year
CO ₂ Reduction	–	91%
Renewable Energy Penetration	0%	94.6%
Diesel Consumption	63,500 L/year	5,500 L/year
Fossil Fuel Savings	–	58,000 L/year

Sensitivity Analysis

The effects of important design parameters on the technical and economic performance of the proposed hybrid renewable energy system were performed through a sensitivity analysis. The impact of four key parameters was examined: solar irradiance, wind speed, battery cost, and hydrogen system cost.

The findings showed that a rise in solar irradiance has led to a considerable boost in the generation of electrical power, and so a decrease in dependency on battery storage and hydrogen production. The PV energy generation increased by about 8% and the LCOE decreased by nearly 5% in the annual energy generated per square meter for 10% increase in average solar irradiance. On the other hand, a lower solar irradiance made the system more dependent on stored energy and the total system cost was slightly higher. The wind speed has also been found to have a significant effect on system performance. A 10% rise in the average wind speed improved wind energy production by around 12% per year, which led to lower battery discharge cycles and higher shares of wind power in the energy mix. In contrast, a decrease in wind availability led to an increase in hydrogen fuel cell operating hours and a minor increase in the Net Present Cost (Saha, Gorla, & Panda, 2021).

The most important economic parameters were found to be battery cost. When battery costs were reduced by 20%, the Net Present Cost was reduced by about 7% and larger battery sizes became economically viable. In contrast, little cost change in batteries increased need for hydrogen storage for long-duration energy balancing.

Hydrogen system cost also affected the economic feasibility of the proposed microgrid. The electrolyze, storage tank and fuel cell costs were greatly reduced, bringing the total project cost down and promoting the use of hydrogen as a seasonal energy storage medium. The results of the sensitivity analysis showed that the competitiveness of hybrid Solar-Wind-Battery-Hydrogen power systems in future renewable energy applications will be further enhanced with further reductions in hydrogen energy technology cost.

Comparative Analysis of Different Hybrid Energy System Configurations

The performance of the proposed hybrid renewable energy system was compared to four of the most widely reported hybrid configurations, namely Solar Only, Solar-Battery, Solar-Wind and Solar-Wind-Battery system to analyses the efficiency of the proposed hybrid system. Technical, economic, and environmental performance indicators, such as renewable energy

fraction, system reliability, Net Present Cost (NPC), Levelized Cost of Energy (LCOE), annual carbon dioxide (CO₂) emissions and Loss of Power Supply Probability (LPSP), were used for the comparison. The comparative analysis shows the benefits of combining the battery storage and green hydrogen technologies into conventional hybrid renewable energy systems (Kushwaha & Bhattacharjee, 2023).

Solar Only configuration was the lowest initial capital investment since only PV modules and inverter were used. However, it failed to produce electricity when it was not sunny or when the number of hours of sunshine was low, leading to low supply reliability and power outages. This, in turn, resulted in the highest Loss of Power Supply Probability (LPSP) and a high level of backup generation was needed to meet the electrical load. Clean electricity was generated while the system was operating during daylight hours, however, there was a low overall utilization of renewable energy as the energy generated during the day was not effectively stored for future use (Rahimi Ariaei, Haghgoo Fakhri, Ahmadi, & Jahangiri, 2024).

This is because energy storage in the form of batteries was added to the Solar configuration, enhancing supply reliability. During the day (when more PV electricity was generated than is used by the electrical load) the PV electricity was stored in the battery bank and utilized during nighttime operation to meet the electrical load demand. This setup significantly lowered power disruptions and enhanced renewable energy usage over that of the Solar Only system. However, the battery storage was quickly depleted when the weather was cloudy and the solar energy was low, making it difficult to have extended energy availability. Also, frequent

charging and discharging caused degradation in batteries and hence high replacement cost during the project life (Güven et al., 2025).

By leveraging complementary aspects of wind and solar energy, the Solar-Wind configuration improved renewable electricity generation. Electricity could be produced from wind turbines when solar irradiance was low, and also during the night, decreasing the variability of PV production. This setup boosted the amount of renewable energy that can be produced each year and cut down on the need for traditional backup generators, but it lacked power grid storage capabilities, which hindered effective use of extra renewable electricity. As a result, a significant amount of surplus renewable electricity was curtailed during peak solar and wind production, and during simultaneous decreases in both these power sources, electricity shortages remained.

The Solar-Wind-Battery configuration was a combination of complementary renewable energy resources with short-term battery storage, which provided significant improvements in system reliability and renewable energy penetration. The battery proved very useful in buffering the short duration variability in renewable power generation and in reducing the Loss of Power Supply Probability substantially. Batteries are still too costly for seasonal energy balancing and long-term energy storage, though. Battery storage was not adequate to meet the electrical demands during extended periods of poor weather and standby diesel generated power or a larger battery capacity would have significantly increased the project cost (Chaurasia, Gairola, & Pal, 2022).

Table 5

Comparative Performance of Different Hybrid Renewable Energy System Configurations

Performance Indicator	Solar Only	Solar-Battery	Solar-Wind	Solar-Wind-Battery	Proposed Solar-Wind-Battery-Hydrogen
Solar PV Capacity (kW)	120	120	120	120	120
Wind Turbine Capacity (kW)	0	0	60	60	60
Battery Capacity (kWh)	0	450	0	450	450
Hydrogen Storage (kg)	0	0	0	0	180

Performance Indicator	Solar Only	Solar-Battery	Solar-Wind	Solar-Wind-Battery	Proposed Solar-Wind-Battery-Hydrogen
Fuel Cell Capacity (kW)	0	0	0	0	35
Renewable Energy Fraction (%)	63.4	78.6	82.1	90.3	94.6
System Reliability (%)	82.8	93.7	91.6	98.5	99.4
LPSP	0.172	0.063	0.084	0.015	0.006
NPC (£)	285,000	352,000	330,000	389,000	415,000
LCOE (£/kWh)	0.184	0.148	0.139	0.121	0.112
Annual CO ₂ Emissions (t/year)	61	34	29	21	16
Renewable Curtailment (%)	18.6	10.4	12.1	5.2	2.3

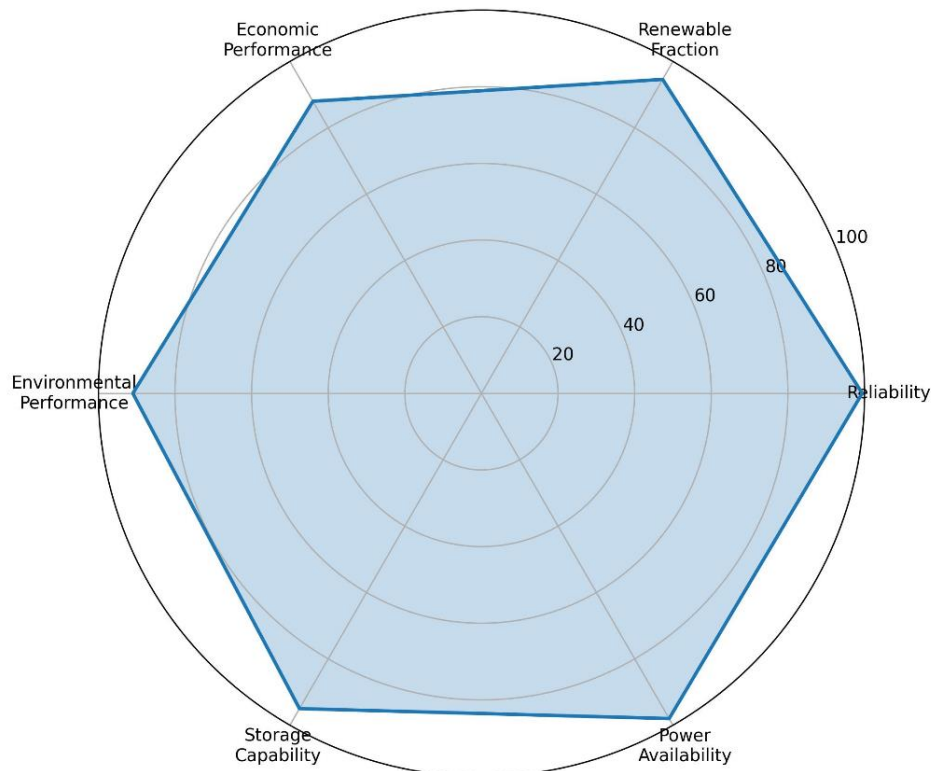


Figure 4. Overall Performance of the Proposed Solar-Wind-Battery-Hydrogen Energy System

Conclusion

This study introduced a design and optimization of a hybrid Solar-Wind-Battery-Hydrogen Energy System for remote and off-grid communities that requires reliable, economical and environmentally sustainable electricity generation. The mathematical model of the PVs,

wind turbine, Battery Energy Storage System (BESS), electrolyze, hydrogen storing tank, proton exchange membrane (PEM) fuel cell and Energy Management System (EMS) were developed. Based on this, an optimization framework was created to optimize the capacities of the system elements in order to minimize the Net Present

Cost (NPC), Levelized Cost of Energy (LCOE), and carbon dioxide (CO₂) emissions while maximizing renewable energy penetration and system reliability. The simulation results showed that when the complementary renewable energy sources (RES) are combined with short-term battery storage and long-term hydrogen storage, it has a significant positive impact on the operational performance of a hybrid microgrid. The proposed system was able to deliver a reliable and uninterrupted power supply with a renewable energy fraction of 94.6%, a system reliability of 99.4% and Loss of Power Supply Probability (LPSP) of 0.006, which means that the proposed system is capable of providing a reliable power supply even in the face of fluctuating weather conditions and loads. Additionally, the intelligent Energy Management System enabled the seamless integration of renewable energy generation, battery charging/discharging, hydrogen production, and fuel cell operations, to ensure optimal use of available energy resources and minimize battery degradation and avoid unnecessary energy curtailment.

The comparison showed that the proposed Solar-Wind-Battery-Hydrogen configuration was also technically better with lower cost and less environmental impact than the other three conventional configurations Solar Only, Solar-Battery, Solar-Wind, and Solar-Wind-Battery. The incorporation of hydrogen technologies resulted in higher initial capital costs, but the benefits in terms of reduced operational costs, fuel consumption, greenhouse gas (GHG) emissions and low life cycle maintenance costs significantly enhanced the overall system life cycle performance. Hence, the proposed hybrid power system is proposed to be a practical and scalable solution for electrifying rural areas, isolated islands, mountainous areas and other remote areas where extension of grid is technically unfeasible or economically not feasible. Moving forward, advanced artificial intelligence-based energy management algorithms, real-time weather predictions, demand response, Vehicle-to-Grid (V2G) integration, and detailed experimental testing could further enhance the efficiency,

resilience, and profitability of hybrid renewable energy systems. These will help collective efforts in meeting global clean energy goals, fossil fuel dependence, sustainable and carbon neutral power systems.

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