Journal of Engineering and Technology Management 73 (2024)

Design and Optimization of a Hybrid Solar-Hydrogen Microgrid for Off-Grid Rural Electrification in Bhopal, India

Shankar Prasad Ghosh
Department of Electrical and Electronics Engineering
IES University, Bhopal, India

Sonali Nandanwar
Department of Electrical and Electronics Engineering
IES College of Technology, Bhopal, India

G. K. Pandey
Department of Electrical and Electronics Engineering
IES University, Bhopal, India

Abstract— **Access to reliable and sustainable electricity is a fundamental requirement for socio-economic development. In off-grid rural areas, traditional power sources often fall short in meeting the growing demand for electricity. This article explores the design and optimization of a cutting-edge solution: a hybrid solar-hydrogen microgrid. This innovative approach aims to provide a reliable and sustainable energy source for off-grid rural electrification in Bhopal, India. The entire hybrid microgrid system was simulated using HOMER Pro software. A pilot microgrid was deployed in a small off-grid village near Bhopal to validate the simulation results.**

*Keywords- **Microgrid system, renewable energy, hydrogen production, electrolyzer, fuel cell, machine learning, demand-side management.***

I. INTRODUCTION

Access to reliable and sustainable electricity is not only a modern convenience but a catalyst for socio-economic development. Unfortunately, many off-grid rural areas, such as those in Bhopal, continue to grapple with the challenges of inadequate power supply, hindering progress and quality of life. In response to this critical need, this article delves into the design and optimization of a cutting-edge solution: a hybrid solar-hydrogen microgrid. This innovative energy system aims to not only overcome the limitations of traditional power sources but to provide a holistic and sustainable approach to rural electrification.

Bhopal, like many other regions with limited access to conventional power infrastructure, stands at the crossroads of technological innovation and social progress. The convergence of solar and hydrogen technologies into a hybrid microgrid represents a paradigm shift in the approach to rural electrification. Bhopal's abundant sunlight serves as an invaluable resource, and harnessing this energy through photovoltaic panels is the first step towards creating a sustainable power source. However, the intermittent nature of solar power demands a sophisticated and efficient energy storage system, making hydrogen an ideal companion in this endeavor.

The choice of Bhopal as the focal point for this endeavor is strategic, given its unique set of challenges and opportunities. In the heart of India, Bhopal presents a microcosm of the global struggle for rural electrification. The region's geographic diversity, coupled with its cultural richness, underscores the urgency of finding solutions that align with the principles of sustainability and resilience. Traditional power infrastructure struggles to reach remote pockets of the city, leaving large segments of the population in the dark, figuratively and literally. As we explore the intricacies of designing and optimizing a hybrid solar-hydrogen microgrid, we simultaneously address the pressing need for energy access and environmental stewardship, aiming to pave the way for a brighter, cleaner, and more equitable future for Bhopal and beyond. Different aspects related to this hybrid microgrid system are illustrated in Table I.

TABLE I. DIFFERENT ASPECTS OF MICROGRID

Aspect	Description
Microgrid	A decentralized energy system capable of functioning autonomously or in coordination with the primary grid, harnessing diverse renewable energy sources like solar, wind, and hydro.
Renewable energy integration	The process of connecting and managing distributed energy resources (e.g. solar, wind, biomass) to the microgrid system
Cost-effectiveness	The ability to optimize energy consumption, reduce total cost for energy, and unlock new revenue streams through grid ancillary services
Sustainability	The ability to reduce CO_2 emissions, maximize the utilization of renewable power generation, and provide local access to power for remote and/or non-electrificated communities
Reliability	The ability to ensure continuous power supply, even when the main grid is down, by switching between stand-alone or grid-connected modes
Case study	An example of a microgrid system deployed at a glass factory in Bhopal, Madhya Pradesh, India, to overcome the challenges of frequent outages and high energy costs

In this context, the collaborative efforts of Futuristic Academy and Tamralipta Mahavidyalaya exemplify the power of partnerships in addressing complex challenges. The fusion of academic expertise, research capabilities, and on-the-ground understanding enhances the potential impact of the proposed microgrid. It establishes a model where academia, industry, and local communities converge to co-create sustainable solutions tailored to the unique needs of Bhopal.

II. RELATED WORK DONE

Ackermann et al. [1], in their research paper, introduce a detailed methodology integrating various software tools to assess distributed renewable energy, particularly wind energy, within an 11 kV distribution network The approach employs an economic optimization tool to assess multiple distributed generation options, forming a framework for technical tools to analyse energy utilization and power quality. Simulations show that properly sized and sited embedded wind generation, supplying active and reactive power, significantly improves power quality, adding substantial economic value.

Akella et al. [2] present an integrated renewable energy system (IRES) model designed for rural electrification in remote regions. By analyzing the energy demand of the specific area, the model is optimized using LINDO software, which determines that the optimized model is the optimal solution for fulfilling the area's energy requirements.

Alam et al. [3] have created a system dynamics model for an integrated energy system tailored to farming, which includes various real-world characteristics like feedback loops, non-linearity, time delays, etc.

In another research paper, Alam et al. [4] make an assessment of household-biomass fuel consumption impact on environmental degradation resulting from deforestation. A quantitative dynamic simulation model for rural household-biomass fuel consumption is developed and simulated by incorporating alternative policies with several variables to assess the system response.

In [5], the authors introduced Huq's model for integrated rural energy systems, utilizing Forrester's system dynamics methodology for policy planning. This model aims to optimize the production of edible, saleable, and flammable outputs by integrating crop production, biogas generation, and rural forestry and agro-based industries, ultimately enhancing the quality of life.

Ashenayi et al. [6] proposed a method for designing an Integrated Renewable Energy System (IRES) that focuses on the loss of power-supply probability (LPSP) as a crucial system parameter and aims to minimize the initial capital investment. Additionally, they created a computer program named IRES to serve as a design tool.

In his research, Banerjee [7] presents a review of different technological options available for distributed generation in India. The study evaluates the most cost effective choice while considering different non-renewable options like IC engines, microturbines and fuel cell and different renewable options like wind, solar photovoltaic, biomass gasification and bagasse cogeneration.

Bekele et al. [8] conducted a feasibility study on providing electricity to a remote model community in Ethiopia using a solar-wind hybrid system, independent of the main electricity grid. Utilizing HOMER software for their analysis, they presented a list of feasible power supply systems, accompanied by sensitivity diagrams that illustrate the impact of wind speeds, PV costs, and diesel prices.

In their article, Bernal et al. [9] has performed an economical study on a gird-connected PV solar energy installations for identifying the profitability based on net present values and pay-back period. Potential impact of Kyoto Protocol has also been included in their study.

In a different study, Bernal et al. [10] reviewed the simulation and optimization techniques and tools necessary for designing various stand-alone hybrid renewable energy systems. Typical configurations of these systems include PV-Wind-Battery and PV-Diesel-Battery, with lead-acid batteries commonly used for energy storage. The authors provided a simulation tool to solve the optimization problem, aiming to minimize the Net Present Cost (NPC) or Levelized Cost of Energy (LCE) for these systems.

In their paper, Veronika et al. [11] propose a bi-level equilibrium model to evaluate how various regulatory frameworks affect storage and network investment in distribution networks. The model features a regulated distribution system operator who makes decisions about network investment and operations, while considering the storage investment and operational decisions of private agents. The study explores regulatory measures like curtailing renewable production, implementing a network fee based on maximum renewable feed-in, and providing subsidies for storage investment.

Vendoti et al. [12] in their project have proposed a cost effective power solution for a hybrid renewable energy system. A comparative analysis has been performed between Genetic Algorithm and Homer Pro Software for reduction of the Total System Net Preset Cost (TNPC), Cost of Energy (COE), unmet load and CO_2 emissions.

In their article, Rovick et al. [13] present an integrated approach for optimally sizing and operating an off-grid hybrid renewable energy microgrid (HREM) specifically designed for rural agricultural communities in the Southern Philippines. This microgrid comprises run-of-the-river hydropower, photovoltaics (PV), a diesel generator, and a battery energy storage system (BESS). They employ multi-objective particle swarm optimization (MOPSO) combined with a proposed multi-case power management strategy. The effectiveness of the HREM design was assessed, providing valuable insights that could aid in the electrification of the region.

The sizing and optimization of a micro-grid with battery storage, supplying the load to an economic activity zone (EAZ) in Tunisia, have been presented in the research paper of Khlifi et al. [14]. They utilized a genetic algorithm in MATLAB to optimize three objective functions: Greenhouse Gas emissions (GHG), Life Cycle Cost (LCC), and Embodied Energy (EE), for three predetermined values of loss of power supply probability (LPSP).

Bhattacharyya et al. [15] provide an overview of various methodologies employed in off-grid electrification projects. They identify the characteristics of each approach and discuss their advantages and disadvantages. The article examines a substantial amount of pertinent literature, including techno-economic feasibility studies, analytical research on methodological applications, and practice-oriented publications.

In their paper, MacA et al. [16] explore the technical challenges associated with using hydrogen storage in conjunction with a PEM electrolyser and PEM fuel cell to maintain a reliable electricity supply, particularly when dealing with intermittent energy sources like solar photovoltaic. They advocate for metal-hydride storage, comparing its energy density to that of Li-ion batteries, and conclude that metal-hydride storage can achieve a significantly smaller package.

Arsalis et al. [17] conducted a study on a decentralized, hybrid photovoltaic-solid oxide fuel cell system aimed at providing energy to a commercial building. They used real load profiles and solar/weather data to assess the system's thermoeconomic performance. The findings revealed that this system reduces the unit cost of electricity by approximately 50% and cuts CO_2 emissions by about 36% compared to traditional methods. This improvement is attributed to advancements in photovoltaic and fuel cell technologies, which have resulted in longer lifespans and reduced specific costs, enabling more cost-effective power and heat generation.

In another study [18], the levelized cost of energy (LCOE) and CO_2 emissions were addressed using the ε-constraint method and particle swarm optimization (PSO) algorithm. Researchers developed cost-emissions Pareto fronts for various hybrid renewable energy system (HRES) configurations to assess their potential for off-grid applications. They examined combinations of photovoltaic panels, wind turbines, batteries, hydrogen, and diesel generators. The hydrogen-based system included an electrolyser, a pressurized H_2 storage tank, and a fuel cell. The results indicated that energy storage devices are essential for reducing fossil fuel dependency, with hydrogen storage being particularly important for enhancing renewable energy system penetration and controlling energy costs in off-grid areas.

III. PROPOSED ARCHITECTURE

The hybrid solar-hydrogen microgrid involves integrating solar panels to generate electricity, an electrolyser to split water into hydrogen and oxygen, and a fuel cell to convert hydrogen back into electricity. A schematic diagram of the microgrid system is shown in Fig. 1.

Efficient solar panels capable of converting sunlight into electricity are chosen. These panels are used to power the electrolyser. The electrolyser splits water (H_2O) into hydrogen (H_2) and oxygen (O_2) using the electricity generated by the solar panels. Proton Exchange Membrane (PEM) electrolysers are used for this purpose due to their efficiency and scalability.

Since hydrogen is a gas, it needs to be stored in a safe and efficient manner. Storage facilities with advanced compression and liquefaction technologies are used. A PEM fuel cell with high efficiency and low operating temperatures is used for converting hydrogen back into electricity.

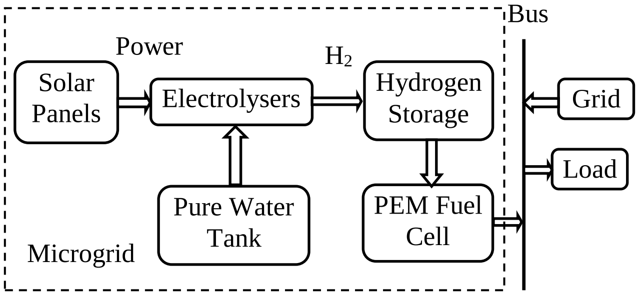

Fig. 1. Architecture of the hybrid solar-hydrogen microgrid

The system is designed to efficiently transfer hydrogen from the electrolyser to the fuel cell. These design steps involve plumbing, valves, and control systems to regulate the flow of hydrogen.

At the final stage, the entire components are integrated into the microgrid system and the system is tested under various conditions to optimize its performance and efficiency. This involves adjusting parameters such as solar panel orientation, electrolyser and fuel cell operating conditions, and hydrogen storage methods. Some additional factors like efficiency, cost-effectiveness, and environmental impact are taken into account throughout the design process.

IV. HYDROGEN PRODUCTION

The process of hydrogen production and storage is the most important stepping stone in the entire course of energy production and consumption within the hybrid solar-hydrogen microgrid system. As we navigate through the details of this phase, it becomes apparent that the efficiency and reliability of hydrogen production are paramount to the success of the entire off-grid electrification initiative.

The two most common methods for producing hydrogen are steam-methane reforming and electrolysis (splitting of water with electricity) [19].

Large-scale hydrogen production from fossil fuels is a well-established technology. A typical configuration is depicted in Fig. 2. The initial phase of the process frequently involves desulfurization of the feedstock, as sulfur can be detrimental to the catalysts used in subsequent stages. Following desulfurization, syngas is generated through steam reforming. Subsequently, the shift reaction is employed to reduce the concentration of CO, although it releases considerably less heat compared to the reforming or decomposition reactions.

Following the shift reaction, the gas stream contains significant amounts of carbon dioxide mixed with hydrogen, necessitating a CO_2 removal step. The final stage in the hydrogen production process involves the removal of residual CO, which could adversely affect the catalyst during the subsequent ammonia synthesis process.

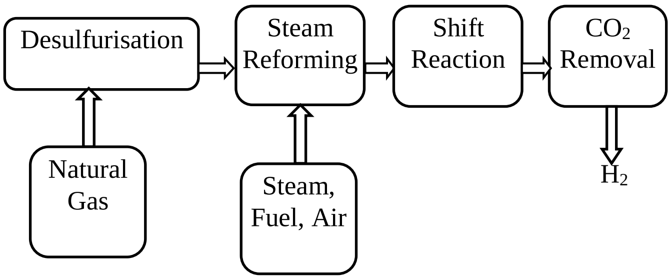

Fig. 2. Typical hydrogen production process

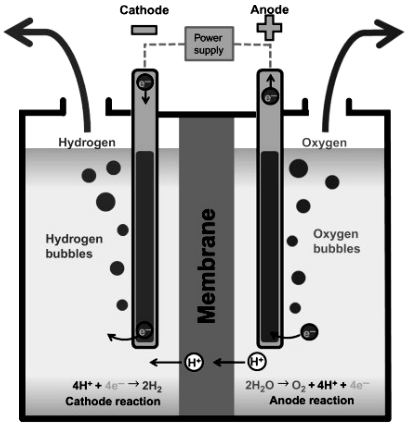

Fig. 3. Schematic diagram of an electrolysis cell

The electrolysis process for hydrogen production is depicted in Fig. 3. An electrolysis cell has two electrodes: a negatively charged cathode and a positively charged anode, both immersed in an acidic electrolyte rich in hydrogen ions (H+). When a voltage of at least 1.23 V is applied, the hydrogen ions move to the cathode, where they combine with electrons to form gaseous hydrogen. At the anode, water molecules react to produce oxygen and release additional hydrogen ions into the electrolyte.

In our work, the solar electrolysis process is used for hydrogen production (Fig. 4). The electrolyser, a sophisticated device central to hydrogen production, harnesses the surplus electricity generated during peak sunlight hours to initiate the electrolysis process, splitting water molecules into hydrogen and oxygen. The efficiency of the electrolyser directly influences the overall effectiveness of the microgrid, emphasizing the importance of utilizing state-of-the-art technologies [20].

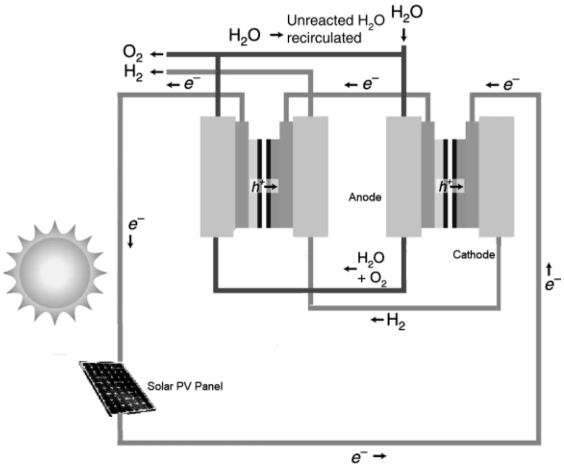

Fig. 4. Schematic diagram of a solar electrolyser

The microgrid's design takes into account the variability of energy generation from solar panels, aligning the hydrogen production process with the ebb and flow of solar power availability. Advanced control systems and machine learning algorithms optimize the operation of the electrolyser, ensuring it responds dynamically to the community's energy demands. This adaptive capability enhances the microgrid's resilience, making it well-suited for the unpredictability of off-grid environments.

V. HYDROGEN STORAGE

As the electrolyser generates hydrogen, the question of storage becomes paramount. The surplus hydrogen produced during periods of high solar power availability needs to be efficiently stored for later use. Hydrogen storage facilities, equipped with advanced compression and liquefaction technologies, address this challenge. These facilities maintain the stability and integrity of the stored hydrogen, ensuring minimal losses and maximizing its availability for energy conversion when needed.

The choice of hydrogen as an energy carrier presents unique advantages. Its high energy density and ability to be stored for extended periods make it an ideal solution for bridging the gaps in intermittent renewable energy sources.

Hydrogen energy used for electrical energy storage is generally straightforward [21]. Excess or off-peak electrical energy is used to produce hydrogen, which is then stored. When there is a demand for electricity, this stored hydrogen is utilized as fuel for power generation. Although the concept is simple and the necessary technology exists, challenges remain in the production, storage, and power generation stages. Overcoming these challenges is crucial for scaling up this energy storage solution and advancing towards a low-carbon economy. Fig. 5 illustrates a basic hydrogen energy storage system integrated with renewable energy sources.

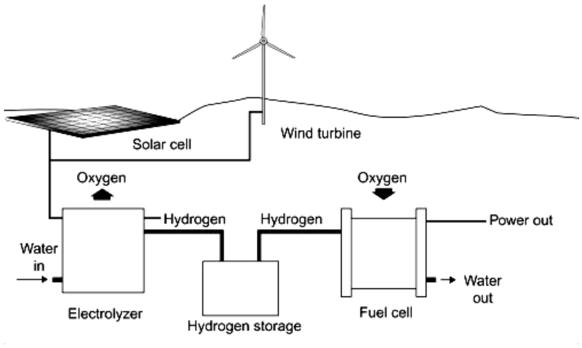

Fig. 5. Hydrogen energy storage system

The storage infrastructure, carefully integrated into the microgrid, becomes a reservoir of energy capable of meeting the community's needs during low solar generation periods or high energy demand.

Moreover, the hydrogen storage system serves as a buffer, enhancing the reliability and stability of the microgrid. It acts as a bridge between energy generation and consumption, smoothing out the inherent fluctuations in renewable energy production. This buffering effect ensures a consistent and uninterrupted power supply, addressing the challenges posed by the intermittent nature of solar power.

The hydrogen production and storage phase within the hybrid solar-hydrogen microgrid not only complements solar power integration but also elevates the entire system to new levels of efficiency and reliability. The careful orchestration of electrolysis, hydrogen storage, and adaptive control systems transforms the microgrid into a resilient energy infrastructure, poised to bring sustainable electrification to the rural communities of Bhopal. The journey continues as we delve into the final stage: the utilization of fuel cells for energy conversion.

VI. FUEL CELL FOR ENERGY CONVERSION

In the grand symphony of the hybrid solar-hydrogen microgrid, fuel cells play a central role in the final act of energy conversion. As we explore this phase, the seamless integration of fuel cell technology into the microgrid unfolds, highlighting its transformative impact on translating stored hydrogen back into electricity.

Fuel cells operate on the principle of electrochemical reactions (Fig. 6), offering an efficient and clean process for converting hydrogen into electrical power. Positioned strategically within the microgrid, these fuel cells become the link between stored hydrogen and the electricity needed to illuminate homes, power appliances, and drive economic activities in Bhopal's off-grid communities.

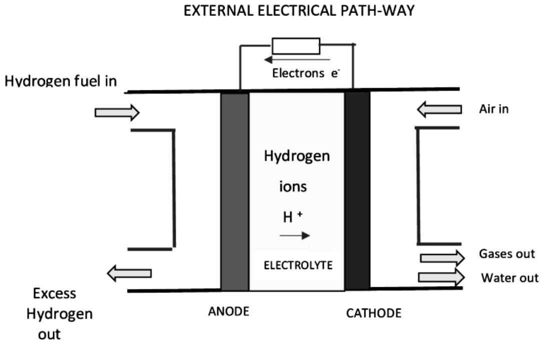

Fig. 6. Schematic diagram of a hydrogen fuel cell

The beauty of fuel cells lies in their simplicity and environmental friendliness. The fuel cell technology adopted in the microgrid operates on the principle of electrochemical conversion, distinguishing it from conventional combustion-based power generation. This distinctive process occurs within the fuel cell stack, where hydrogen from the storage facilities reacts with oxygen from the air. The electrochemical reaction produces electricity, heat, and water vapor as byproducts. Importantly, the process occurs without combustion, eliminating the release of harmful pollutants and greenhouse gases into the atmosphere.

The integration of fuel cells completes the energy loop within the microgrid. It ensures that the stored hydrogen, originating from surplus solar energy, is efficiently converted back into electricity when the demand arises. This closed-loop system, characterized by its sustainability and minimal environmental impact, aligns with the principles of green energy solutions.

The adaptability of fuel cells to varying energy demands is a crucial aspect of their integration into the microgrid. Bhopal's off-grid communities experience dynamic fluctuations in energy needs throughout the day. Fuel cells respond swiftly to these changes, ensuring a continuous and reliable power supply. This responsiveness enhances the microgrid's stability, making it adept at meeting the evolving energy requirements of the community.

Moreover, the fuel cell technology employed in the microgrid is scalable. The modular nature of fuel cell systems allows for seamless expansion to match the growing energy demands of Bhopal's communities. As the population expands or new economic activities emerge, additional fuel cells can be integrated into the microgrid infrastructure without compromising efficiency. This scalability feature ensures the microgrid's long-term viability and adaptability to the changing energy landscape.

Furthermore, the decentralized nature of fuel cells enhances the reliability and resilience of the microgrid. Instead of relying on a single central power source, the microgrid can distribute fuel cells across various locations within the community. This decentralized approach not only minimizes transmission losses but also ensures that even in the event of a localized issue, the broader microgrid continues to function, providing uninterrupted power to the community.

The life cycle of the fuel cell technology within the microgrid is designed with sustainability in mind. As it generates electricity, the byproduct water vapor can be captured and reused, contributing to a closed-loop water management system. This dual benefit of electricity production and water generation aligns with principles of resource efficiency and environmental stewardship, embodying the microgrid's commitment to holistic sustainability.

Fuel cells serve as the most important part of the hybrid solar-hydrogen microgrid, orchestrating the final act of converting stored hydrogen into clean electricity. Their efficiency, adaptability, scalability, and sustainability make them integral to the success of Bhopal's rural electrification initiative. As we witness the collaborative synergy of solar power integration, hydrogen production, and fuel cell technology, the hybrid microgrid emerges not only as an energy infrastructure but as a catalyst for transformative change in the lives of Bhopal's residents. The journey continues as we explore the broader implications and future prospects of this pioneering energy solution.

In the final act of our exploration, we reflect on the collective impact of these integrated technologies. The hybrid solar-hydrogen microgrid stands as a beacon of innovation, resilience, and sustainability, illuminating a path towards a brighter and more inclusive energy future for the resilient communities of Bhopal and beyond.

VII. OPTIMISATION STRATEGIES

The success of the hybrid solar-hydrogen microgrid in Bhopal hinges not only on its innovative design but also on the efficacy of optimization strategies employed to enhance its performance, resilience, and overall impact. This phase of our exploration delves into the multifaceted approaches and considerations that guide the ongoing optimization of the microgrid [22].

1. Machine Learning Algorithms:

Harnessing the power of machine learning algorithms is pivotal in adapting the microgrid to the dynamic energy landscape of Bhopal. These algorithms continuously analyze data from the solar panels, electrolyser, hydrogen storage, and fuel cells. By understanding patterns in energy generation, consumption, and storage, the microgrid can dynamically adjust its operation to meet the community's evolving needs. Predictive analytics also play a crucial role, forecasting energy demand patterns based on historical data and enabling proactive adjustments for optimal performance.

2. Demand-Side Management:

Effective demand-side management is integral to optimizing energy consumption within the microgrid. By engaging with the community and understanding their usage patterns, the microgrid can implement strategies such as load shifting and peak shaving. These practices ensure that electricity-intensive tasks are performed during periods of abundant solar power, reducing reliance on stored hydrogen during high-demand hours. This approach not only enhances the microgrid's efficiency but also minimizes the need for additional energy storage capacity.

3. Hydrogen Production Optimization:

The electrolyser, responsible for hydrogen production, undergoes continuous optimization. Parameters such as electrolyser efficiency, response time, and maintenance schedules are fine-tuned to maximize hydrogen yield while minimizing energy losses. The integration of smart sensors and real-time monitoring allows for immediate detection of any deviations from optimal performance, enabling timely adjustments and ensuring the reliability of the hydrogen production process.

4. Storage Management Strategies:

The hydrogen storage facilities are managed with precision to balance energy availability and demand. Advanced control systems regulate the compression and liquefaction processes, optimizing the storage capacity and minimizing losses. Additionally, predictive modeling aids in determining the optimal hydrogen storage levels, ensuring that the microgrid is adequately prepared to meet energy demands even during periods of reduced solar power generation.

5. Grid Connectivity and Redundancy:

While the microgrid operates predominantly in an off-grid mode, the potential for grid connectivity is considered in the optimization strategies. In cases of unforeseen circumstances or extreme energy demands, the microgrid can leverage external grid support. Redundancy measures are also implemented to ensure the continuous operation of critical systems. This dual approach enhances the microgrid's reliability, providing a safety net for uninterrupted energy supply.

6. Community Engagement and Education:

Optimization extends beyond technical considerations to include community engagement and education. Informed and engaged communities play a crucial role in the success of the microgrid. Workshops, awareness programs, and regular communication channels empower residents to make informed decisions about their energy usage. This collaborative approach fosters a sense of ownership and responsibility, contributing to the sustainability of the microgrid.

As we navigate the intricacies of optimization strategies, it becomes evident that the hybrid solar-hydrogen microgrid is not a static solution but an evolving and adaptive system. Continuous monitoring, data-driven decision-making, and community involvement form the pillars of a resilient and effective microgrid that addresses the unique challenges and opportunities of rural electrification in Bhopal. The journey of optimization is ongoing, and its outcomes hold the promise of a sustainable and inclusive energy future for the resilient communities of Bhopal and beyond.

VIII. SIMULATION RESULTS

A detailed simulation was carried out with HOMER Pro software to evaluate the performance of the hybrid solar-hydrogen microgrid designed for off-grid rural electrification in Bhopal where the daily average solar irradiance ranges from 3.67 kWh/m^2-day to 6.45 kWh/m^2-day with 5.5 hours of annual average sunshine. The simulation model incorporated solar photovoltaic (PV) panels, an electrolyzer for hydrogen production, hydrogen storage tanks, and fuel cells for energy conversion. Key parameters considered included local solar irradiance data, energy consumption patterns of a typical rural household in Bhopal, and the efficiency of each component in the system.

TABLE II. DESIGN SPECIFICATIONS

Components	Parameters	Specifications
Solar PV Array	Capital cost	Rs. 55,000/kW
	Replacement cost	Rs. 55,000/kW
	Lifetime	25 Years
	Efficiency at standard conditions	16%
	Operating cell temperature	45°C
	Derating factor	85^%
Fuel Cell	Capital cost	Rs. 2,50,000/kW
	Replacement cost	Rs. 2,00,000/kW
	Operation & maintenance cost	Rs. 2/hr.
	Lifetime	15,000hr.
	Efficiency	60^%
Battery	Capital cost	Rs. 10,000
	Replacement cost	Rs. 10,000
	Operation & maintenance cost	Rs. 1,000/Yr.
	Lifetime	5 Years
	Efficiency	80%
	Nominal voltage	12V
	Nominal capacity	200Ah
Electrolyser	Capital cost	Rs. 1,00,000/kW
	Replacement cost	Rs. 50,000/kW
	Operation & maintenance cost	Rs. 1,000/Yr.
	Lifetime	15 Years
	Efficiency	70%
Hydrogen Storage Tank	Capital cost	Rs. 45,000/kW
	Replacement cost	Rs. 30,000/kW
	Operation & maintenance cost	Rs. 1,000/Yr.
	Lifetime	25 Years
	Efficiency	90%

Since over-sizing of the system would incur extra costs while under-sizing may cause a collapse of the system for not achieving the target, it is very important to optimise the system for proper size and cost. The design specifications of the components of the system used for optimisation are given in Table II. The schematic diagram of the hybrid system in HOMER Pro software is shown in Fig. 7.

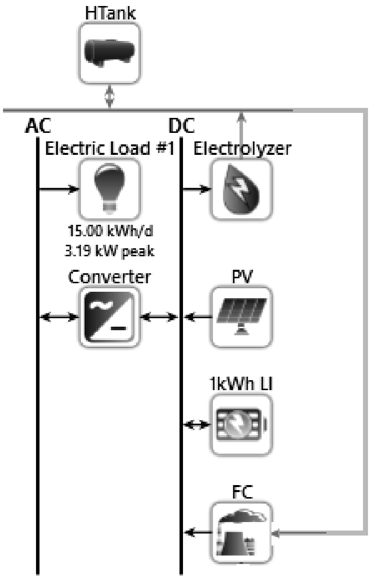

Fig. 7. Schematic diagram of PV-FC hybrid system in HOMER Pro software

The month-wise average solar radiation and the clearness index of the specified location are shown in Fig. 8. The annual average radiation comes to be 5.08 kWh/m^2 per day. Month-wise average temperature variation of Bhopal is given in Fig. 9 which depicts an annual average temperature of 25.44°C.

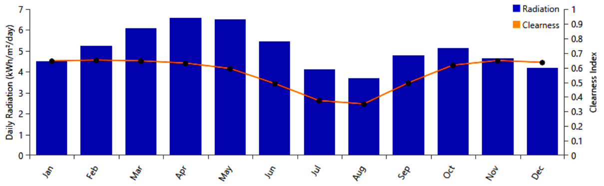

Fig. 8. Month-wise solar radiation and clearness index

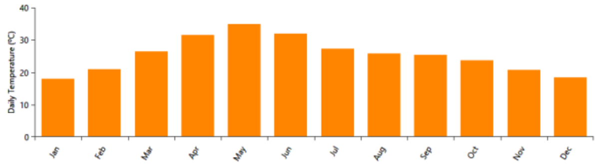

Fig. 9. Month-wise average temperature

The total energy generated by the hybrid system is 7,31,645 kWh per year. This electrical energy is utilized to supply all AC and DC loads. The month-wise energy production by the PV-Fuel cell hybrid system for the selected location is shown in Fig. 10.

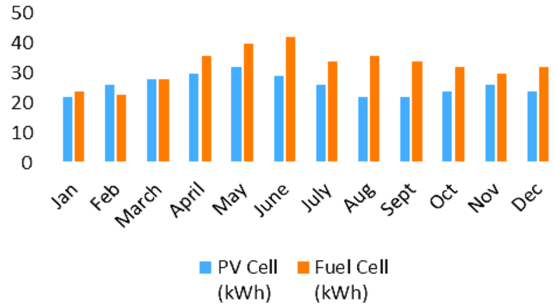

Fig. 10. Month-wise energy production by PV-Fuel cell hybrid system

The HOMER software achieves the modelling and optimisation of the PV-Fuel Cell hybrid system. The simulation results are shown in Table III.

TABLE III. SIMULATION RESULTS

NPC (Rs.)	LCOE (Rs./kWh)	Energy production (kWh/Yr.)	Energy consumption (kWh/Yr.)	Excess energy (kWh/Yr.)
2,65,73,774.25	5.51	7,31,645	4,08,734	2,59,563

The simulation results indicated that the hybrid microgrid could reliably meet the energy demands of the target community. The solar PV system generated an average of 5 kWh/day per kW of installed capacity, leveraging Bhopal's high solar irradiance. During peak sunlight hours, the excess energy produced by the PV panels was used to power the electrolyzer, producing hydrogen for storage.

The electrolyzer efficiency was modeled at 70%, resulting in the production of approximately 0.9 kg of hydrogen per day per kW of surplus solar power. Hydrogen storage tanks were designed to accommodate up to 30 days' worth of hydrogen production to ensure reliability during extended periods of low solar generation. The storage system's efficiency was maintained at 90%, with minimal hydrogen loss over time.

Fuel cells were used to convert the stored hydrogen back into electricity when solar power was insufficient to meet the demand. The fuel cells operated at an efficiency of 60%, providing a continuous power output that matched the community's energy consumption profile. The system demonstrated the capability to maintain a stable and reliable power supply, even during prolonged cloudy periods or at night.

TABLE IV. CONTRIBUTION OF DIFFERENT POLLUTANTS

Pollutants	Emission (kg/year)
Carbon dioxide (CO_2)	–3.67
Carbon monoxide (CO)	2.14
Nitrogen oxides (NO_X)	23.6
Sulphur dioxide (SO_2)	0
Unburned hydrocarbons	0.30
Particulates	0

The contribution of different pollutants to the PV-Fuel Cell system is shown in Table IV. Since the hydrogen which is used as the fuel in the Fuel Cell is obtained by the process of electrolysis and harnessing solar energy, the cost of energy for this system is the minimum.

The main parameters of our study are Net Present Cost (NPC), Levelised Cost of Energy (LCOE) while the other constraints like replacement cost, operation and maintenance cost and other initial costs are taken into consideration. Economic analysis showed a significant reduction in energy costs compared to conventional diesel generators, with the levelized cost of electricity (LCOE) estimated at Rs. 5.51 per kWh, factoring in the initial capital investment, operation, and maintenance costs. Environmentally, the microgrid reduced CO_2 emissions by approximately 95% compared to diesel-based systems, contributing to a cleaner and healthier environment.

IX. EXPERIMENTAL RESULTS

A pilot microgrid was deployed in a small off-grid village near Bhopal to validate the simulation results. The setup included a 10 kW solar PV array, a 5 kW electrolyzer, hydrogen storage tanks with a capacity of 500 kg, and a 5 kW fuel cell system.

Performance Monitoring:

The pilot microgrid's performance was monitored over a period of one year. Data on solar irradiance, hydrogen production, storage levels, and electricity output were collected and analyzed.

Energy Reliability and Community Impact:

The experimental results aligned closely with the simulation outcomes. The microgrid provided an uninterrupted power supply throughout the year, significantly improving the quality of life for the villagers. Access to reliable electricity enabled better educational opportunities, improved healthcare services, and stimulated local economic activities.

Technical Challenges and Solutions:

Several technical challenges were encountered during the pilot deployment, including the integration of control systems and optimizing the operation of the electrolyzer and fuel cells. These challenges were addressed through iterative improvements and fine-tuning of the system parameters.

Community Feedback and Acceptance:

Community feedback was overwhelmingly positive. The villagers appreciated the reliable and clean energy source, which reduced their dependence on kerosene lamps and diesel generators. The socio-cultural acceptance of the technology was high, with community members actively participating in the maintenance and operation of the microgrid.

The design and optimization of the hybrid solar-hydrogen microgrid for off-grid rural electrification in Bhopal demonstrated both simulation and experimental success. The system proved to be a viable and sustainable solution for addressing the energy needs of rural communities. The integration of solar and hydrogen technologies not only provided reliable power but also fostered socio-economic development and environmental stewardship in the region. The positive results from the pilot deployment suggest that this model can be scaled and replicated in similar rural settings across India and other parts of the world.

X. BENEFITS AND IMPACTS

The implementation of the hybrid solar-hydrogen microgrid in Bhopal transcends beyond the territory of energy provision, helping in a multitude of benefits and transformative impacts that resonate across social, economic, and environmental dimensions. This section explores the tangible outcomes and positive changes catalyzed by the microgrid within the community.

1. Energy Access and Reliability:

The foremost impact of the microgrid is the provision of reliable and sustainable energy access to Bhopal's off-grid communities. Previously devoid of consistent electricity, residents now experience improved lighting, powering of essential appliances, and extended hours of productivity. The microgrid's reliability ensures that essential services, such as healthcare facilities and educational institutions, operate seamlessly, fostering an environment conducive to overall community development.

2. Economic Empowerment:

The microgrid serves as a catalyst for economic empowerment within the community. Access to electricity unlocks numerous opportunities, enabling small businesses to thrive, supporting cottage industries, and facilitating the establishment of new ventures. Productivity gains in agriculture, improved market access, and the emergence of entrepreneurial activities contribute to the economic upliftment of residents, breaking the cycle of poverty in the region.

3. Environmental Sustainability:

The adoption of clean energy solutions in the microgrid significantly reduces the environmental impact of energy generation. By harnessing solar power and utilizing hydrogen as an energy carrier, the microgrid minimizes carbon emissions and pollution. The shift towards sustainable energy practices aligns with global efforts to combat climate change, positioning Bhopal as a beacon of environmental stewardship and sustainability.

4. Health and Well-being:

Reliable access to electricity positively impacts health outcomes within the community. Improved lighting facilitates safer nighttime activities, and electrification of healthcare facilities ensures the availability of essential medical services. The reduction of indoor air pollution, often associated with traditional energy sources, contributes to better respiratory health, particularly for women and children. The overall enhancement of well-being is a testament to the holistic benefits of the microgrid.

5. Community Resilience:

The hybrid microgrid enhances the community's resilience to external shocks and challenges. During unforeseen events, such as extreme weather conditions or emergencies, the microgrid's adaptability and redundancy measures ensure a continuous power supply. This resilience extends to economic shocks, providing a stable energy foundation that enables the community to withstand and recover from adverse situations more effectively.

6. Educational Advancements:

The availability of electricity transforms educational opportunities for the community's children. Well-lit homes and access to electronic devices extend study hours, improving academic performance. Furthermore, electrified schools can leverage technology for enhanced teaching methods, creating a conducive environment for quality education. The microgrid becomes a catalyst for educational advancements, empowering the younger generation with the tools for a brighter future.

7. Gender Empowerment:

Gender empowerment is a distinctive outcome of the microgrid's impact. Reliable electricity access alleviates the burden on women, traditionally responsible for household chores, by replacing manual tasks with electrical appliances. This shift contributes to a more equitable distribution of responsibilities and enables women to engage in income-generating activities, fostering greater gender equality within the community.

XI. CONCLUSION

This innovative energy solution transcends conventional paradigms, embodying a vision of sustainable development and empowerment for off-grid communities. The journey through solar power integration, hydrogen production, fuel cell technology, optimization strategies, and the resulting benefits and impacts paints a holistic picture of a transformative energy ecosystem.

The hybrid microgrid serves not merely as a source of electricity but as a beacon of resilience, adaptability, and sustainability. It marks a departure from traditional energy models, embracing clean technologies and decentralized solutions tailored to the specific needs of Bhopal's residents. The community is no longer relegated to the periphery of progress but is an active participant in shaping its energy future.

The hybrid solar-hydrogen microgrid is more than a localized energy project; it is a catalyst for broader societal transformations. Economic empowerment, environmental sustainability, gender equality, and improved health outcomes underscore the multifaceted impact on the community. The journey of the hybrid microgrid in Bhopal is a testament to the transformative potential of sustainable energy solutions. It demonstrates that by harmonizing technological innovation with community engagement and environmental consciousness, we can create resilient and inclusive models for rural electrification.

REFERENCES

[1] Ackermann T, K. Garner, and A, Gardiner, 1999, “Embedded wind generation in weak grids economic optimisation and power quality simulation”. Renewable Energy, 18(2):205–221.

[2] Akella, A. K., M. P. Sharma and R. P. Saini, 2007, “Optimum utilisation of renewable energy sources in a remote area”, Renewable and Sustainable Energy Reviews, 11(5), pp. 894-908.

[3] Alam, MS, BK Bala and MZ Huq, 1997, “Simulation of integrated rural energy system for farming in Bangladesh”, Energy, 22(6), pp. 591-599.

[4] Alam, MS, KK Islam and AMZ Huq, 1999, “Simulation of rural household fuel consumption in Bangladesh”, Energy, 24(8), pp. 743-752

[5] Alam, MS, MZ Huq and BK Bala, 1990, “An integrated rural energy model for a village in Bangladesh”, Energy, 15(2), pp. 131-139.

[6] Ashenayi, K., and R. Ramakumar, 1990, “IRES – a program to design integrated renewable energy system”, IEEE Transactions on Energy Conversion, 15(12), pp. 1143-1152.

[7] Banerjee R., 2006, “Comparison of options for distributed generation in India”. Energy Policy, 34, pp. 101–111.

[8] Bekele, G. and B. Palm, 2010, “Feasibility study for a sustainable solar-wind-based hybrid energy system for application in Ethiopia”, Applied Energy, 87(2), pp. 487-495.

[9] Bernal-Agustin JL, and R. Dufo-Lopez, 2006, “Economical and environmental analysis of grid connected photovoltaic systems in Spain”. Renewable Energy; 31(8): 1107–1128.

[10] Bernal-Agustin, JL and R. Dufo-Lopez, 2009, “Simulation and optimization of stand-alone hybrid renewable energy systems”, Renewable and Sustainable Energy Reviews, 13(8), pp. 2111-2118.

[11] Veronika G, Julia G, Bastian Ruckel, Christian S and Gregor Zottl, 2020, “Storage investment and network expansion in distribution networks: The impact of regulatory frameworks”, Applied Energy, vol. 262, 114017.

[12] Vendoti S, Muralidhar M. and Kiranmayi R, 2020, “Modelling and optimization of an off-grid hybrid renewable energy system for electrification in a rural areas” Energy Report, vol. 6, 594-604.

[13] Rovick T, Yosuke N, Yining C, Yicheng Z, Noel E. and Anacita T, 2022, “Optimization of Hybrid Renewable Energy Microgrid for Rural Agricultural Area in Southern Philippines”, Energies, 15(6), 2251.

[14] Khlifi, F.; Cherif, H.; Belhadj, J, 2021, “Environmental and Economic Optimization and Sizing of a Micro-Grid with Battery Storage for an Industrial Application”, Energies, 14, 5913.

[15] Bhattacharyya S. C., 2012, “Review of alternative methodologies for analysing off-grid electricity supply”, Renewable and Sustainable Energy Reviews, 16(1), 677-694.

[16] E. MacA. Gray, C. J. Webb, J. Andrews, B. Shabani, P. J. Tsai, S. L. I. Chan, “Hydrogen storage for off-grid power supply”, International Journal of Hydrogen Energy, vol. 36, issue 1, January 2011, 654-663.

[17] Arsalis, A., Georghiou, G.E. “A decentralized, hybrid photovoltaic-solid oxide fuel cell system for application to a commercial building”, Energies 2018, 11, 3512.

[18] Marocco, P., Ferrero, D., Lanzini, A., Santarelli, M., “The role of hydrogen in the optimal design of off-grid hybrid renewable energy systems”, J. Energy Storage 2022, 46, 103893.

[19] “Solar Hydrogen Production, Processes, Systems and Technologies”, Book edited by Francesco Calise, Massimo Dentice D’Accadia, Massimo Santarelli, Andrea Lanzini and Domenico Ferrero, Academic Press, 2019, ISBN 978-0-12-814853-2.

[20] Jieyang Jia, Linsey C. Seitz, Jesse D. Benck, Yijie Huo, Yusi Chen, Jia Wei Desmond Ng, Taner Bilir, James S. Harris and Thomas F. Jaramillo, “Solar water splitting by photovoltaic-electrolysis with a solar-to-hydrogen efficiency over 30%”, Nature Communications, 13237 (2016).

[21] Power System Energy Storage Technologies, Book by Paul Breeze, Academic Press, 2018, ISBN 978-0-12-812902-9.

[22] Alexandros Arsalis, George E. Georghiou and Panos Papanastasiou, “Recent Research Progress in Hybrid Photovoltaic–Regenerative Hydrogen Fuel Cell Microgrid Systems”, Energies 2022, 15(10), 3512.