The Scientific Temper (2024) Vol. 15 (2): 2248-2257
E-ISSN: 2231-6396, ISSN: 0976-8653
Doi: 10.58414/SCIENTIFICTEMPER.2024.15.2.38
https://scientifictemper.com/

REVIEW ARTICLE

A comparative study of AI-driven techno-economic analysis for grid-tied solar PV-fuel cell hybrid power systems

Pooja Soni[1*], Vikramaditya Dave[1], Sujit Kumar[2], Hemani Paliwal[3]

Abstract

The increasing global demand for clean and sustainable energy solutions has led to the integration of "renewable energy sources" and innovative technologies in power generation systems. In this context, "grid-tied solar photovoltaic (PV)-fuel cell hybrid power systems" have drawn considerable interest because of their potential to provide reliable and efficient energy generation. However, the complex interaction between solar PV and fuel cell components and the fluctuating nature of renewable energy sources necessitates a comprehensive techno-economic analysis. This research paper presents a comparative study of AI-driven approaches for conducting techno-economic analysis of "grid-tied solar PV-fuel cell hybrid power systems." The study uses various AI techniques to analyze these hybrid systems' performance, economic viability, and environmental impact.

Keywords: Solar PV-fuel cell, Hybrid power systems, Artificial intelligence, Renewable energy.

Introduction

The global pursuit of sustainable and clean energy solutions has propelled the integration of renewable energy technologies into power generation systems. According to the World Watch Institute, buildings are the biggest energy consumers, contributing 36% of all carbon emissions and 40% of annual worldwide energy consumption, primarily in urban areas (Jain *et al.*, 2014). Among these technologies, solar photovoltaic (PV) systems and fuel cells have emerged as frontrunners, offering abundant and efficient sources of electricity with minimal environmental impact. To harness the complementary attributes of these technologies, "grid-tied solar PV-fuel cell hybrid power systems" have gained significant attention (Ghenai & Bettayeb, 2019). These hybrid systems combine the intermittent yet abundant energy from solar PV with fuel cells' continuous and responsive power generation, thereby addressing the intermittency challenge often associated with standalone renewable sources.

The pressing need for such hybrid power systems arises from the escalating demand for reliable, sustainable, and economically viable energy solutions. As traditional energy derived from fossil fuels contributes to environmental damage and climate change, governments, industries, and research institutions worldwide focus on adopting cleaner alternatives (Bühler *et al.*, 2015; Renewable Transition, 2021). Solar PV and fuel cells provide an attractive solution. Still, both technologies exhibit limitations – solar PV's output fluctuates with weather conditions, and fuel cell operation can be influenced by fuel availability and cost. A hybrid system that amalgamates these technologies aims to mitigate these limitations, ensuring a consistent and resilient energy supply.

In this context, conducting a comprehensive techno-economic analysis of "grid-tied solar PV-fuel cell hybrid power systems" becomes imperative. The intricate interplay between "solar PV" and "fuel cell" components and the dynamic nature of renewable energy sources necessitates a nuanced understanding of performance, economic viability, and environmental impact. Moreover, traditional analysis methods might struggle to capture the

[1]Department of Electrical Engineering, MPUAT, CTAE, Udaipur, Rajasthan, India.

[2]Department of Electrical and Electronics Engineering, Dayananda Sagar College of Engineering, Bengaluru, Karnataka, India.

[3]Department of Electrical Engineering, Institute of Engineering and Technology, MLSU, Udaipur, Rajasthan, India.

***Corresponding Author:** Pooja Soni, Department of Electrical Engineering, MPUAT, CTAE, Udaipur, Rajasthan, India., E-Mail: poojaswarnakar93@gmail.com

How to cite this article: Soni, P., Dave, V., Kumar, S., Paliwal, H. (2024). A comparative study of AI-driven techno-economic analysis for grid-tied solar PV-fuel cell hybrid power systems. The Scientific Temper, **15**(2):2248-2257.

Doi: 10.58414/SCIENTIFICTEMPER.2024.15.2.38

Source of support: Nil

Conflict of interest: None.

Received: 21/04/2024 **Accepted:** 20/05/2024 **Published** : 15/06/2024

complexities inherent in these systems (Akan, 2023). This paper presents a comparative study that uses AI-driven approaches to enhance the accuracy and depth of techno-economic analysis for "grid-tied solar PV-fuel cell hybrid power systems." Through this study, we aim to deal with the difficulties brought on by conventional analysis methods and demonstrate the potential of AI in shaping the future of sustainable energy systems.

Solar PV technology harnesses sunlight to generate electricity through the photovoltaic effect. This technology has matured, becoming a reliable and commercially viable energy source. However, solar PV systems are constrained by their dependence on sunlight availability, making them intermittent power sources. On the other hand, fuel cells are electrochemical machines that directly transform the chemical energy of energy sources, such as hydrogen, into electricity. They offer high energy efficiency and low emissions, making them promising candidates for clean energy generation. Nevertheless, the availability and cost of hydrogen fuel can impact the economic viability of fuel cell systems (Ghenai & Bettayeb, 2019; Inman *et al.*, 2013). Figure 1 illustrates the hybrid power system.

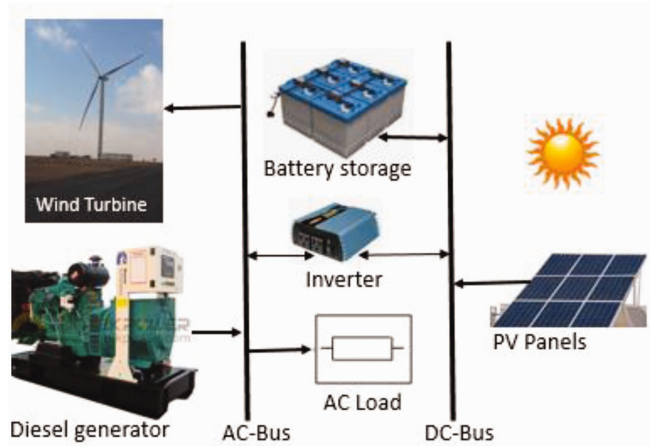

Figure 1: Hybrid power system

The synergy between solar PV and fuel cells in hybrid systems seeks to capitalize on their strengths while mitigating their limitations. During periods of ample sunlight, solar PV systems can generate excess energy; it is possible to electrolyze water to create hydrogen. This hydrogen can then be kept and used to power fuel cells when solar generation is inadequate, ensuring a continuous and stable energy supply.

Photovoltaic (PV) systems are one way to convert solar radiation into electricity. However, the high cost of installing PV systems has hindered their widespread adoption. Artificial intelligence (AI) algorithms can make PV systems more affordable and efficient. AI can model PV systems, size them appropriately, control them, diagnose faults, and estimate output. Here are some specific instances of how AI is being utilized in PV systems:

- AI may be used to create more accurate models of PV systems. This can enhance the design and sizing of PV systems, leading to lower costs and higher efficiency.
- AI can be used to develop more robust and efficient controllers for PV systems. This can help to enhance the performance of "PV systems" under varying circumstances.
- AI can be used to diagnose faults in PV systems. This can help to prevent costly outages and extend the lifespan of "PV systems."
- AI could be utilized to estimate the output of PV systems. PV systems might be operated more efficiently and integrated into the grid more successfully using this data.
- Although the use of AI in solar power plants is still in its infancy, it can ultimately alter how we produce and utilize solar energy. As AI technology advances, we may anticipate increasingly more creative and effective use of AI in PV systems. Figure 2 depicts the use of AI in solar energy systems.

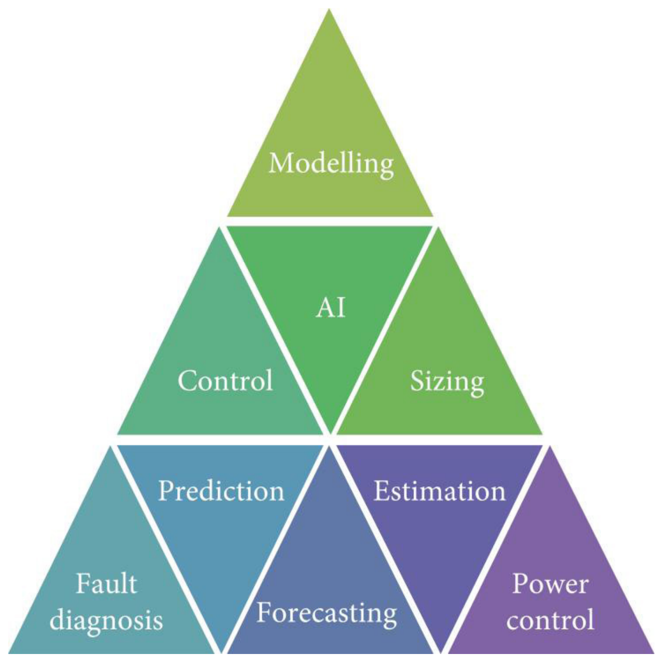

Figure 2: Use of AI in solar energy system

The integration of these technologies necessitates a holistic analysis that considers technical feasibility, economic viability, and environmental sustainability. Traditional techno-economic analysis methods involve deterministic modeling that may not adequately capture the dynamic behavior of hybrid systems. As a result, there is a growing interest in leveraging AI techniques, such as machine learning and neural networks, to model the intricate relationships between various system variables. AI-driven models have the potential to provide more accurate predictions, optimize system operation, and enhance the overall understanding of hybrid power systems (Maghami & Mutambara, 2023).

As the global energy landscape evolves, this research contributes to the ongoing discussions surrounding sustainable energy solutions. It highlights the role of AI in advancing the feasibility and viability of hybrid power systems.

Integrating AI can significantly improve system performance, but it is essential to consider the potential drawbacks carefully.

Some of the critical challenges and opportunities associated with AI integration include:

Complex System Dynamics

"Hybrid power systems" involving "solar PV" and "fuel cells" exhibit intricate interactions between multiple components, including energy generation, storage, and conversion devices. Traditional analysis methods might struggle to accurately model and predict the system's behavior under varying conditions.

Nonlinear Relationships

The relationships between input factors, such as "solar irradiance," "temperature," fuel availability, and electricity demand, can be nonlinear and complex. With their ability to capture nonlinear patterns, AI techniques can provide more accurate predictions and optimize system performance.

Intermittency and Variability

Both solar PV and fuel cell technologies are subject to intermittency and variability – solar PV due to changing weather conditions and fuel cells due to varying hydrogen availability. AI-driven models can better handle such variability and optimize the system's operation to ensure a consistent power output.

Data-Driven Insights

AI techniques can leverage historical and real-time data to identify patterns, correlations, and trends that conventional methods might not be able to show analysis. This data-driven approach enhances the accuracy of predictions and the identification of optimal operating strategies.

Optimization Challenges

Optimizing the operation of hybrid power systems for maximum economic benefit and efficiency is a complex task. AI-driven techniques like reinforcement learning can adaptively learn optimal control strategies in response to changing conditions (Maghami & Mutambara, 2023).

Dynamic Decision-Making

AI models can provide real-time decision support, adapting to immediate changes in weather, demand, and market prices. This dynamic decision-making capability is crucial for ensuring efficient system operation.

Customization and Scalability

Each hybrid power system configuration can be unique based on geographical location, system size, and component specifications. AI-driven approaches can adapt to various system configurations and scale to analyze more extensive and complex systems.

Environmental Considerations

Assessing the environmental impact of hybrid systems requires analyzing emissions, carbon footprint, and other sustainability indicators. AI-driven techniques can offer detailed insights into the environmental benefits of hybrid power systems (Maghami & Mutambara, 2023).

Bias

AI systems are susceptible to bias when trained on biased data. Decisions may, therefore, be made that are unjust or incorrect. Even if the data is not discriminatory, the algorithms used to train AI systems can still be biased. This can happen if the algorithms are not designed to be fair or if they are not adequately trained. For example, an algorithm that is designed to predict recidivism rates may be biased against people of color if it is not sufficiently trained to take into account factors such as socioeconomic status and criminal history.

Given these challenges, AI-driven techno-economic analysis is vital for accurately assessing the feasibility, performance, and economic viability of "grid-tied solar PV-fuel cell hybrid power systems." Its ability to handle complexity, uncertainty, and dynamic interactions positions AI as essential in developing sustainable energy solutions.

Heydari & Askarzadeh, (2016) they created a "hybrid PV/BG/FC power generation system" for Iran's electrification of a standalone region. The main goal is to choose the best configuration for the "fuel cell system" while considering various initial funding costs. The hybrid system's performance is assessed using the (LPSP) loss of power supply probability measure in the study. The analysis of the impact of capital costs for fuel cells, the optimization of power generation allocation, the highlighting of trade-offs, and the financial importance of a fuel cell system's initial investment when assessing the system's general efficiency and configuration are some of the key findings.

Najafi Ashtiani *et al*., (2020) they employed several PV monitoring methodologies to examine the technical and financial credibility of "grid-connected hybrid energy systems" comprising PV and fuel cells (FC). The research showed that vertical single-axis trackers are the most effective for PV generation, green energy penetration, CO_2 emissions, power sold to the grid, and net current cost. The best PV-FC system design relies on a vertical single-axis tracker. The vertical single-axis tracker is the most effective PV tracking approach, considerably increasing efficiency and profitability. By supplying backup power on overcast days or at night and cutting CO_2 emissions, fuel cells can improve hybrid energy systems' performance even more. These discoveries can be used to build and enhance grid-connected hybrid energy systems, boosting the penetration of "renewable energy sources" and lowering dependency on fossil fuels.

Odoi-Yorke & Woenagnon, 2021 assess the technical and financial viability of installing a "solar PV/fuel cell hybrid power system" to provide power to Ghana's remote telecom base station. According to the research, a "PV/fuel cell hybrid system" had an LCOE of about 0.222 USD/kWh, was cost-competitive, and was 67% less expensive than a diesel power system. The LCOE, being 30% cheaper than a PV/battery/diesel hybrid system, showed cost-effectiveness. The hybrid system had a considerable positive environmental impact, saving 67 and approximately 43 tCO2/yr, respectively, compared to diesel power and PV/battery/diesel hybrid systems. The system's LCOE was favorable after evaluating the study's resistance to changes in discount rates and capital subsidies. The results show the promise of low-carbon technology for "off-grid telecom sites" with constrained wind and biomass resources, which have global ramifications for decision-makers, legislators, and investors.

Toufik *et al.*, 2022 studied the techno-economic efficiency of "grid-connected hybrid energy systems (HES)" in Algeria that combine "photovoltaic (PV)" and "reformer fuel-cell (RF-FC) technologies." It tested different PV tracking systems, comprising fixed systems, a two-axis monitoring system, continuous vertical and horizontal axis trackers, and continuous vertical axis trackers. The study discovered that the vertical single axis tracker (VSAT), which showed superior economic performance, low "Net present cost (NPC)," "Cost of Energy (COE)," and a positive "Return on investment (ROI)," was the most economically advantageous design. The study also emphasized the necessity for thoroughly evaluating each tracker's advantages and disadvantages to determine whether energy gains outweigh related expenses. This study advances knowledge of grid-connected hybrid energy systems and the more extensive discussion of environmentally friendly and cost-effective solutions.

Nur Farzana Athirah Mohd Fadzli *et al.*, 2023 investigate Malaysia's rural areas' development of a "hybrid renewable energy system (HRES)." The authors studied three configurations in their techno-economic analysis: "Standalone diesel generators," "Hybrid PV-diesel systems" without batteries, and hybrid PV-Diesel systems with batteries. The hybrid PV-diesel with battery arrangement was the most financially viable choice since it had the lowest "Levelized cost of energy (LCOE)" and net present cost (NPC). According to the sensitivity analysis, diesel fuel and PV module prices have a sizable impact on LCOE and NPC. The authors suggest the hybrid PV-diesel with battery configuration for future HRES initiatives in rural areas.

Kahwash *et al.*, 2023, concentrated on developing "Two coupled thermal-electrical dispatch strategies for grid-connected hybrid multi-energy systems" to increase efficiency by combining system-level heat and electricity supplies and using forecasting to prioritize thermal load supply during renewable surplus. Key findings show that the suggested dispatch algorithms created systems with lower levelized costs than utility gas and electricity. Because it prioritized the delivery of thermal demand during periods of renewable surplus, forecasting was particularly helpful in lowering the cost of heating. Given this situation's significant seasonality and tendencies, LSTM emerged as the most reliable forecasting algorithm. Implications of the research include developing novel forecasting and optimization methods and optimizing the construction and operation of grid-connected hybrid multi-energy systems.

Studies using AI for Enhancement of PV in Solar Energy Systems

Kuo & Huang, 2018 offer a unique method for enhancing forecasting solar radiation accuracy using an advanced deep convolutional neural network model dubbed SolarNet. To maximize the integration of PV energy into smart grids, it is necessary to improve the precision of solar radiation level forecasts while considering nonlinearity and volatility. The SolarNet model forecasts the sun radiation levels for the following 14 days using information gathered from a pyranometer sensor. As a result of its high forecasting accuracy, low mean absolute error (MAE), good generalizability, and robustness in medium-term forecasting scenarios, SolarNet beats other benchmark models. This confirms the efficacy and viability of employing a "Convolutional neural network model" like "SolarNet" for forecasting solar radiation and emphasizes the possibility for new research areas in forecasting.

Meena *et al.*, 2022 investigate how "Solar power systems," particularly "Standalone, grid-connected," and hybrid systems, can be scaled using artificial intelligence (AI) techniques to lessen their environmental impact. The paper presents a hybrid AI sizing model built on multilayered perceptrons that combines the advantages of both AI and traditional sizing techniques. The model offers precise sizing suggestions and supports a range of system configurations, including single--, dual--, and triple-diode combinations. One of the key findings is a hybrid AI sizing model that combines multilayered perceptrons with existing hybrid-sizing models, exhibiting its strengths while preserving traditional sizing approaches. The model is an effective tool for scaling solar power systems in practical settings due to its performance comparison, data-driven adaptation, and enhanced environmental impact.

Tang *et al.*, 2022 identify linear faults in photovoltaic (PV) modules; this research provides a computerized PV module linear flaws detecting system. The system uses edge devices, servers, and cloud servers in an edge-cloud computing framework to reduce computational burden and strike a compromise between detection accuracy and complexity of computation. The deep learning-based approach shows a successful trade-off between fault detection efficiency and accuracy. The method decreases communication overhead and is evaluated using real-world data by condensing the size of sent electroluminescence images. This method is a must to assess the condition and operation of massive PV systems.

Reddy *et al*., 2023 aim to build and analyze a "hybrid power system" that integrates "renewable energy sources," namely photovoltaic (PV) and proton exchange membrane fuel cells (PEMFC), to ensure a consistent and dependable power supply under a variety of environmental situations. The study focused on integrating PV modules and PEMFC to maximize power extraction and optimize PEMFC performance. Advanced control techniques were created, including a switching inductor-based voltage multiplier cell (VMC) design for effective voltage conversion and utilization, a maximum power point tracking (MPP) strategy for PEMFC, and a fuzzy logic controller (FLC) for PV. According to the performance study and simulation, integrating PV and PEMFC into a hybrid power system improves sustainability and dependability. It ensures that electricity is continuously generated even when solar irradiation is low. The VMC design produced more considerable voltage gains than traditional boost converters, indicating its potential for practical applications. A hybrid power system that can adapt to shifting conditions and effectively satisfy load requirements is the product of the integration of cutting-edge control methodologies and cutting-edge components.

Prabhakaran *et al*., 2023 address the issue of defect localization and detection in photovoltaic (PV) panels; this paper introduces a unique approach known as the real-time multi variant deep learning model (RMVDM). The RMVDM creates several DCS values to classify defects using a "Multi variant deep learning model" with layers tailored for various neuron classes. Intricate patterns connected to various flaws are taught to the model utilizing extracted features. The RMVDM effectively detects and localizes defects with 97% accuracy, resulting in excellent efficiency. Combining defect class support measures, multi variant deep learning and the HOTL approach results in more excellent accuracy rates and less time complexity. This study advances the efficiency and dependability of PV panels by advancing fault-detecting technology.

Rezaei *et al*., 2023 Develop a solar and wind-powered remote microgrid with an optimized renewable energy system (RES). The system uses machine learning algorithms to forecast solar and wind power outputs, enabling the microgrid to adjust to weather-related changes. The hybrid solar/wind system, which consists of a "60 kW" wind turbine array and a 100 kW distributed PV system, was designed using the system advisor model (SAM) software. In estimating solar power generation and the system's capacity to supply energy, the research shows how accurate random forest regression models can be. The microgrid's reliability is increased by reducing reliance on unstable renewable sources by integrating precise forecasts and hybrid system design.

Methodology

Data Gathering

This comparison study is based on accurate and thorough data collection. Historical meteorological information, solar irradiance, temperature profiles, fuel cell efficiency statistics, energy demand profiles, and market prices are gathered for the selected geographic area. The data sets span a representative period to account for changes in weather, demand patterns, and sun availability.

Model for Traditional Analysis

In the conventional analysis model, systems are modeled using well-known programs like HOMER or MATLAB/Simulink. The model incorporates fuel cells, solar PV arrays, hydrogen production electrolyzers, energy storage devices, and grid connections. Based on historical data inputs, deterministic methods are used to calculate system performance measures, including capacity factor, energy production, and system losses.

Models for AI-Driven Analysis

To depict the dynamic and intricate interactions inside the hybrid power system, several AI-driven models are created

Machine Learning Regression Model

A machine-learning regression model is developed to forecast solar PV output based on historical solar irradiance and temperature data. This model improves the precision of estimates for solar power generation under various weather scenarios.

A trained neural network models the nonlinear interactions between solar PV output, fuel cell efficiency, energy demand, and market prices. The neural network can manage intricate relationships and detect the effects of changing parameters.

Model for Reinforcement Learning

A reinforcement learning model continuously improves the hybrid system's performance. The model learns optimal control techniques to maximize economic gains while abiding by component and system requirements-imposed constraints.

Performance Assessment

The precision and dependability of the AI-driven models are assessed through performance indicators.

Accuracy of solar PV prediction

By contrasting the model's predictions with actual historical data, the accuracy of the machine learning regression model in forecasting solar PV production is determined.

Comparison of system performance

The capacity factor and energy output determined by AI-driven models are contrasted with those discovered through conventional analysis. This comparison demonstrates the ability of the AI models to represent complex system dynamics.

Financial Analysis

Various measures are used to evaluate economic viability.

Levelized cost of electricity

Various AI-driven and conventional approaches are used to determine the levelized cost of electricity (LCOE). A more precise LCOE estimate is made possible by the forecasts made by the AI models for market prices, fuel cell efficiency, and solar PV production.

Net present value and internal rate of return

They are computed using AI-driven and conventional approaches to give insights into the project's long-term financial viability.

Sensitivity Evaluation

A sensitivity analysis assesses how well the models respond to changes in input parameters like fuel prices, solar panel efficiency, and market pricing. This examination sheds light on the robustness and adaptability of the models to changing circumstances.

This research describes a thorough technique for conducting a comparative assessment of AI-driven techno-economic analysis for grid-tied solar PV-fuel cell hybrid power systems. Combining conventional approaches with cutting-edge AI techniques aims to improve the precision, dependability, and depth of comprehension while assessing these hybrid systems' functionality, commercial feasibility, and environmental effects.

Result and Discussion

The hybrid electrical systems investigated in this research paper encompass the integration of solar PV panels and fuel cells to create grid-tied hybrid power systems. The aim is to optimize these systems' performance, economic feasibility, and environmental impact using AI-driven approaches. A system that combines a fuel cell and PV technology to generate power and link it to the electrical grid is shown in Figure 3.

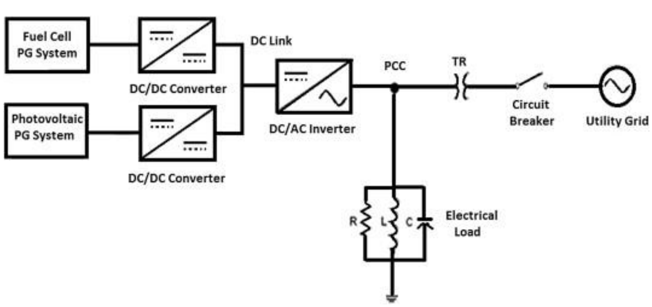

Figure 3: Grid-connected fuel cell/PV hybrid power generator

Solar PV panels are an integral component of the hybrid power system, generating electricity from sunlight through the photovoltaic effect. The technical details of the solar PV panels utilized in the current work are as follows: In designing our hybrid electrical systems, we considered load data specific to the "southern part of India, Chennai (Tamil Nadu)." The load data indicates a consistent demand of 1000W over 12 hours. Additionally, we accounted for the local environmental conditions, including a "wind velocity of 5 m/s" and" solar radiation of 5.08 kWh/sqm," making this data essential for our system design.

For the solar system, we optimized the sizing to meet the 1000 W load requirement, with panels ranging from 120 to 500 kW in capacity. The efficiency of these panels, ranging from 18 to 22%, was considered alongside historical solar irradiance and temperature data to model energy output accurately. The wind system was designed to complement the load with a 100-kW capacity. Efficiencies were factored in, and the system was tailored to the local wind conditions. Similarly, the hydro system was engineered to generate 1000 W of power, aligning with the load data. The design factored in water head and other specifications to ensure efficient operation.

Solar Irradiance and Temperature

Historical solar irradiance and temperature data are incorporated to model the solar PV panels' energy output accurately.

Data Gathering

Fuel cells provide continuous power generation by electrochemically converting hydrogen into electricity. The fuel cells utilized in this study adhere to the following technical specifications:

Capacity

The fuel cell capacity is 100 kW for all configurations, ensuring consistent comparison.

Efficiency

The fuel cells' electrical efficiency is approximately 68%, while their overall efficiency, including heat recovery, reaches around 80%.

Hydrogen supply

The availability and cost of hydrogen fuel are considered variables in the analysis to assess economic feasibility.

Inverters

Direct current (DC) supplied by solar PV panels and fuel cells must be converted into alternating current (AC) appropriate for grid connection, and this is where inverters come into play. Technical details of the inverters include:

Capacity

Inverter capacities range from 125 to 210 kW, accommodating the power output of the hybrid system configurations.

Table 1: Components and technical details of hybrid electrical systems

Load data	*Values*	*Component*	*Technical details*
Location	Chennai (Tamil Nadu)	Solar PV panels	- Capacity: 120 – 500 kW (varying sizes)
Load	1000 W		- Efficiency: 18 – 22%
Wind velocity	5 m/s		- Solar Irradiance and Temperature data used
Solar radiation	5.08 kWh/sqm	Fuel cells	- Capacity: 100 kW (consistent for all)
Water supply source	River		- Efficiency: Electrical - 68%, Overall - 80%
			- Hydrogen Supply considered for economic analysis
		Inverters	- Capacity: 125 – 210 kW
			- Efficiency: 96% (DC-AC conversion losses)

Efficiency

The inverter efficiency is assumed to be 96%, accounting for DC-AC power conversion losses. Table 1 shows the components and technical details of hybrid electrical systems.

Inverters are pivotal components in grid-tied hybrid power systems, facilitating AC created by converting DC produced by solar PV panels and fuel cells. That is compatible with grid connections. The technical specifications and details of the inverters, including their capacity and efficiency, are instrumental in determining the overall performance and efficiency of the hybrid systems. The capacity of the inverters is designed to harmonize with the power output of the hybrid system configurations. In the current work, the inverters span a range of capacities, from 125 to 210 kW. This diversity in inverter capacity allows for accommodating the power generation variations stemming from different system sizes and configurations. To manage the energy flow efficiently, we designed charge controllers to handle the expected charging current, calculated based on the 1000 W load and a 12V battery system.

The battery system was sized to store the required energy, ensuring 12 hours of operation. About 32 batteries with a total capacity of 1500AH and 12 V were chosen to meet the demand profile. Efficiency is a crucial parameter that directly impacts the energy conversion process within the hybrid system. The assumed efficiency of the inverters in this study is 96%. This efficiency accounts for the losses incurred during the conversion of DC power to AC power, and it reflects the overall effectiveness of the inverter in maintaining the quality of electricity output. Notably, while the 96% efficiency serves as a representative assumption, real-world efficiency figures can vary based on factors such as the specific inverter technology, manufacturer, and operating conditions. In practice, selecting a suitable inverter that balances efficiency, reliability, and cost becomes critical when designing and implementing hybrid power systems.

Cost Estimation

Table 2 estimates the cost of a hybrid renewable energy system and provides a breakdown of cost estimations associated with its design and execution. The system is designed to meet a daily average load demand of 500 W, divided into three categories: Solar energy, wind energy, and hydro-energy, each contributing two units of 500 W.

The costs related to the solar energy component are detailed. It includes purchasing ten solar panels, each with 150 W and 12 V capacity, totaling Rs. 30,000. Additionally, an erection and fixing cost, representing 30% of the solar panels cost, amounting to Rs. 9,000. The overall cost for the solar system is Rs. 39,000.

The costs associated with the wind energy component. It includes acquiring a single wind turbine with a 1 kW capacity of Rs. 10,000. The erection and fixing cost for the wind turbine, representing 30% of its price, is Rs. 3,000." The estimated wind system cost is Rs. 13,000.

The costs for the hydro-energy component are described. It is noted that no additional expenses were incurred for the existing overhead tank with a water pump. The expense of the hydro turbine generator is 7,500 rupees, plus fixing fees. Thus, the final cost of the hydro-system is Rs. 7,500.

The cost of charge controllers, where two controllers with a capacity of 100 A each are considered. The total cost for the charge controllers is Rs. 4,200.

For the storage battery component, the cost of 32 batteries, each with a capacity of 1500AH, is provided, totaling Rs. 83,200.

The price of the inverter, which has a 1500 W capacity, is specified here and comes to Rs. 5,000.

The total costs for each component are summarised. They include the expected prices for the hydroelectric generator system (Rs. 7,500, minus the overhead tank and pump), the wind system (Rs. 13,000), the solar system (Rs. 39,000), and miscellaneous accessories (Rs. 92,400), including charge controllers, inverter devices, and storage batteries.

Table 2: Cost estimation of hybrid renewable energy system

Load data	*Daily average demand*
Solar energy	Two units (500 W)
Wind energy	Two units (500 W)
Hydro-energy	Two units (500 W)

Table 3: The cost recovery period for this hybrid renewable energy system

Component	*Cost estimation*
Cost estimation of solar system	
Cost of 10 solar panels (150W, 12V each)	Rs. 30,000
Erection and fixing cost (30% of solar panels)	Rs. 9,000
Total cost for solar system	Rs. 39,000
Cost estimation of wind system	
Cost of 1 wind turbine (1kW)	Rs. 10,000
Erection and fixing cost (30% of wind turbine)	Rs. 3,000
Total cost for wind system	Rs. 13,000
Cost estimation of hydro-system	
Existing overhead tank with water pump	No Additional Cost Incurred
Cost of hydro turbine generator (including fixing)	Rs. 7,500
Total cost of hydro-system	Rs. 7,500
Cost of charge controller	
Cost of 2 charge controllers (100 A capacity)	Rs. 4,200
Cost of storage battery	
Cost of 32 storage batteries (1500 AH capacity)	Rs. 83,200
Cost of inverter	
Cost of inverter (1500 W capacity)	Rs. 5,000
Total cost of hybrid renewable system	
Estimated cost for solar system	Rs. 39,000
Estimated cost for wind system	Rs. 13,000
Estimated cost for hydro turbine generator (Excluding *et al.*)	Rs. 7,500
Cost of other accessories (Charge *et al.*)	Rs. 92,400
Total expenditure incurred for 1 house (Considering Govt. Subsidies)	Rs. 1,51,900
Cost recovery period	
Cost recovery period for 1 house (At Average 200 Units per Month for 9 Years)	Rs. 1,57,680

Considering government subsidies, the total expenditure incurred for setting up the hybrid renewable energy system for one house is Rs. 1,51,900.

The last row of Table 3 calculates the cost recovery period for this hybrid renewable energy system when applied to a house with an average monthly consumption of 200 units over nine years. The total cost recovery is estimated at Rs. 1,57,680.

Table 3 thoroughly analyzes the cost structure and recovery period for the described hybrid renewable energy system, making it easier to understand the project's financial aspects.

Significance in Hybrid Systems

The efficiency of the inverters plays a part in calculating the total effectiveness of the grid-tied hybrid power systems. Efficient power conversion helps minimize energy losses during the transition from DC to AC, ensuring that the maximum possible energy generated by the solar PV panels and fuel cells is effectively supplied to the grid and the building's electrical systems.

Inverter efficiency is considered in the AI-driven techno-economic analysis as part of the comparative study conducted in this research paper. The impact of inverter efficiency on the performance, economic feasibility, and environmental impact of the hybrid systems is evaluated alongside other crucial parameters, contributing to a comprehensive understanding of the intricate interactions within these systems (Soni *et al*., 2024).

Hence, inverters are critical in grid-tied hybrid power systems because they facilitate power conversion for grid compatibility. Inverters' capacity and efficiency directly impact hybrid systems' overall performance and efficiency. Including inverter efficiency as a variable in the AI-driven analysis further enhances the accuracy and depth of the techno-economic assessment, guiding optimizing these systems for improved sustainability and effectiveness (Pooja Soni *et al*., 2024).

Comparison with Past Studies

In this study, a 2.5 kW PV produces 3887 kWh of electricity. This is similar to the past study's (Najafi Ashtiani *et al*., 2020) PV size, which is unspecified but likely close in capacity to meet similar energy production levels.

This study used a 4 kWh battery and a 1.14 kW inverter. In contrast, the past study does not specify the battery size but uses a 1.14 kW inverter. The inverter size seems to be consistent between the two studies.

In this study, the levelized cost of electricity (COE) is approximately $0.174 per kWh, and the net present cost (NPC) is $23,978. The initial capital cost is $4,158. Our COE and NPC are lower than the previous study, suggesting a potentially more cost-effective system.

This study breaks down the component costs, including the costs of the battery and charge controller, PV, grid connection, reliability, greenhouse emissions, and inverter. In contrast, the past study provided a combined cost for the battery and charge controller, PV, grid, reliability, greenhouse emissions, and inverter. It appears that our research provides a more detailed cost breakdown.

The study reports a renewable fraction of 42.9%, indicating the proportion of energy generated from renewable sources. The past research does not specify this metric.

The study reports a COE of $0.209 per kW and an NPC of $28,409.1. These values provide insights into our system's cost-effectiveness.

These research results indicate a solar PV and battery system with favorable COE and NPC values, suggesting economic feasibility. The breakdown of component costs and consideration of the renewable fraction add depth to the financial analysis. Comparatively, our study presents detailed cost information and potentially offers a more cost-effective solution than the past study, which lacks some specificity in component sizes and costs.

Conclusion

This paper presents a comparative study of AI-driven techno-economic analysis for grid-tied solar PV-fuel cell hybrid power systems. The study considers two different AI techniques, namely, genetic algorithm (GA) and particle swarm optimization (PSO), to optimize the sizing and operating parameters of the hybrid system. The results show that both GA and PSO can be used to obtain a near-optimal solution for the hybrid system. However, GA is more computationally expensive than PSO.

The study also compares the technical and economic performance of the hybrid system with a standalone solar PV system. The outcomes show that the hybrid system has a lower levelized cost of electricity (LCOE) than the standalone solar PV system. This is because the fuel cell in the hybrid system can provide power during low solar irradiation times, like at night or on cloudy days.

The study concludes that AI-driven techno-economic analysis is a promising tool for optimizing the design and operation of grid-tied solar PV-fuel cell hybrid power systems. AI can help reduce the hybrid system's LCOE and make it a more competitive option for renewable energy generation.

References

Akan, T. (2023). Can renewable energy mitigate the impacts of inflation and policy interest on climate change? *Renewable Energy*, 214, 255–289.

Bühler, D., Schuetze, T., & Junge, R. (2015). Towards Development of a Labelfor Zero Emission Buildings: A Tool to Evaluate Potential Zero Emission Buildings. *Sustainability*, 7(5), 5071–5093.

Ghenai, C., & Bettayeb, M. (2019). Grid-Tied Solar PV/Fuel Cell Hybrid Power System for University Building. *Energy Procedia*, 159, 96–103.

Heydari, A., & Askarzadeh, A. (2016). Techno-economicanalys is of a PV/biomass/fuel cell energy system considering different fuel cell system initial capital costs. *Solar Energy*, 133, 409–420.

Inman, R.H., Pedro, H.T., & Coimbra, C.F. (2013,December).Solar forecasting methods for renewable energy integration. *Progress in Energy and Combustion Science*, 39(6), 535–576.

Jain, R.K., Smith, K.M., Culligan, P.J., & Taylor, J.E. (2014). Forecasting energy consumption of multi-family residential buildings using support vector regression: Investigating the impact of temporal and spatial monitoring granularity on performance accuracy. *Applied Energy*, 123, 168–178.

Kahwash, F., Barakat, B., & Maheri, A. (2023). Coupled thermo-electricaldispatch strategy with AI forecasting for optimal sizing of grid-connectedhybrid renewable energy systems. *Energy Conversion and Management*,293,1-25.

Kumar Sujit, Sharma Sasanka Sekhor, Giri Jayant, Makki Emad, Sathish T., &Panchal Hitesh. (2024). Perovskite materials with improved stability and environmental friendliness for photo voltaics. *Frontiers in Mechanical Engineering*,10,1-18.

Maghami, M. R., & Mutambara, A. G. O. (2023). Challenges associated withHybrid Energy Systems: An artificial intelligence solution. *Energy Reports*,9,924–940.

Meena, R.S., Singh, A., Urhekar, S., Rohit Bhakar, Garg, N.K., Israr, M., Kothari, D. P., Chiranjeevi, C., & Srinivasan, P. (2022, September 17). Artificial Intelligence-Based Deep Learning Model for the Performance Enhancement of Photovoltaic Panels in Solar Energy Systems. *International Journal of Photoenergy*, 2022, 1–8.

Najafi Ashtiani, M., Toopshekan, A., Razi Astaraei, F., Yousefi, H., & Maleki, A.(2020). Techno-economic analysis of a grid-connected PV/battery systemusing the teaching-learning-based optimization algorithm. *Solar Energy*, 203,69–82.

Nur Farzana Athirah Mohd Fadzli, Azlin Mohd Azmi, Nofri Yenita Dahlan, Zubir Ahmad Mohd Ismail, & Sreenath Sukumaran. (2023). An Analysis of Hybrid Renewable Energy System Using HOMER Pro: A Case Study in Sungai Tiang Camp, Perak. *Journal of Advanced Research in Applied Sciences and Engineering Technology*, 31(3), 79–92.

Odoi-Yorke, F., & Woenagnon, A. (2021). Techno-economic assessment of solarPV/fuel cell hybrid power system for telecom base stations in Ghana.*CogentEngineering*, 8(1), 1-25.

Pooja Soni, R. Naveena Bhargavi, Vikramaditya Dave and Hemani Paliwal. (2024). Artificial Intelligence-Enabled Techno- Economic Analysis and Optimization of Grid-Tied Solar PV-Fuel Cell Hybrid Power Systems for Enhanced Performance. In 2024 International Conferenceon Renewable Energy, *Green Computing and Sustainable Development (ICREGCSD)*, 472,1-15.

Prabhakaran, S., Annie Uthra, R., & Preetharoselyn, J. (2023). Deep Learning-Based Model for Defect Detection and Localization on Photovoltaic Panels. *Computer Systems Science and Engineering*, 44(3),2683–2700.

Reddy, B. R. S., Reddy, V. V., & Kumar, M. V. (2023). Modelling and analysis of DC-DC converters with AI-based MPP tracking approaches for grid-tied PV-fuel cell systems. *Electric Power Systems Research*,216, 1-25.

Rezaei, A.,Balal, A., & Jafarabadi, Y.P. (2023).Using machine learning prediction to design an optimized renewable energy system for a remote area in Italy. *International Journal of Applied Power Engineering*, 12(3), 331-340.

Sichilalu, S. M., Tazvinga, H., & Xia, X. (2016). Integrated Energy Management of Grid-tied-PV-fuel Cell Hybrid System. *Energy Procedia*, 103, 111–116.

Singh, A., & Baredar, P. (2016). Techno-economic assessment of a solar PV, fuel cell, and biomass gasifier hybrid energy system. *Energy Reports*, 2, 254–260.

Soni, P., Dave, V., Repalle, N.B. (2024). AI Based Performance Boost in Solar PV Fuel Cell Hybrids. In: Gundebommu, S.L., Sadasivuni, L., Malladi, L.S. (eds) Renewable Energy, Green Computing, and Sustainable Development. REGS 2023.*Communications in Computer and Information Science*, 2081. Springer, Cham.

Takatsu, N., & Farzaneh, H. (2020). Techno-Economic Analysis of a Novel Hydrogen-Based Hybrid Renewable Energy System for Both Grid-Tied and Off-Grid Power Supply in Japan: The Case of Fukushima Prefecture. *Applied Sciences*, 10 (12), 1-19.

Tamjid Shabestari, S., Kasaeian, A., Vaziri Rad, M.A., Forootan Fard, H., Yan, W.M., & Pourfayaz, F.(2022).Techno-financial evaluation of a hybrid renewable solution for supplying the

predicted power outages by machine learning methods in rural areas. *Renewable Energy*, 194, 1303–1325.
Tang, W., Yang, Q., Hu, X., & Yan, W. (2022). Deep learning-based linear defects detection system for large-scale photovoltaic plants based on an edge-cloud computing infrastructure. *Solar Energy*, 231, 527–535.
Toufik, T., DEKKICHE, M., & Denai, M. (2022). Techno-Economic Comparative Study of Grid-Connected Pv/Reformer/Fc Hybrid Systems with Distinct Solar Tracking Systems. *Energy Conversion and Management:X*,18,1-17.