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Optimizing Grid-Connected Solar PV-Fuel Cell Hybrid Systems through Artificial Intelligence-Assisted Techno-Economic Analysis

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Abstract: This paper presents the simulation, modeling, and optimization of a Grid-tied system tailored for a commercial building. The primary aim is to design a system that efficiently meets the electricity needs, prioritizing renewable energy sources, minimizing surplus power, reducing energy costs, and cutting greenhouse gas emissions. Through simulation and optimization techniques, the study evaluates various configurations of a hybrid solar photovoltaic (PV) and fuel cell system. The findings reveal that integrating solar PV with a fuel cell, alongside a solar-based electrolyzer for hydrogen production and employing cycle charging control, yields optimal performance. Specifically, the hybrid system generates 68% of its power from solar PV and 28% from the fuel cell.

Keywords*:* Renewable energy; solar PV; fuel cell; electrolyzer; hybrid power system; microgrid; modeling; simulation; optimization; control.

I. INTRODUCTION

Grid-tied solar PV fuel cell systems marks a significant advancement in sustainable energy solutions. These systems integrate solar photovoltaic (PV) technology with fuel cell technology, offering a hybrid approach to electricity generation. In grid-tied configurations, these systems are connected to the main utility grid, allowing for seamless integration and interaction with the existing infrastructure.

Grid-tied solar PV fuel cell systems leverage the complementary benefits of both solar PV and fuel cell technologies. Solar PV harnesses energy from sunlight to generate electricity, while fuel cells convert chemical energy from fuels like hydrogen into electricity through electrochemical reactions. By combining these technologies, grid-tied systems can maximize energy production and enhance overall system efficiency.

One of the key advantages of grid-tied solar PV fuel cell systems is their ability to contribute clean energy to the grid while also drawing supplementary power from the grid when needed. This dynamic interaction enables efficient energy management, ensuring a reliable and stable electricity supply for consumers.

Moreover, grid-tied systems facilitate the integration of renewable energy sources into the existing grid infrastructure, helping to reduce dependence on fossil fuels and mitigate greenhouse gas emissions. They also offer potential economic benefits through mechanisms such as net metering, allowing consumers to offset their electricity bills by exporting excess energy to the grid.

A microgrid power system encompasses a discrete energy framework comprising various distributed energy sources, including renewables such as wind, solar, geothermal, biomass, hydro, and ocean-based energy. It also incorporates generators fueled by both traditional and alternative energy sources, energy storage systems, loads catering to residential, commercial, and industrial needs, power conditioning units like inverters and converters, and demand management and control systems.

This microgrid energy setup is designed to function either in parallel with or independently from the main utility grid, offering local control and enhancing energy independence. Such locally managed microgrid systems contribute to energy resilience by providing backup during utility grid disruptions caused by severe weather events or natural disasters, thereby ensuring a more reliable energy supply and reducing transmission losses.

Essentially, microgrids serve as modern, small-scale centralized electricity systems, aligning with community objectives such as diversifying energy sources, reducing carbon emissions through renewable integration, ensuring energy reliability, resilience against power outages, and cost reduction.

Hybrid PV (photovoltaic) and fuel cell systems, augmented with hydrogen tanks, electrolyzers, converters, and integrated into electric loads and grid systems, marks a significant stride towards a more sustainable and versatile energy landscape.

Hybrid PV and fuel cell systems combine the strengths of solar PV technology, which converts sunlight into electricity, with fuel cell technology, which generates electricity through electrochemical reactions. By integrating these technologies, hybrid systems can capitalize on the intermittent nature of solar power and the consistent output of fuel cells, ensuring a more reliable and consistent energy supply.

Incorporating hydrogen tanks and electrolyzers into these hybrid systems adds a new dimension of energy storage and flexibility. Excess electricity generated by the PV panels can be used to produce hydrogen through electrolysis, which can then be stored in tanks for later use in fuel cells or other applications. This enables the storage of renewable energy for times when sunlight is not available, thereby enhancing the overall efficiency and reliability of the system.

Converters play a crucial role in hybrid systems by managing the flow of electricity between different components and optimizing energy conversion efficiency. They ensure seamless integration of the various energy sources and storage elements, maximizing overall system performance.

Electric loads represent the end-users of the electricity generated by hybrid systems, encompassing residential, commercial, and industrial applications. By directly supplying electricity to these loads, hybrid systems contribute to reducing reliance on traditional grid infrastructure and enable greater energy independence.

Integrating hybrid systems into grid infrastructure further enhances their versatility and impact. These systems can operate in parallel with the grid, supplementing or offsetting electricity demand, and even feeding excess energy back into the grid. This two-way interaction not only improves grid stability but also facilitates the adoption of renewable energy sources on a larger scale.

Hydrogen fuel cells represent a cutting-edge technology in the realm of clean energy. These devices operate through an electrochemical reaction between hydrogen and oxygen, emitting only water vapor and heat as byproducts, thus making them exceptionally environmentally friendly with zero greenhouse gas emissions during operation. Renowned for their high efficiency in converting chemical energy directly into electricity, fuel cells find application across diverse sectors, from stationary power generation for buildings and industrial facilities to powering vehicles, buses, trains, and even aircraft. Their reliability in delivering continuous power, coupled with scalability to meet varying energy demands, underscores their versatility. Moreover, fuel cells operate quietly, ensuring minimal noise pollution in residential and indoor environments. With a longer lifespan compared to traditional batteries and combustion engines, fuel cell systems require minimal maintenance. Additionally, their ability to utilize different fuels, including hydrogen, natural gas, methanol, or biomass-derived hydrogen, provides flexibility in energy sources. However, challenges such as the cost of hydrogen production, infrastructure development for storage and distribution, and ongoing technological advancements to enhance efficiency and reduce manufacturing costs, must be addressed to unlock their full potential in the global energy landscape.

Overall, the introduction of hybrid PV and fuel cell systems, combined with hydrogen storage, electrolyzers, converters, electric loads, and grid integration, represents a holistic approach to sustainable energy generation and consumption. By leveraging multiple technologies and optimizing their interaction, these systems offer a promising pathway towards a cleaner, more resilient energy future.

II. LITERATURE REVIEW

Numerous studies in the literature explore microgrid power systems. For instance, one study integrated renewable sources like micro-hydro (MHP) and photovoltaic (PV) systems into a microgrid model connected to the grid [1]. Results demonstrated optimal performance of power plants utilizing renewable sources, with the highest capacity MHP microgrid exhibiting the lowest energy costs, significant CO2 emissions reduction, and the largest proportion of renewable energy. However, these outcomes necessitated substantial initial capital investment. Another study proposed a biomass-based PV power plant to supply electricity to agricultural wells [2]. Findings suggested that combining PV and biomass systems could create a reliable and cost-effective hybrid energy solution. Previous investigations have also explored hybrid technology combinations for electricity generation from various renewable resources, including small-scale hydropower, solar PV systems, wind turbines, bio-diesel generators, and fuel cells [3]–[9].

Simulation, modeling and optimization using HOMER software and Simulink [10]–[17] were also used to identify the optimal off-grid options. The results show that a hybrid combination of renewable energy generators at an off-grid location can be a cost-effective alternative to grid extension.

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Micro-power optimization model was used in [10] to design renewable energy-based micro grid system: solar-biomass hybrid system for the electrification of the city of Sharjah. Dynamic simulation was used in [12] to design PV-dieselbattery off grid power system. A switched model predictive control for energy dispatching of PV-diesel-battery hybrid power system was investigated in [13]. Simulink was used, in [14], for economic analysis and environmental impacts of hybrid PV-diesel-battery systems for remote villages. Different control strategies were used, in [15], and [16], for modeling hybrid PV-wind-engine-battery and PV-diesel-battery hybrid power systems, respectively.

III. PROPOSED METHODOLOGY

This research aims to explore possibility of usage of Hybrid Renewable Energy System for a Grid-tied Solar PV- Fuel cell based micro power system. The proposed system will be designed for an area with a particular load demand. In Hybrid Power Systems, the optimal size of each system component is a complex task and involves several variables. So the aim is to have a good relation between performance and cost, also optimally designed hybrid system should be cost effective and reliable.

The concept of injecting photovoltaic power into utility grid has earned widespread acceptance in these days of renewable energy generation & distribution. Grid-connected inverters have evolved significantly with high diversity. Efficiency, size, weight, reliability etc. have all improved significantly with the development of modern and innovative inverter configurations and these factors have influenced the cost of producing inverters. Amongst the several fuel cells types used, hydrogen has become the most efficient and reliable fuel type. As hydrogen has become an important intermediary for the energy transition and it can be produced from renewable energy sources, re-electrified to provide electricity and heat, as well as stored for future use.

An on-grid or grid-tied solar system is a system that works along with the grid. This means that any excess or deficiency of power can be fed to the grid through net metering. Many residential users are opting for an on-grid solar system as they get a chance to enjoy credit for the excess power their system produces and save on their electricity bills. You will always have power either from the solar system or from the grid. They do not have batteries.

In this study, HOMER optimization model will be used. HOMER is capable to model and simulate a considerable number of system combinations, in order to achieve the best technical and economical results for a system. Input data required for HOMER are Meteorological data, Load profile, Economic data such as capital, and replacement cost, Fuel price, price of transaction electricity with the grid etc. Also depending upon climatic condition and renewable energy resources available, suitable data will be collected. Large numbers of options are available for different sizes of the components to be used. To fulfill that load demand of selected area different combination of hybrid renewable sources will be studied. Out of several possible combinations most economic and environmental friendly combination will be selected. This selection is made with the help of simulation results obtained from HOMER software.

HOMER is very popular and commercial software developed by National Renewable Energy Laboratory (NREL)/USA. This software is used for designing and planning HRES; evaluate technical and financially feasible options for off-grid and on-grid power systems. Various components of HRES can be modeled in HOMER such as wind turbines, solar PV array, fuel cells, small hydropower, biomass, converter, storage system, batteries and diesel/conventional generators. Inputs to the HOMER software are meteorological data such as wind speed, solar insolation, temperature etc., load profile of the area, technical details of generator, capital, replacement and operational & maintenance costs of components, controls and dispatch strategy. HOMER can perform simulation, optimization and sensitivity analysis of the HRES

Grid Tied Systems is connected to a larger independent grid typically the public electricity grid and feeds energy directly into the grid. The feeding of electricity into the grid requires the transformation of DC into AC by a synchronizing grid-tie inverter (also called grid interactive inverter).

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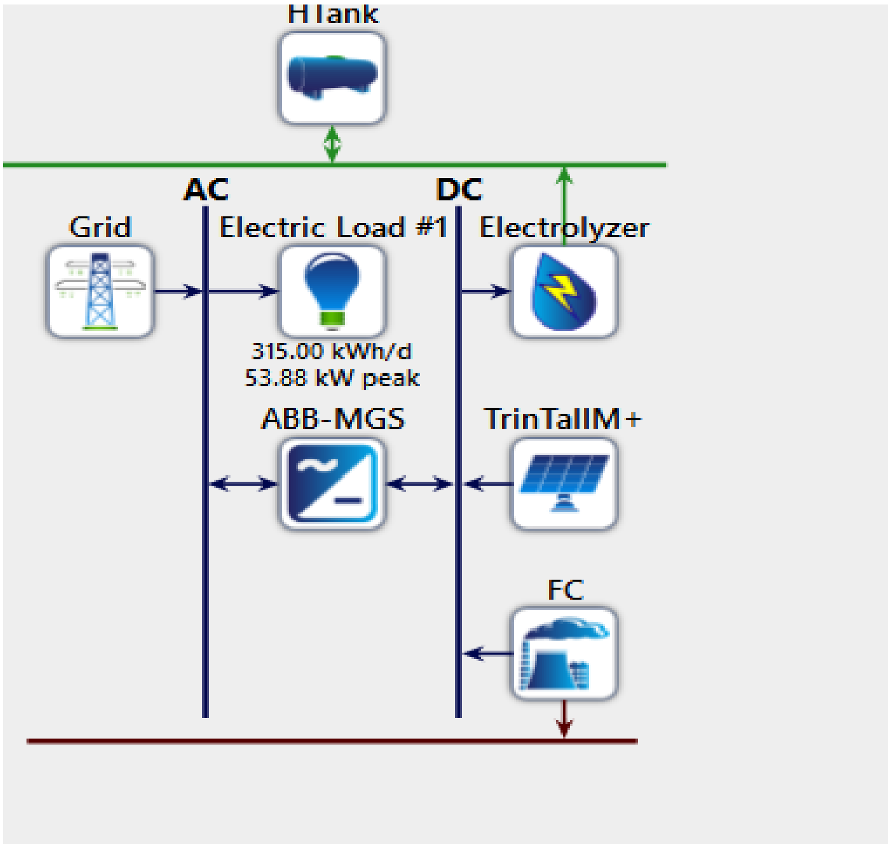

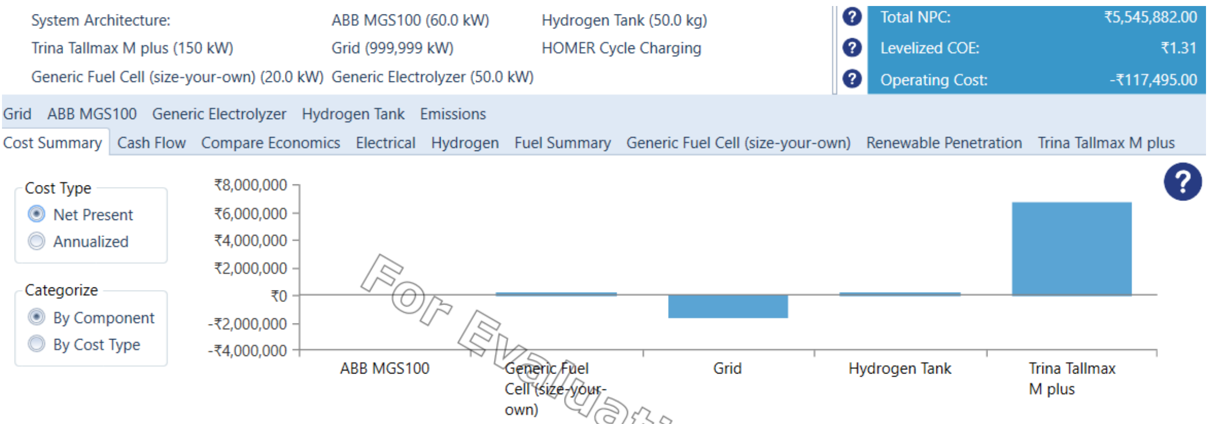

Component	Capital (₹)	Replacement (₹)	O&M (₹)	Fuel (₹)	Salvage (₹)	Total (₹)
▷ ABB MGS100	₹4,800.00	₹1,484.96	₹6,463.76	₹0.00	-₹279.48	₹12,469.23
▷ Generic Fuel Cell (size-your-own)	₹60,000.00	₹66,141.24	₹16,741.13	₹100,385.24	-₹9,133.14	₹234,134.47
▷ Grid	₹0.00	₹0.00	-₹1,707,185.34	₹0.00	₹0.00	-₹1,707,185.34
▷ Hydrogen Tank	₹250,000.00	₹0.00	₹6,463.76	₹0.00	₹0.00	₹256,463.76
▷ Trina Tallmax M plus	₹6,750,000.00	₹0.00	₹0.00	₹0.00	₹0.00	₹6,750,000.00
System	₹7,064,800.00	₹67,626.20	-₹1,677,516.69	₹100,385.24	-₹9,412.63	₹5,545,882.12

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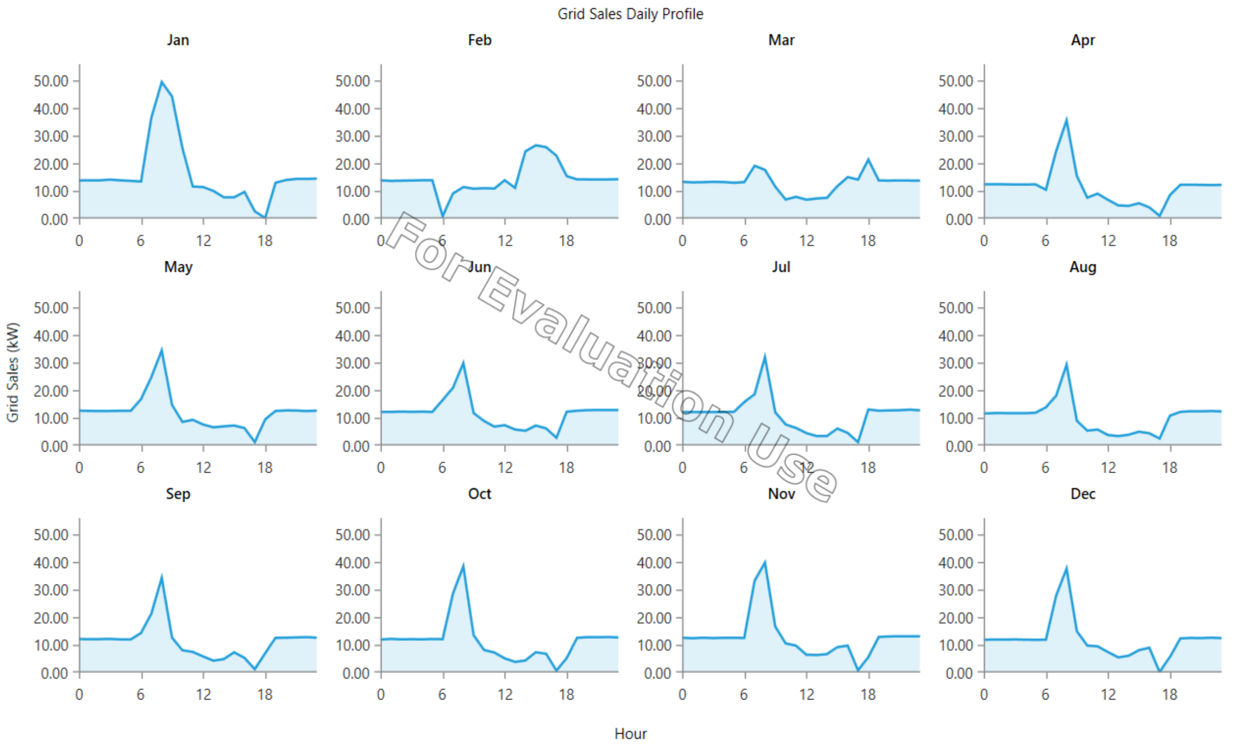

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Hydrogen Tank	₹250,000.00	₹0.00	₹6,463.76	₹0.00	₹0.00	₹256,463.76
Trina Tallmax M plus	₹6,750,000.00	₹0.00	₹0.00	₹0.00	₹0.00	₹6,750,000.00
System	₹7,064,800.00	₹67,626.20	-₹1,677,516.69	₹100,385.24	-₹9,412.63	₹5,545,882.12

IV. RESULTS

Results of HOMER Pro software HOMER software aims to minimize the cost of energy (COE) both in finding the optimal system configuration and in operating the system; economics play a crucial role in the simulation. The parameter considered to compare the economics of different configuration is the cost of energy (COE), and the total NPC is taken as the economic figure of merit. HOMER simulates the operation of a system by making energy balance calculations in each hourly time step of the year. For each time step, HOMER compares the electric demand in that time step to the energy that the system can supply in that time step. Then, it calculates the flow of energy to and from each component of the system.

HOMER performs these energy balance calculations for each system configurations that were considered. It then determines whether a configuration is feasible, i.e., whether it can meet the electric demand under the specified conditions, and estimates the cost of installing and operating the system over the lifetime of the project. After simulating all of the possible system configurations, HOMER displayed a list of configurations sorted by net present cost (NPC) and cost of energy (COE), which can be used to compare the different system design options.

The NPC of a component is the net present value of all the costs of installing and operating that component over the project lifetime, minus the present value of all the revenues that it earns over the project lifetime. HOMER calculates the NPC of each component in the system, and of the system as a whole. The optimization results show that the 58.2 KW solar PV, 10 KW fuel cell and 18 KW electrolyzer with 44.2 KW converter gives the cheapest configuration. The cost of energy (COE) of this configuration is ₹3.77 and the net present cost (NPC) of the system is ₹545,882.00.

V. CONCLUSION

This work's main objective is to assist officials, decision-makers, and the private sector in identifying advantages, opportunities Interest in generating electricity from renewable energy is increasing worldwide. With the very deep reliance on fossil fuels, the following details are frightening: The coal and oil manufacture in the world will achieve its greatest threshold soon, thereafter, it will keep on decreasing. World uranium production is expected to attain its zenith level in 2035. Nuclear fuel can be recycled, but it is a riskier procedure and the clearance of the spent fuel is also at high risk. So the total world is giving consideration towards the Renewable Energy System (RES). To further address the environmental issues arising from the obnoxious emissions, more efficient supercritical coal-based units are being commissioned and old and inefficient coal-based capacity is being retired. Renewable energy sources are environmentally clean without causing greenhouse gas and cheap alternative to fossil fuels. To overcome or at least limit some of the problems associated with conventional energy sources, renewable energy resources are the solution. Renewable energy resources are highly site-specific, stochastic in nature, and are fairly evenly distributed around the world with little or no costs. They are greatly dependent on the climatic conditions, geographical factors, and seasons of the site under consideration. Therefore Hybrid Renewable Energy Systems (HRES) having integration of fossil fuels with renewable sources is the best solution. However, for better performance of HRES, environmental factors and a proper combination of suitable renewable energy sources is very important. System reliability during various climatic conditions and the overall cost of the system is a serious concern in designing HRES. Therefore grid-connected HRES is the best option for urban areas where a utility grid is available but using HRES can reduce dependency on the grid and reduces emission in the atmosphere.

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