IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 17 May 2024, accepted 27 May 2024, date of publication 28 May 2024, date of current version 5 June 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3406895

RESEARCH ARTICLE

Feasibility Study and Economic Analysis of PV/Wind-Powered Hydrogen Production Plant

KHAIRY SAYED[1], MOHAMED KHAMIES[1], AHMED G. ABOKHALIL[2,3], MAHMOUD AREF[3], MAHMOUD A. MOSSA[4], MISHARI METAB ALMALKI[5], AND THAMER A. H. ALGHAMDI[6,7]
[1]Faculty of Engineering, Sohag University, Sohag 82524, Egypt
[2]Department of Sustainable and Renewable Energy Engineering, College of Engineering, University of Sharjah, Sharjah, United Arab Emirates
[3]Department of Electrical Engineering, Assiut University, Assiut 71516, Egypt
[4]Electrical Engineering Department, Faculty of Engineering, Minia University, Minia 61111, Egypt
[5]Department of Electrical Engineering, Faculty of Engineering, Al-Baha University, Alaqiq 65779-7738, Saudi Arabia
[6]Department of Electrical Engineering, Faculty of Engineering, Al-Baha University, Al Bahah 65779, Saudi Arabia
[7]Wolfson Centre for Magnetics, School of Engineering, Cardiff University, CF24 3AA Cardiff, U.K.

Corresponding authors: Mahmoud A. Mossa (mahmoud_a_mossa@mu.edu.eg) and Thamer A. H. Alghamdi (Alghamdit1@cardiff.ac.uk)

ABSTRACT In Egypt, the production of power and the associated environmental problems are starting to take the stage. One environmentally responsible way to lessen the power crisis is to employ renewable energy sources effectively and efficiently. This paper proposes to develop a hydrogen energy storage-based green (or environmentally friendly) power plant on many Egyptian cities such as Sohag city. To produce green hydrogen, the proposed power station uses energy storage, solar, and wind power. Energy storage systems are used to store extra energy produced by wind turbines and solar panels and to supply energy when the output of renewable energy is low. An optimized design of the proposed power plant uses hydrogen energy to satisfy peak load requirements and reduce GHG (greenhouse gas) emissions. Electrolysis is the method used in the proposed solar/wind power plant to create hydrogen. Water can be split into hydrogen and oxygen via electrolysis, a process that uses electricity. Renewable energy sources can be used to power this procedure, ensuring that the hydrogen produced is "green" and does not contribute to greenhouse gas emissions. The design of the power plant incorporates advanced electrolysis technology, such as proton exchange membrane (PEM) electrolyzers, which are efficient and well-suited for integrating with renewable energy sources.

INDEX TERMS Cost-effective, DC/AC microgrid, green hydrogen, PV/wind, RES integration, sustainable energy.

I. INTRODUCTION

Nowadays, our biggest obstacle is the climate catastrophe. Despite being a vital component of the battle, wind power is insufficient to prevent a 2°C rise in global temperatures, as stipulated by the United Nations Paris Agreement. Ingenuity and enthusiasm are needed to decarbonize all economic sectors, including transportation and heavy industries [1]. Over the next several years, green hydrogen is expected to emerge as one of the key solutions leading to a green economy. One excellent technique to spread the advantages of renewable energy sources outside the power industry is green hydrogen. One of the biggest solar parks in the world, Egypt's enormous solar park in Upper Egypt's Aswan has a 1.8 GW max capacity [2]. Green hydrogen is a versatile energy source that finds use in transportation, heating and cooling systems, and industries. It can be produced by several methods, including coal mining, oil distillation, desalination of brackish water, and natural gas conversion. Recently, there has been a notable global increase in interest in the synthesis of green hydrogen using renewable resources, namely hydropower, wind power, and solar energy. Unfortunately, due to their lack of infrastructure, insufficient funding, and insufficient technology in this new area, developing nations

The associate editor coordinating the review of this manuscript and approving it for publication was Ton Duc Do.

are currently unable to take advantage of the prospects presented by the shift to green hydrogen [3].

Green hydrogen has garnered increasing attention throughout time because of its many benefits and boundless potential, most notably as a productive and sustainable energy source. However, the hydrogen production process can be expensive in terms of both money and technology. For that, fossil fuels are mostly used in their manufacture. As a result, green hydrogen generation was introduced using renewable energy sources, especially photovoltaics (PV), to electrolyze hydrogen. The most effective method of manufacturing is electrolysis, which yields green hydrogen with no carbon footprint. From an economic standpoint, the process of manufacturing hydrogen is still somewhat costly because it depends on several PV and electrolyzed-related parameters, including the price of PV modules, the price of the electrolyzed stack, and the balance of the plant. As mentioned above, the levelized cost of hydrogen (LCOH) is significantly influenced by the type of PV [3], [4]. One of the main influencing variables on the LCOH is also the PV's efficiency. According to Ref. [5], the LCOH is greatly impacted by a few nation-specific factors, such as capital expenditures and electricity pricing. As a result, the LCOH is lower in regions receiving more solar energy and vice versa.

Even in the rare instances where developing nations, like Egypt, are able to enter the green hydrogen market, they still have to deal with obstacles brought on by some nations' propensity to support regional in a method that reduces the production costs of green hydrogen producers. As a result, there is an imbalance in the global hydrogen market, which makes underdeveloped nations' green hydrogen less competitive than that of developed nations. The Middle East and North Africa, with their autonomous renewable energy supplies and close proximity to open markets, have enormous potential to become major providers of green hydrogen. During COP27, Egypt intends to declare the country's green hydrogen production strategy, with the goal of producing it at the lowest cost possible globally. As stated in a statement, Egypt's cabinet aims to assist Egypt in contributing to 8% of the global hydrogen market through the implementation of an approach developed in cooperation with the Arab Union for Sustainable Development and Environment (AUSDE) and the European Bank for Reconstruction and Development (EBRD). In order to provide a clean energy transit route to Europe, Egypt is attempting to attract investments in the production of green hydrogen. In order to do this, the nation has signed many memoranda of understanding (MoUs) with foreign partners over the course of the last year on the production of green ammonia and hydrogen. The Suez Canal Economic Zone (SCZone) will see the development of a 5 billion Dollar green hydrogen and ammonia factory in collaboration with Scatec, according to a memorandum of understanding signed in March 2022 between Egypt and the latter company. A million tonnes of product may be produced annually at the factory, and another million tonnes can be produced if necessary [6], [7].

The global production of hydrogen is 75 million tonnes per year. The majority of it is produced by fossil fuels, primarily coal and natural gas. This amounts to 830 million tonnes of carbon dioxide released annually, nearly equal to Germany's annual CO_2 emissions, and accounts for 6% of the world's natural gas consumption and 2% of the world's coal use. All of this hydrogen production using renewable energy will contribute significantly to the reduction of emissions. This little molecule has a vast potential market. Hydrogen can be produced without emitting greenhouse gases if renewable energy powers the electrolyzers that separate water into hydrogen and oxygen. This kind of hydrogen generation is frequently referred to as "green hydrogen." Decarbonizing a number of industries can be aided by clean hydrogen generated from fossil fuels via carbon capture or from renewable or nuclear energy. The fuel tank of a container ship can be filled using wind energy made possible by green hydrogen and the fuels it derives, such as green ammonia. The decarbonization potential of renewable energy sources can be greatly increased in this way by using hydrogen [8].

Renewable energy sources such as solar PV and wind power can be utilized to generate green hydrogen, which has many uses in a variety of industries and multiple advantages. Green hydrogen offers several significant advantages and applications [9]. Firstly, it provides clean energy as it is produced without generating greenhouse gas emissions, making it a sustainable and environmentally friendly energy carrier. Secondly, it serves as an energy storage solution, allowing excess renewable energy to be converted into hydrogen for use as fuel or electricity during periods of low demand. Thirdly, green hydrogen plays a crucial role in decarbonizing hard-to-abate sectors like heavy industry, long-haul transportation, and heating where electrification may not be feasible. Additionally, hydrogen enhances energy security by diversifying energy sources and reducing dependence on fossil fuels, thereby contributing to overall energy security and resilience. Furthermore, the development of a green hydrogen economy can stimulate economic growth, create new jobs, and attract investment in renewable energy technologies and infrastructure. Green hydrogen finds applications in various sectors including industrial processes like ammonia production, transportation through hydrogen fuel cells for zero-emission vehicles, energy storage for grid stability, power generation using fuel cells, heating and cooling systems in buildings and industries, synthetic fuels production for carbon-neutral transportation options, and even energy export from regions abundant in renewable resources to high-energy consumption areas, thereby contributing to global energy trade and security [10], [11], [12].

Overall, green hydrogen offers a flexible and sustainable energy solution with the potential to drive the transition to a low-carbon economy by addressing energy challenges across multiple sectors and applications as shown in Figure 1.

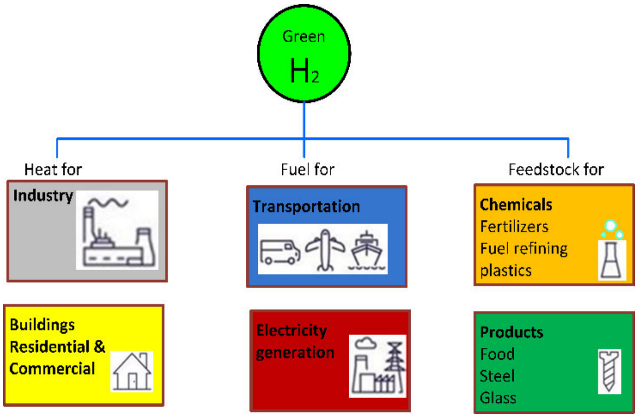

FIGURE 1. Green hydrogen's applications.

A hydrogen-generating power plant designed for environmental sustainability, efficiency, and cost-effectiveness can significantly contribute to renewable energy and sustainable development. It can reduce greenhouse gas emissions by using renewable energy sources, enhance grid stability, optimize energy utilization, and minimize energy losses. Additionally, by demonstrating economic viability and developing a sustainable business model, it can attract investment, drive innovation, and accelerate the transition to a more sustainable energy system. Overall, such a power plant can serve as a model for sustainable energy development and inspire further innovation in renewable energy solutions.

The technical and financial elements of employing PV systems to produce hydrogen through electrolysis are assessed in a techno-economic analysis of different grid-connected photovoltaic (PV) system configurations for green hydrogen production. This analysis considers different configurations of PV systems, such as fixed-tilt, single-axis tracking, and dual-axis tracking systems, to understand their impact on the efficiency and cost of hydrogen production [13]. The technical aspect of the analysis involves assessing the performance of each PV system configuration in terms of electricity generation and its suitability for powering electrolyzers to produce hydrogen. Factors such as solar irradiance, system efficiency, and capacity factor are considered to determine the amount of electricity that can be generated by each configuration.

The economic aspect involves evaluating the overall cost of hydrogen production using each PV system configuration. This includes considering the initial capital cost of installing the PV systems, the operational and maintenance costs, as well as the cost of the electrolysis process. Additionally, the LCOH is calculated for each configuration to compare the cost-effectiveness of producing hydrogen using PV systems [14]. By conducting this techno-economic analysis, researchers and stakeholders can determine the most suitable PV system configuration for green hydrogen production based on a balance between technical performance and economic feasibility. This information can help in making informed decisions about the deployment of grid-connected PV systems for green hydrogen production and contribute to the transition towards renewable energy systems.

This paper is to design a power plant that can produce hydrogen using renewable energy sources like wind and solar electricity. The objective is to tackle the growing apprehension regarding the ecological consequences of conventional power plants and the necessity of shifting towards more sustainable and clean energy sources. The study will also consider the proposed design's economic feasibility, considering the costs associated with renewable energy infrastructure, electrolysis technology, and hydrogen storage. The novelty of the paper lies in the estimation of the Levelized Cost of Electricity (LCOE) and Levelized Cost of Hydrogen (LCOH) for a specific project location. The Capital Recovery Factor (CRF) is determined through a calculation that considers the interest rate or discount rate and the expected lifespan of the system. Additionally, the Internal Rate of Return (IRR) is identified as the discount rate that equates the net present value (NPV) of all cash flows from the investment to zero. The cash flow curve is highlighted as a crucial tool for financial analysis of a green hydrogen plant, providing a comprehensive overview of the project's financial performance over time. Furthermore, the Net Present Cost (NPC) is typically computed by discounting all cash flows, including costs and benefits, to present value using a suitable discount rate. The concept of Present Worth is also emphasized in this context.

II. METHOD AND MATERIALS

A. PV/WIND HYDROGEN PRODUCTION PLANT DESIGN

The design steps for a PV/wind-powered hydrogen production plant involve a comprehensive process that considers technical, economic, and regulatory aspects. Figure 2 shows the block diagram of the design steps of the PV/wind-powered hydrogen production plant. Below are the key design steps for such a plant [15], [16]:

1. Resource Assessment:

- Conduct a thorough assessment of solar and wind resources at the proposed site to understand the availability and variability of these renewable energy sources. This involves analyzing historical data, conducting on-site measurements, and using simulation tools to estimate the potential electricity generation from PV and wind systems.

2. System Sizing and Configuration:

- Determine the optimal sizing and configuration of the PV and wind systems based on the resource assessment. Consider factors such as system capacity, technology selection (e.g., PV panel type, wind turbine model), and the incorporation of energy storage technologies to guarantee a steady and dependable power source for hydrogen generation.

3. Electrolysis Technology Selection:

- Select the appropriate electrolysis technology (e.g., alkaline, PEM, solid oxide electrolysis) based on factors such as efficiency, scalability, and compatibility with variable renewable energy inputs. Consider the required hydrogen production capacity and the dynamic response of the electrolyzer to varying electricity inputs from PV and wind systems.

4. System Integration and Control:

- Develop an integrated control system that manages the operation of PV, wind, energy storage, and electrolysis units to optimize hydrogen production while ensuring grid stability. This involves designing control algorithms, power electronics interfaces, and communication protocols for seamless coordination between renewable energy generation and hydrogen production.

5. Hydrogen Storage and Compression:

- Design the storage and compression infrastructure for hydrogen produced by the electrolysis process. Evaluate options such as gaseous or liquid hydrogen storage, as well as compression technologies to store and transport hydrogen for various end-use applications.

6. Safety and Regulatory Compliance:

- Ensure compliance with safety standards and regulations related to hydrogen production, storage, and handling. This includes conducting risk assessments, implementing safety measures, and obtaining necessary permits and approvals from relevant authorities.

7. Economic Analysis:

- Calculate the overall cost of the hydrogen manufacturing facility using solar and wind energy by doing a techno-economic study. Assess capital expenses, operational costs, and expected revenue from hydrogen sales or other applications, and compute the levelized cost of hydrogen (LCOH) to assess the project's economic feasibility.

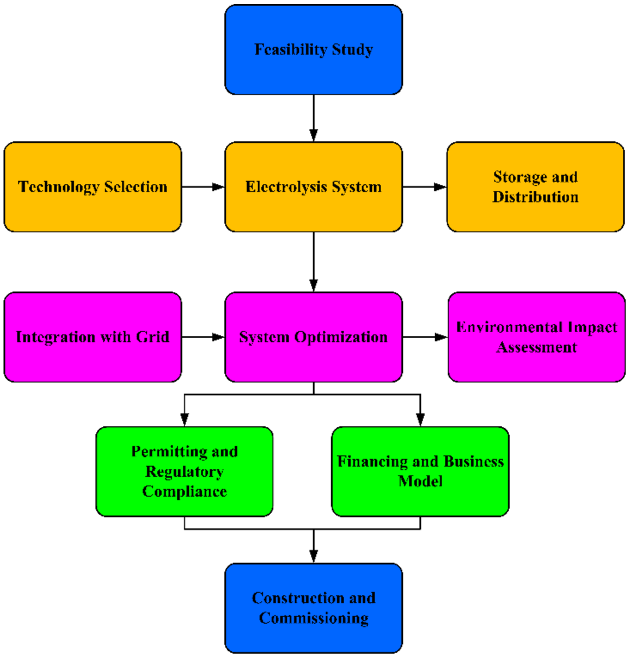

FIGURE 2. Block diagram of the design steps of the PV/wind-powered hydrogen production plant.

8. Environmental Impact Assessment:

- Assess the environmental impact of the plant, considering factors such as carbon emissions reduction, land use, water consumption, and potential ecological effects. Implement measures to minimize environmental footprint and ensure sustainable operation.

9. Project Financing and Implementation:

- Develop a financing strategy for the project, considering options such as grants, incentives, loans, or private investment. Create a detailed project implementation plan that includes procurement, construction, commissioning, and ongoing operation and maintenance activities.

10. Monitoring and Performance Evaluation:

- Establish a comprehensive monitoring and evaluation framework to track the performance of the PV/wind-powered hydrogen production plant. Collect data on energy generation, hydrogen production, system efficiency, and economic indicators to continuously optimize plant operation and inform future decision-making.

By following these design steps, developers can plan and implement PV/wind-powered hydrogen production plants that leverage renewable energy resources to produce clean hydrogen for various industrial, transportation, and energy storage applications.

Achieving sustainability objectives related to green hydrogen requires a multifaceted approach involving technological advancements, policy support, market incentives, and stakeholder collaboration. Key strategies include investing in renewable energy infrastructure to ensure a clean power source for green hydrogen production, fostering technological innovation to enhance system efficiency and reduce costs, implementing supportive policies like renewable energy targets and subsidies, fostering public-private partnerships to drive innovation and scale up production, developing markets for green hydrogen in sectors like transportation and industry, and building the necessary infrastructure for production, storage, and distribution. By implementing these strategies collectively, the transition to green hydrogen can lead to a cleaner, more resilient and sustainable energy future.

III. SYSTEM DESCRIPTION

A schematic of a stand-alone photovoltaic (PV)/wind turbine/battery system including solar PV cells, DC-DC converters, wind turbines, electrolyzers, hydrogen tanks, and a specific load is shown in Figure 3. Solar energy serves as the primary source, and wind turbines serve as backup storage devices. To meet the needed power, the wind turbine acts as a secondary (auxiliary) source.

Using a solar PV/wind standalone system for residential loads offers numerous advantages. Firstly, both wind turbines and solar PV systems utilize renewable energy sources like sunlight and wind, reducing reliance on fossil fuels and lowering greenhouse gas emissions for a cleaner environment. Secondly, homeowners can achieve energy independence by generating electricity from these sources, enhancing energy security during disruptions or power outages. Additionally, electricity bills can be significantly reduced or eliminated through solar PV and wind energy generation, with excess energy stored in batteries or converted to hydrogen for later use. Moreover, the minimal carbon footprint of these systems contributes to combating climate change, while their long lifespans of 20 to 30 years ensure prolonged benefits without major replacements. The versatility of installation options, quiet operation, and availability of incentives and tax credits further make solar PV and wind systems a cost-effective and sustainable choice for residential energy needs.

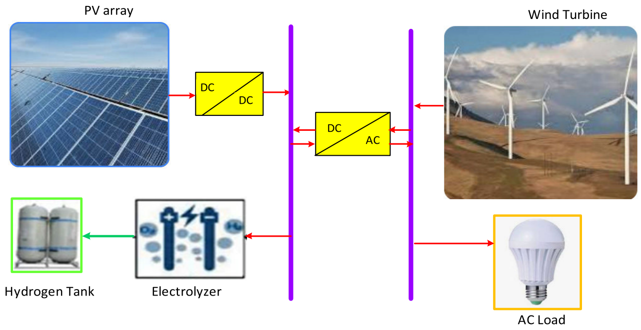

FIGURE 3. **Block diagram of a PV/Wind hydrogen generation system.**

A solar PV/wind turbine standalone system for residential load offers numerous advantages, including renewable energy generation, energy independence, cost savings, environmental benefits, and long-term reliability.

The electrolyzer load is the main focus of this paper. For more accurate and detailed modeling, one would need to incorporate more complex behaviors such as non-linear V-I characteristics, multiple temperature-dependent variables, and considerations for the specific materials and design of the electrolyzer being modeled. A comprehensive model would be implemented in simulation software that can handle the complex differential equations that govern the system's behavior.

IV. SYSTEM COMPONENT SPECIFICATIONS

The following section describes each component of the system and lists the technical specifications.

A. PV MODULE SPECIFICATIONS

Table 1 lists the circuit parameters for the PV module. Test settings for the electrical standards include a cell temperature of 25 °C, a spectrum of 1.5 air masses, and an irradiance of 1 kW/m^2 [17]. The PV is a Canadian Solar 340W mono-solar panel with type Canadian Solar CS1H-340MS mono-crystalline.

TABLE 1. **Circuit parameters for the PV module.**

Rated Power	340 W
Maximum power Voltage (V_{mp})	37.8 V
Maximum power Current (I_{mp})	9 A
Open-circuit voltage (V_{oc})	44.5 V
Short-circuit current (I_{sc})	9.57 A
number of series connected cells (N_s)	60
Max DC Voltage of the System	DC 1000 V
Efficiency of module	20.16%

B. ELECTROLYZER

The process of electrolysis is the result of two separate processes occurring at the electrodes, where water electrolysis is a technique for generating hydrogen (and O2) [16]:

$$H_2O - 2e^- \rightarrow \frac{1}{2}O_2 + 2H^+ \tag{1}$$

$$2H^+ + 2e^- \rightarrow H_2 n = 2eq./mol_{H_2} M_{H_2} = 2g/mol \tag{2}$$

This analysis shows how much opportunity there is to manage the power subsystem in a fully electrified society and to turn the excess energy into hydrogen carriers. Water electrolyzers can only be used with load sequences during off-peak hours or by adjusting current densities in response to changes in electricity demand. The 10 kW PEM Water Electrolysis System's technical specifications are displayed in Table 2.

TABLE 2. **10 kW PEM water electrolysis system's specifications.**

Stack	LBE-P12C, 12 cell x 1ea
Size (L x W x H)	620 X 910 X 720 mm
Power Consumption	< 10 kW
Production of Hydrogen/h	up to 2000 L per hour
Production of Oxygen/h	up to 1000 L per hour
Pressure	0 - 5 bars
Temperature	10 - 60°C
Percentage Pure Hydrogen	99.97 - 99.99%
Percentage Pure Oxygen	99%
Input Voltage	380 VAC, 3-phase
Water source quality	16–18 MΩ of resistance in either deionized or distilled water

PEM electrolyzers are a highly efficient and scalable technology for producing green hydrogen from renewable energy sources like solar and wind power. With their fast response time, low maintenance requirements, and ability to generate high-purity hydrogen gas, PEM electrolyzers offer a promising solution for integrating renewable energy systems and enabling the transition to a more sustainable energy future. Their grid stability benefits and flexibility in adjusting hydrogen production levels make them a valuable asset in the quest for decarbonization and the advancement of clean energy technologies.

C. WIND TURBINE SPECIFICATIONS

When selecting specifications for a 100 kW wind turbine, various aspects need to be considered to ensure that all the key attributes and requirements of the turbine are described.

Table 3 lists the specification of the studied wind turbine. Certainly, the output power of a Horizontal Axis Wind Turbine (HAWT) is highly dependent on the wind speed at

TABLE 3. 100 kW wind turbine specifications.

Item	value
Rated power	100.0 kW
Cut-in wind speed	2.5 m/s
Rated wind speed	10.0 m/s
Cut-out wind speed	20.0 m/s
Diameter	25.0 m
Swept area:	490.9 m²
Number of blades:	3
Rotor speed, max:	50.0 U/min
Tip-speed	65 m/s
Generator	Permanent magnet alternator. SCF technology
Speed, max:	50.0 U/min
Voltage	690.0 V

the installation site. Here are the detailed specifications of a 100 kW HAWT with emphasis on power output relative to wind speed [18], [19], [20].

V. SIZING PROCEDURE

The total energy needed from PV is equivalent to the energy required by the electrolyzer plus the energy needed by the load during the day plus the energy needed by the battery charger, divided by the number of operating hours to get the kWp of PV panels. This information is used to calculate the size of the PV system [21], [22], [23].

The first step in sizing is to determine the energy requirements. This can be done by calculating the total energy consumption of the residential load, taking into account the daily and seasonal variations. Consider the wattage and duration of use for each appliance or device. The peak load and the lowest load are 3 kW and 1 kW respectively. The electrolizer works from 8 to 5 p.m. However, the electrolyzer cannot work at night [24].

The hydrogen generation rate using a 10 kW electrolyzer is 2000 per hour. Since it is working for 8 hours, the total generated hydrogen is 16000 L.

Figure 4 shows the sizing procedure flowchart. The input data includes information on weather conditions (such as sunlight intensity and duration), residential load requirements, and system constraints (such as maximum capacity of the PV panels, and wind turbine).

Based on the input data and system specifications, the available energy from the PV panels, and wind is calculated. This involves estimating the energy generation from the PV panels, hydrogen production from the electrolyzer, and energy storage in the battery.

The calculated available energy is compared against the residential load demand to determine if it can be satisfied by the system. If the available energy exceeds the load demand, the system can meet the requirements. Otherwise, additional energy sources or storage options may be needed.

The system is ranked based on the cost of energy generated and the cost of hydrogen production. This ranking considers factors such as initial investment costs, operating costs, maintenance costs, and efficiency of energy conversion. Systems with lower overall costs and higher efficiency are ranked higher in terms of cost-effectiveness.

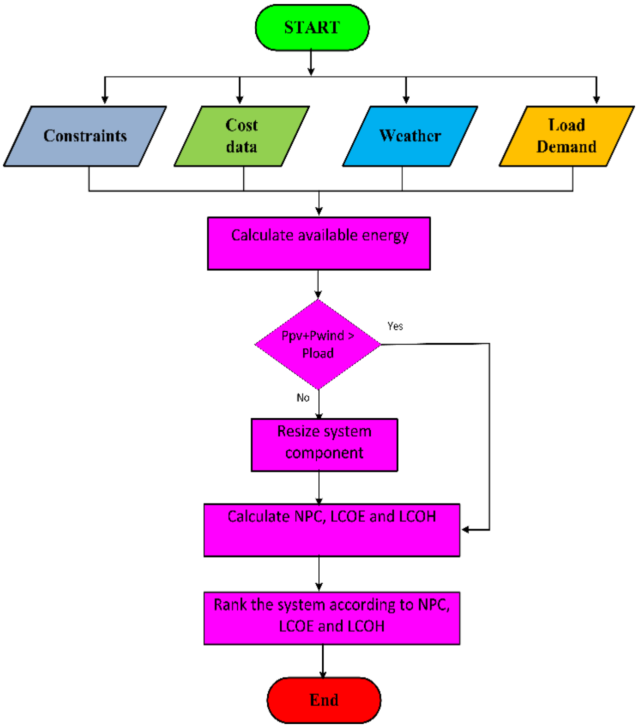

FIGURE 4. Flowchart of sizing method.

The cost of energy refers to the total cost incurred to generate electricity using PV panels and wind. This includes the initial investment in equipment, maintenance costs, and operational expenses over the system's lifetime. The cost of hydrogen production relates to the expenses associated with electrolyzing water to produce hydrogen for the wind turbine. This cost includes electricity consumption, maintenance of the electrolyzer, and hydrogen storage.

By ranking the system according to the cost of energy and hydrogen, decision-makers can identify the most economically viable configuration that meets both energy demand and sustainability goals.

Overall, this flow chart provides a structured approach to evaluating and optimizing the performance of the PV/wind standalone system based on input data, energy calculations, load demand assessment, and cost considerations.

A. SOLAR PANEL OUTPUT CALCULATION

Two things are the simplest ways to determine how much energy solar PV panels will generate [25], [26]

1. What is the daily amount of sunlight received at the location?
2. How much power the panels are capable of producing in watts?

To calculate the useful energy delivered by a PV system, you would need to consider factors such as the system's installed capacity (in watts or kilowatts), its efficiency in converting sunlight into electricity, the amount of sunlight received at the location where the system is installed (insolation), and any losses due to shading, orientation, or system inefficiencies.

The formula to calculate the useful energy delivered by a PV system is:

$$\begin{aligned}&\text{Useful Energy (kWh)}\\&\quad = \text{System Capacity (kW)}\\&\qquad {}^{*}\text{Average Daily Solar Insolation(kWh/m}_2\text{/day)}\\&\qquad {}^{*}\text{Performance Ratio}\end{aligned}$$

The performance ratio takes into account losses in the system due to factors such as temperature, soiling, and shading. By accurately calculating the useful energy delivered by a PV system, you can assess its effectiveness in meeting your energy needs and evaluate its economic and environmental benefits. Just multiply these two numbers together to get your total daily wattage production. For example, if you reside in an area with six hours of sunlight each day. and your solar panels can produce 250 watts each, then you would multiply 600 (the number of sun hours) by 250 (watts per panel) to get 150,000 watts. This means that your solar panels will produce a total of 150,000 watts each day. The following calculation can be used to determine your solar panel system's annual output:

$$E = A * r * H * PR \tag{3}$$

where E = Energy (kWh)

A is the area of solar panel (m^2)

r is the solar panel efficiency or yield (%)

H is the annual average solar radiation on tilted panels

PR is the performance ratio, the coefficient for losses (range between 0.5 and 0.9, default value = 0.75)

For additional clarification, the value of r represents the yield of a solar panel, which is calculated by dividing its electrical output (measured in kWp) by its area. The module's Performance Ratio (PR), which considers performance independent of panel tilt or orientation, is a crucial metric for evaluating the quality of a solar system. All losses are included. Figure 5 shows solar irradiance at the selected location in Sohag City during the day. Figure 6 displays the average monthly solar irradiance in Sohag City. Figure 7 shows the average wind speed in Sohag city.

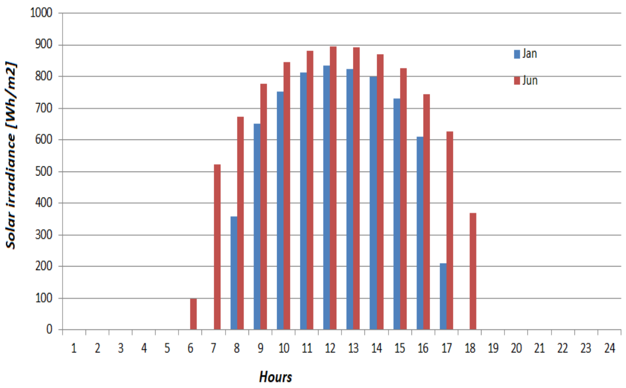

FIGURE 5. Solar irradiance at selected location in Sohag city during day.

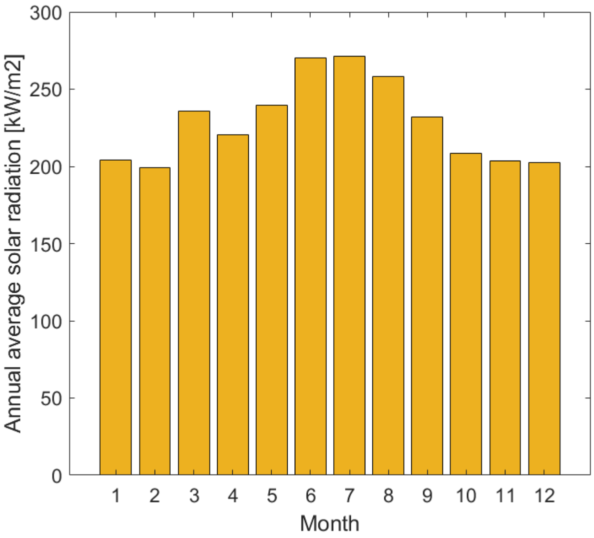

FIGURE 6. Average monthly solar irradiance in Sohag City [21].

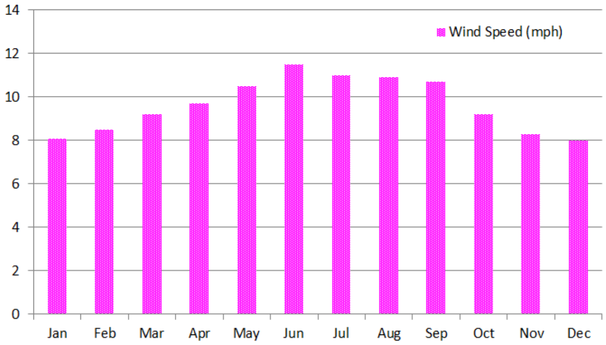

FIGURE 7. Average wind speed in Sohag city.

VI. COST ANALYSIS

MATLAB code was used to develop a model that simulates the production process for this investigation. For carrying the necessary values, each input and output in the model was given a float variable symbol, which is a letter. The model structure was then followed to develop a set of equations utilizing these variables. A techno-economic study was also carried out to forecast the viability of utilizing a PV solar system with capital expenditure based on the time required to reach the breakeven point and the net present value (NPV) throughout the life cycle. When determining whether to invest, one should be aware of the three cost components that make up cycle cost: the initial capital cost (CC), replacement cost (RC), and operation and management (OM) cost. The expenses of components CC, OM, and RC are known at the time of investment, but they will be incurred later. A PV system's rated output power (rated CC) is directly correlated with it. The cost of the PV array includes the balance of system (BOS) expenses, cabling, controllers, chargers, inverters, storage batteries, instrumentation, land area, and installation foundation costs, as well as the support structure for PV modules. When comparing a PV system to other renewable and non-RES systems, the CC is larger, and the OM cost is incredibly cheap. Two types of OM costs can be distinguished: fixed costs, independent of plant production, and variable costs, directly related to system output. Variable costs include fuel handling, wear and tear, etc., while fixed costs include site insurance, regular safety, and insurance.

Calculating the lifetime cost of the system requires consideration of the time value of money. In the long run, two factors determine the value of money: the inflation rate (i) and the discount rate (d). Inflation rates account for the progressive decline in the value of money over time. A product that costs C_p will cost C (1+ i) after a year, and so on. Because of the inflation rate, the future cost of n years C_n can be found in [28] as:

$$C(n) = C_p(1+i)^n \tag{4}$$

Money's value is increased in respect to its current value by the interest rate, but it is increased in reference to its future worth by the discount rate.

$$\textit{Discount rate } (d) = \frac{\textit{future value} - \textit{present value}}{\textit{future value}} \tag{5}$$

The future cash flow present value is calculated using a rate known as the discount rate. The potential rate of return that can be achieved by funding a different project with a comparable level of risk is represented by it, along with the opportunity cost of capital [29]. A dollar received today is worth more than a dollar received in the future due to the time value of money, which is taken into account by the discount rate. Many variables, including the risk profile of the project, market interest rates, and the investor's necessary rate of return, can affect the discount rate's value. A few percentage points to double digits can be found in its conventional expression, which is a percentage. The average cost of financing a project using both debt and equity is represented by the weighted average cost of capital (WACC), a discount rate that is frequently employed in financial analysis. Two more approaches are to use the project's cost of capital or the risk-free rate plus a risk premium. The particular discount rate used should be suitable for the project under review, taking into account its special features and risk profile. In the same way, as an inflation rate, the increase in money's value over n years, M(n), as a result of the discount rate, d, is as follows:

$$M(n) = Mo(1+d)^n \tag{6}$$

where Mo represents the total amount of money. When the discount rate is larger than the rate of inflation, money becomes more valuable.

A product's present worth (PW) is the total amount of money that must be invested now, discounted for inflation, and deducted for discounting in order to buy the product in the future (n years from now). Assume that the cost of a product will increase in the future due to both inflation and the discount rate (assuming the latter is larger than the former). The ratio of the product's future cost to its future value is known as the PW factor for future one-time investments.

$$P_f = \frac{\textit{future cost}}{\textit{future value}} = \frac{(1+i)^n}{(1+d)^n} = (\frac{1+i}{1+d})^n \tag{7}$$

The product's current cost is C_0, and present-value for a one-time investment for n year from now would be:

$$P_w = C_o P_f = C_o(\frac{1+i}{1+d})^n \tag{8}$$

A concept used in finance to calculate the present value of future cash flows or investments is called present worth, commonly known as present value. It's used to find out how much a project or investment is currently worth in US dollars. To calculate the present value, future cash flows or expenses would be subtracted using a specific interest rate or discount rate. This is due to the fact that money obtained or spent in the future will be worth less than money spent or gained now due to factors like inflation and the opportunity cost of investing that money elsewhere. The formula below can be used to calculate the present worth:

$$\textit{Present Worth} = \textit{Cash Flow}/(1 + \textit{Discount Rate})\hat{}n \tag{9}$$

where:

- Cash Flow refers to the future cash inflows or outflows.
- Discount Rate is the interest rate used to discount the cash flows.
- n represents the period in which the cash flow occurs.

One can evaluate the financial viability of a project or investment and compare various investment possibilities equally by computing its present worth. When an investment has a positive present worth, it means that the expected return will be higher than the discount rate; conversely, when it has a negative present worth, the expected return will be lower. Costs for fuel and maintenance were incurred in the LCC analysis. By applying Equation (4)–(7), which estimates recurrent investment once a year, the PW of future investment is determined. The total of the product's lifetime present value costs is the energy system's lifetime cost of consumption (LCC).

$$LCC = CC + OM + RC + FC \tag{10}$$

where RC is the replacement cost's present value, FC is the fuel cost, OM is the present value of all future operations and maintenance, and CC is the initial capital costs.

The annualized cost of the PV and wind turbine refers to the total cost of owning and operating the system annually. It considers the cost of initial investment, ongoing maintenance and operating expenses, and any additional costs associated with the system. The annualized cost of a system is determined by dividing its overall cost by its anticipated lifespan and then adding any yearly operational charges. It is possible to express this as:

$$\begin{aligned}&\mathit{Annualized\ Cost}\\&\quad = (\mathit{Total\ Cost\ of\ System/Expected\ Lifespan})\\&\qquad + \mathit{Annual\ Operating\ Expenses}\end{aligned} \tag{11}$$

The specific values for the total cost, expected lifespan, and annual operating expenses would depend on the PV and wind turbine system being evaluated. These costs can vary depending on factors such as the size of the system, installation costs, maintenance requirements, and fuel costs for the wind turbine component. It is important to note that the annualized cost is used to compare different energy systems or projects on an equal basis. By considering both the initial investment and ongoing expenses, it provides a more comprehensive measure of the true cost of ownership over time. The total cost of the hybrid energy system (CHES), which includes the cost of the solar PV system (CPV), wind turbine (CFC), battery (CBat), electrolyzer (Cez), power converter (CCon), and hydrogen tank (CHT), is equal to the sum of the costs of each of its individual components.

$$C_{HES} = C_{PV} + C_{FC} + C_{Bat} + C_{ez} + C_{Con} + \mathrm{C}_{HT} \tag{12}$$

The cost of each component of hybrid energy system,

$$C_i = N_i \times \left[Cap_i + (ReC_i + NR_i) + OMC_i\right] \tag{13}$$

where $\mathrm{C_i}$ is the hybrid energy system component (wind turbine, power converter, electrolyzer, hydrogen tank, and solar PV), N_i = Number/Size of component in the hybrid energy system, Capital Cost Hybrid Energy System Component (Cap_i), NR_i = Number of replacements, $Re\ C_i$ = Replacement Cost of Hybrid Energy System Component and $\mathrm{OMC_i}$ = Operational and maintenance cost component of a hybrid energy system.

The computation approach handles the load demand. Secondly, it evaluates the total net present cost (NPC) of the system, which represents the system's life-cycle costs, comprising the initial setup costs (IC), part replacement costs (RC), operation and maintenance costs (OM), fuel costs (FC), and the costs associated with obtaining power from the network.

Using the following equation, the net present cost (NPC):

$$C_{NPC} = \frac{C_{AT}}{CRF(i_r P_l)} \tag{14}$$

$$\mathrm{CRF} = \frac{i_r(1+i_r)^N}{(1+i_r)^N - 1} \tag{15}$$

when, $\mathrm{P_L}$ stands for project life (25 years), $\mathrm{i_r}$ for real interest rate (6.3%), N for number of years, $\mathrm{C_{AT}}$ for total annualized cost, CRF for capital recovery factor, and $\mathrm{C_{NPC}}$ for net present cost.

In financial computations, the capital recovery factor (CRF) is a factor that establishes the annual payment necessary to recoup the initial investment cost throughout the system's lifetime. It considers the projected lifetime of the system as well as the discount rate. The formula is used to determine the CRF.:

$$\begin{aligned}CRF &= (\mathit{discount\ rate} * (1 + \mathit{discount\ rate})\hat{\ }n)/((1\\&\quad + \mathit{discount\ rate})\hat{\ }n - 1)\end{aligned} \tag{16}$$

where:

- Discount rate: the rate of discounting future cash flows to their current worth. It represents the opportunity cost of capital.

- n: System's expected lifespan in years.

A. CALCULATION OF KWH COST

The CRF is provided by equation (17). This is a crucial component of economic analysis.

$$CRF = \frac{i\,(1+i)^N}{(1+i)^N - 1} == \frac{0.06(1+0.06)^{25}}{(1+0.06)^{25} - 1} = 0.0782 \tag{17}$$

where N represents the project lifespan in years and i is the interest rate.

$$\mathit{Total\ cost} = NPC + O\&MCost \tag{18}$$

where NPC, which comprises the costs of the PV, batteries, and inverter, is the minimal Net Present Cost. Cost of operation and maintenance is known as O&M Cost.

Total annualized cost is expressed by:

$$C_{ann} = CRF(i, R_{proj}).C_{NPC} \tag{19}$$

$$COE\ (\mathit{Cost\ Of\ Energy}) = C_{ann,tot}/E_{served} \tag{20}$$

The discount factor d can be calculated using the following equation:

$$d = \frac{\mathbf{1}}{(\mathbf{1}\ \boldsymbol{C}\ \boldsymbol{i})^{\mathbf{N}}} = \frac{1}{(\mathbf{1}+\mathbf{0.06})^{\mathbf{25}}} = 0.23 \tag{21}$$

Global radiation should be measured in HG kwh/$\mathrm{m^2}$/d each day. If monthly values are available, the daily average value of global radiation can be computed using (eq. 22) using the monthly average values. On the module's surface, the radiation is.

$$H_{G,t} = (1.1\ \mathit{to}\ 1.5) \times H_G \tag{22}$$

where $\mathrm{H_G}$ is the PV array surface's daily average global irradiation (kwh/$\mathrm{m^2}$).

Calculation of kWh cost is expressed by:

$$\begin{aligned}&\mathit{Operation\ cost\ of\ year\ of\ project\ installation}\\&\quad = Y\frac{(1.06)^{-20} - 1}{(1.06)^{-1} - 1}\end{aligned} \tag{23}$$

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} = \frac{0.06(1+0.06)^{20}}{(1+0.06)^{20} - 1} = 0.0872 \tag{24}$$

$$C_{ann} = CRF\left(i, R_{proj}\right).C_{NPC} \tag{25}$$

$$COE\ \ (\mathit{cost\ of\ energy}) = \frac{C_{ann,tot}}{E_{served}} \tag{26}$$

The cost of producing power from renewable energy projects is measured financially using the levelized cost of electricity (LCOE). When all costs are taken into account, including the initial investment, ongoing operating and maintenance costs, fuel prices (if applicable), and any revenue earned, it shows the average cost of producing one unit of energy over the course of the project. The whole lifetime costs of the project are divided by the total lifetime power generation to determine the LCOE. It allows for a comparison of different renewable energy technologies and helps determine their competitiveness with other sources of electricity generation, such as fossil fuels. The formula to calculate the LCOE is:

$$LCOE = (Total\ Lifetime - Costs)/(Total\ Lifetime - Electricity\ Generation) \tag{27}$$

The LCOE is typically expressed in dollars per kilowatt-hour (kWh) or cents per kilowatt-hour (c/kWh), making it easier to compare with the cost of electricity from conventional sources. A lower LCOE indicates a more cost-effective renewable energy project, as it means the cost of generating electricity is lower. Nonetheless, it's crucial to take into account additional elements such as environmental impact, reliability, and grid integration when evaluating renewable energy projects.

B. PAYBACK PERIOD

The time frame for recovering the investment made in a solar photovoltaic system must be ascertained after funding the installation. The payback period refers to the time frame within which the invested funds can be retrieved. Estimating the system's LCC and payback duration will allow determining the payback period. Calculated by dividing the initial investment in a photovoltaic system by the yearly COE savings resulting from the system, the figure known as the simple payback period is determined.

$$Payback\ period = \frac{initial\ investment\ cost}{annual\ cost\ of\ energy\ saving} \tag{28}$$

The amount of time needed to recoup the cost of the investment is known as the payback time (PB):

$$PB = \frac{C_0}{\sum_{t=1}^{T} \frac{C_t}{(1+i)^t}} \tag{29}$$

where If C_0 represents the total initial asset cost, i is the discount rate, and C_t is the net cash inflow for the period t.

C. NET PRESENT VALUE (NPV)

The total of all the capital costs, replacement costs, operating and maintenance costs, and costs associated with purchasing power from the grid that the system accrues over its lifetime is the net present cost of the system. This amount is deducted from the present value of all revenues, which include salvage value and the price for power that the hybrid energy system supplies to the grid. The difference between the present value of cash inflows and withdrawals is referred to as "net present value" (NPV):

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+i)^t} - C_o \tag{30}$$

A system's total net-present-cost (NPC) is equal to the present value of all proposed system costs it will incur over its lifetime less the present value of all the revenue it will get. Costs encompass a range of expenses such as initial investment costs, ongoing maintenance and replacement costs, fuel prices, pollution penalties cost, and grid power electricity costs. Salvage value and grid sales revenue are examples of revenue streams. The entire discounted cash flow for each year of the project's lifespan is added up to determine the overall NPC. The total NPC is the primary economic output, the metric used to rank each system configuration in the optimization findings, and the foundation for determining the levelized cost of energy and the total annualized cost of energy.

D. DEGREE OF SELF-SUFFICIENCY

The amount of electricity consumed that is supplied by distributed solar PV generation at the consumption site is known as the self-sufficiency ratio:

$$SS = \frac{EC_{PV}}{EC_{Total}} \tag{31}$$

where EC_{Total} is the total amount of electricity consumed, EC_{PV} is the electricity consumed during the manufacture of solar panels, and SS is the self-sufficiency ratio.

E. INTERNAL RATE OF RETURN (IRR)

A financial ratio called the internal rate of return (IRR) expresses how much of a project's return there is in relation to its investment. The anticipated cash flows are used to compute this ratio: The project's cash flow's net-present-value is equal to zero when the discount-rate known as IRR is applied:

$$IRR = \sum_{t=1}^{T} \frac{C_t}{(1+i)^t} - C_o \tag{32}$$

However, the cost analysis can be summarized by the flowchart given in Figure 8. Annualized Cost is the Total Cost of the System / Expected Lifespan) in addition to Annual Operating Expenses. Therefore, the Total Cost of the System is the sum of initial investment costs and any additional expenses incurred during the system's lifetime. Expected Lifespan is the estimated number of years the system is expected to remain operational. Annual Operating Expenses are ongoing costs associated with maintenance, repairs, and other operational expenses on an annual basis.

Capital Recovery Factor (CRF) Calculation is done depending on Interest rate or discount rate and expected lifespan of the system. Internal Rate of Return (IRR) is the

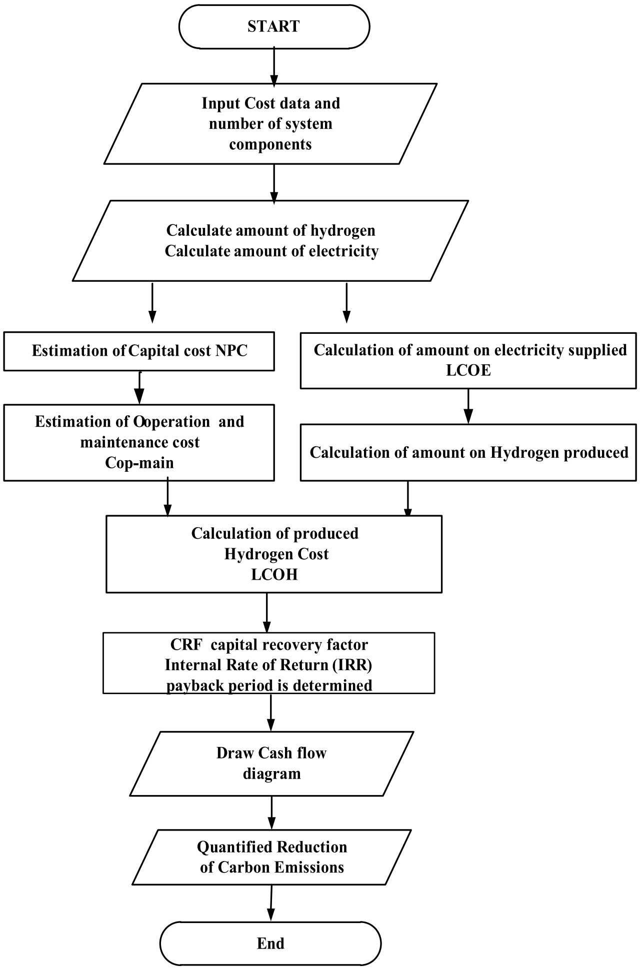

FIGURE 8. **Flowchart of economic cost analysis.**

discount rate that makes the net present value (NPV) of all cash flows from a particular investment equal to zero. It represents the annualized return on investment and indicates the profitability of the project.

The payback period is the time it takes for the cumulative cash flows from an investment to equal the initial investment cost. It is a measure of how long it will take for the project to recoup its initial costs.

A cash flow diagram visually represents the inflows and outflows of cash over time for a project or investment. It typically includes initial investment costs, operating expenses, revenues, and cash flows from the project over its lifespan.

By analyzing these financial metrics, decision-makers can assess the economic viability and profitability of the PV/wind standalone system. The CRF, IRR, and payback period provide insights into the system's financial performance and help in making informed decisions regarding investments in renewable energy systems. If you provide specific data on the total cost of the system, expected lifespan, annual operating expenses, interest rate, and cash flows, one can calculate the CRF, and IRR, and draw a cash flow diagram for further analysis.

VII. QUANTIFIED REDUCTION OF CARBON EMISSIONS

The purchase of electricity from the power grid can be replaced with the self-consumption of electricity based on solar PV. Fossil fuel power plants generate a significant portion of the electricity used in power grids in the majority of countries [30]. Therefore, one can approximate the simulation of the saved carbon emissions resulting from distributed solar PV generating by multiplying the self-consumption production by the average emissions of the country's power plants:

$$eCo2_{avoided} = EC_{PV} \times eCO2_{factor} \tag{33}$$

where EC_{PV} is the amount of energy produced by solar panels that is consumed in kWh, $eCO2_{factor}$ is the average coefficient of emissions of the nation's power plants in CO2/kWh, and $eCO2_{avoided}$ is the amount of CO2 emissions avoided in kgCO2.

One of the significant benefits of a PV/wind turbine and battery standalone energy system is the quantifiable reduction of carbon emissions. Solar PV systems generate electricity from sunlight, which is a clean and renewable energy source. By utilizing solar PV for electricity generation, the system reduces the reliance on fossil fuel-based power generation, thus reducing the emission of carbon. The amount of carbon emissions reduced can be calculated by comparing the emissions associated with electricity generation from the power grid to the emissions generated by the PV/wind turbine and battery system. Power grids often rely on fossil fuel-based power plants, such as coal or natural gas, which produce greenhouse gases when generating electricity. Solar PV systems, on the other hand, do not emit any greenhouse gases during operation. Therefore, electricity self-consumption based on solar PV becomes a substitute for purchasing electricity from the power grid, resulting in a direct reduction in carbon emissions. The quantification of carbon emission reductions can be an essential factor in assessing the environmental benefits and sustainability of the PV/wind turbine and battery standalone energy system. It provides a tangible metric to evaluate the system's contribution to mitigating climate change and reducing the overall carbon footprint.

Another important aspect to consider in the economic analysis is the concept of electricity self-consumption based on solar PV. This refers to using the electricity generated by the PV system directly on-site instead of relying on electricity purchased from the power grid. By maximizing self-consumption, the system reduces the need to purchase electricity, resulting in potential cost savings. This is particularly beneficial if the cost of electricity from the power grid is higher than the cost of generating electricity from the PV system. Furthermore, increasing self-consumption also improves the overall efficiency of the PV/wind turbine and battery system. It minimizes transmission and distribution losses associated with electricity transportation through the grid, as well as reducing the strain on the grid during peak demand periods. In some cases, excess electricity generated by the PV system can be stored in batteries for later use or even fed back into the grid, depending on the local regulations and incentives. This further enhances the economic viability of the system by enabling revenue generation through feed-in tariffs or power purchase agreements.

VIII. RESULTS

By implementing these methods, PV system owners can maximize the energy output and overall performance of their systems, leading to increased electricity generation and potential financial benefits.

The monthly output energy of the PV is shown in Figure 9, where the maximum output energy is achieved during the May and July months. Where the length of daylight changes throughout the year, impacting daily energy production.

The monthly output energy of the wind is shown in Figure 10, where the maximum output energy is achieved during the May and July months. Where, the wind speed changes throughout the year, impacting daily energy production.

The produced Energy by wind and PV are displayed in Figure 11 and total energy is utilized by the Electrolyzer to produce Hydrogen. The total quantity of hydrogen and oxygen is displayed in Figure 12.

Taking into account the cost of capital, the resulting CRF represents the yearly payment necessary to recoup the initial capital investment in the PV/ wind project. We can estimate the yearly payments required to recoup the initial investment by using the CRF that has been calculated. The CRF is only one part of the financial analysis for a PV project, so keep in mind that it does not take into consideration ongoing operational and maintenance costs. The capital recovery factor is shown in Figure 13.

The NPC curve, Fig. 14 considers variables like the initial investment, operating costs, revenues, and discount rates, and aids in visualizing the project's economic viability under various scenarios. Analyze the NPC curve's form. At lower discount rates, the project is more financially attractive, as indicated by a downward-sloping curve. The project's IRR, or the point at which the NPC curve crosses the x-axis, indicates when it becomes financially feasible.

The cash flow curve is an important tool for financial analysis since it offers a thorough picture of the project's financial performance over time. It's commonly used in conjunction with metrics like NPV and IRR to assess the microgrid's hydrogen production system's economic viability.

The salvage value in the last year helps to create a positive cash flow. The first investment in year 0 is represented as a negative cash flow. The following years show positive cash flows, indicating revenues exceeding operating and maintenance costs. Figure 15 shows the cash flow diagram of the system. The present worth of a PV-wind system represents the total value of all expected cash flows accompanying the system, discounted to their present value at a specific point in time. It is an important financial metric that helps assess the economic feasibility and profitability of investing in such a renewable energy system. Figure 16 displays the present worth of the proposed system.

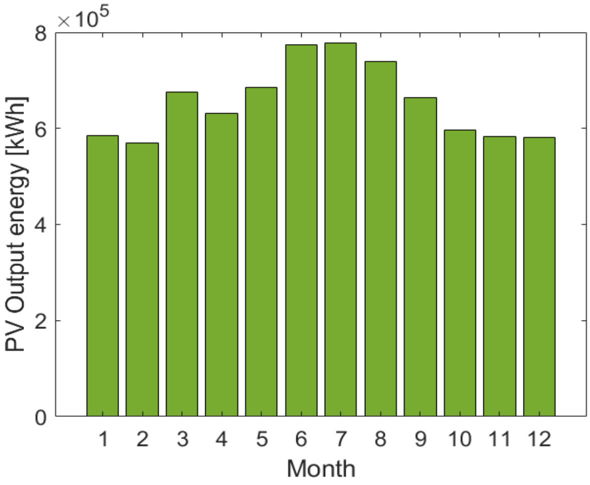

FIGURE 9. PV output energy per month.

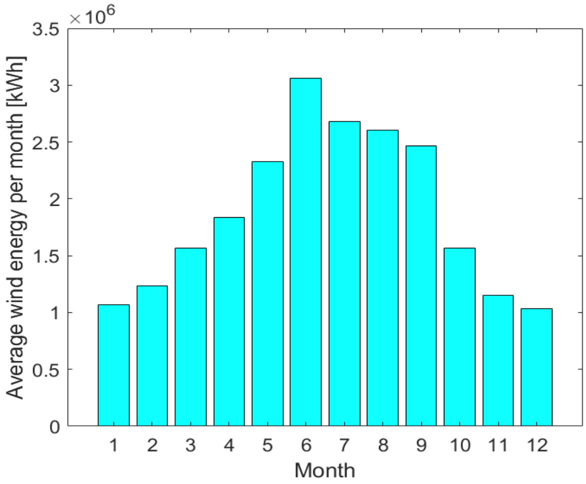

FIGURE 10. Produced energy per month.

During the system's lifetime, the original investment costs, fuel expenses, operating and maintenance costs, and other pertinent costs can all be taken into account to determine the NPC of the PV-wind-electrolyzer system. The NPC is typically calculated by discounting all cash flows (costs and benefits) to present value using an appropriate discount rate. It's important to note that the calculation of NPC can vary depending on specific project details, assumptions, and financial parameters. It's recommended to consult with a financial analyst or use specialized software tools for more accurate calculations.

Calculating the present worth involves discounting all future costs and benefits associated with the PV-wind system back to their current value using an appropriate discount rate. This makes it possible to compare various investment options fairly since it takes time worth of money into account and accounts for the risk associated with future cash flows.

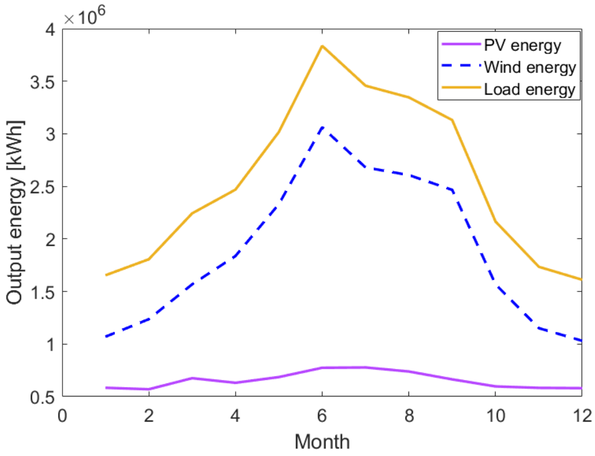

FIGURE 11. Produced energy and electrolyzer energy.

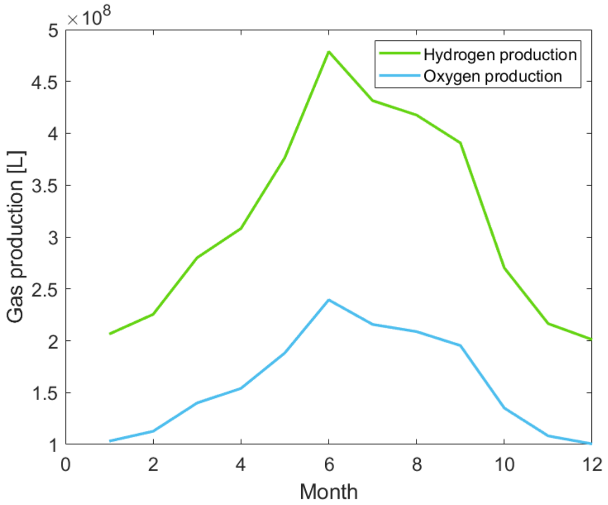

FIGURE 12. Oxygen gas production in cubic meters per month.

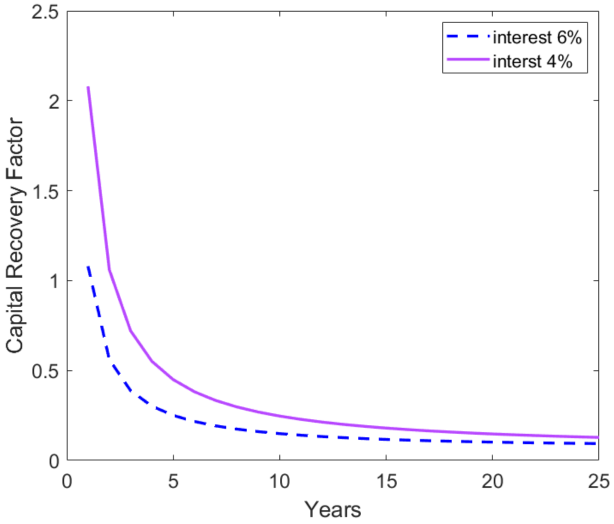

FIGURE 13. Capital recovery factor.

A PV-wind system is considered financially feasible if its current worth is positive, meaning that during its lifetime, it is predicted to provide more revenue or savings than its initial investment and operational costs. On the other hand, a negative present value indicates that the system could not be financially viable.

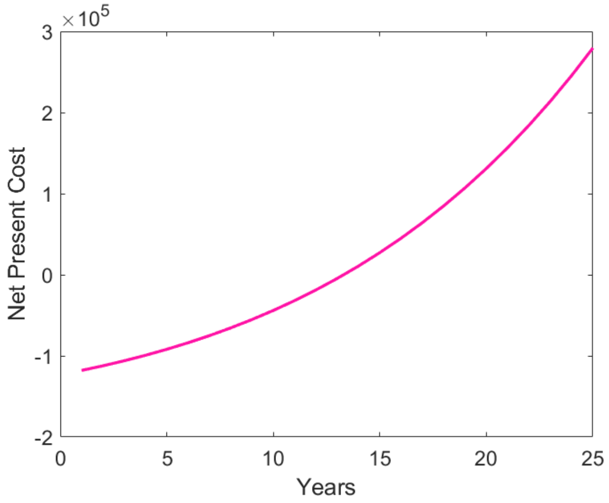

FIGURE 14. Net present cost.

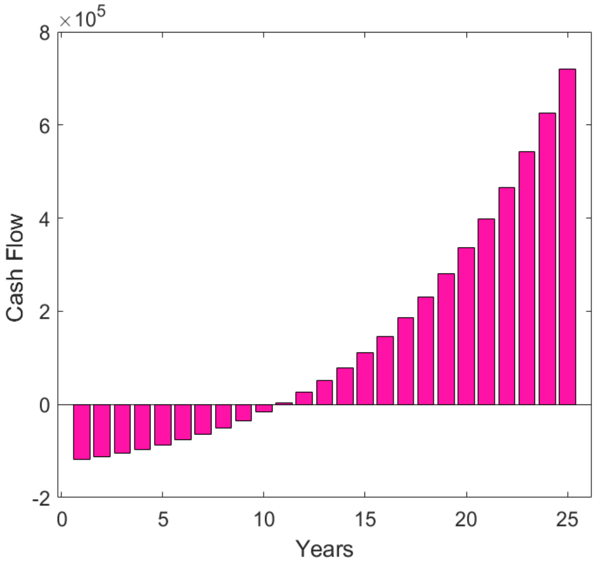

FIGURE 15. Cash flow of the proposed system.

The present value of a PV-wind system is determined in large part by factors including the cost of the original investment, ongoing operating and maintenance costs, energy production, fuel costs, incentives, tax credits, and discount rates. Evaluating the financial feasibility and dangers of investing in renewable energy systems, such as PV-wind, can be aided by performing a detailed financial analysis and sensitivity analysis.

One of the most important metrics for comparing the cost-effectiveness of producing hydrogen from different sources, such as electrolysis, steam methane reforming (SMR), and other technologies, is the levelized cost of hydrogen (LCOH). It shows the average cost of creating

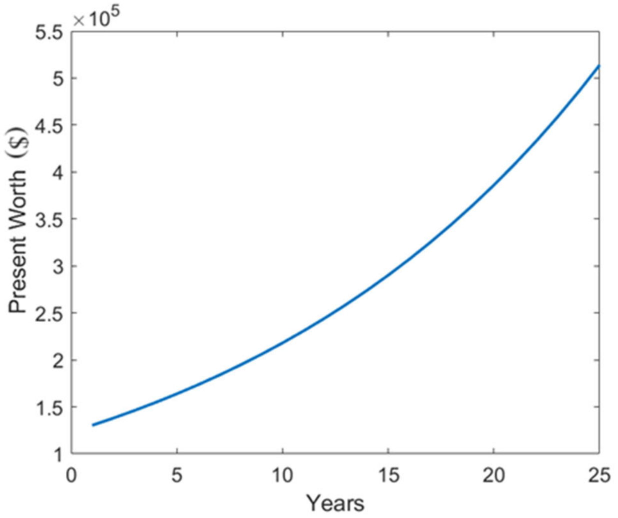

FIGURE 16. **Present worth of the proposed system.**

hydrogen for the course of the project, accounting for all expenses related to fuel intake, production, operation, and maintenance.

Calculating the LCOH involves considering the total costs of producing hydrogen, including capital costs, operating expenses, maintenance costs, fuel costs (if applicable), and any other relevant expenses. These costs are then spread out over the expected lifetime of the hydrogen production facility and discounted to their present value using an appropriate discount rate. However, LCOE and LCOH are achieved 0.022 \$/kWh, 11.06 \$/kg.

By calculating the LCOH, stakeholders can compare the cost of hydrogen production from different technologies and sources on a level playing field. This allows for informed decision-making regarding investment in hydrogen production projects and helps identify the most cost-effective options for achieving decarbonization goals.

Factors such as electricity prices, capital costs, efficiency of the production technology, utilization rates, and potential incentives or subsidies can all impact the LCOH of hydrogen production. As technology advances and economies of scale are achieved, the LCOH of hydrogen is expected to decrease, making it a more competitive option for various applications, including energy storage, transportation, and industrial processes.

In summary, the insights derived from the estimation of LCOE, LCOH, CRF, and IRR have far-reaching implications for engineering applications in the renewable energy sector. They provide a solid foundation for evaluating the financial aspects of projects, guiding decision-making processes, and ultimately contributing to the successful implementation of sustainable energy solutions.

IX. CONCLUSION

The design of a hydrogen-generating power plant powered by renewable energy sources has been discussed in this study, highlighting the potential and challenges of green hydrogen integration for sustainable energy. Factors such as workforce transition, infrastructure development, policy frameworks, technological advancements, environmental impact assessments, and economic viability were critically evaluated to emphasize the importance of thorough preparation and collaboration for green hydrogen to realize its full potential in creating a cleaner and more sustainable energy future. The study proposed methods for integrating multiple renewable energy sources into a single plant, demonstrating that combining solar and wind farms can enhance energy reliability and efficiency in hydrogen production. Cost analysis revealed that the cost of producing hydrogen decreases with higher solar radiation intensity and working pressure. Financial metrics such as LCOE, LCOH, CRF, and IRR were estimated for the project location, providing valuable insights for assessing the financial performance and feasibility of green hydrogen plants and guiding decision-making processes in the renewable energy sector.

REFERENCES

[1] S. Azodolmolky, J. Perelló, M. Angelou, F Agraz, L. Velasco, S. Spadaro, Y. Pointurier, A. Francescon, C. V. Saradhi, P. Kokkinos, and E. Varvarigos, "Experimental demonstration of an impairment aware network planning and operation tool for transparent/translucent optical networks," *J. Lightw. Technol.*, vol. 29, no. 4, pp. 439–448, Sep. 2011.

[2] *Green Hydrogen Fuel for Future*. Accessed: Jul. 2020. [Online]. Available: https://www.siemensgamesa.com/products-and-services/hybrid-and-storage/green-hydrogen

[3] M. Lamagna and D. A. Garcia, "Renewable energy penetration strengthened using a reversible solid oxide cell installed in a building," *CSEE J. Power Energy Syst.*, vol. 8, no. 2, pp. 360–368, Mar. 2022, doi: 10.17775/CSEEJPES.2021.04920.

[4] Z. Zhong, J. Fang, K. Hu, D. Huang, X. Ai, X. Yang, J. Wen, Y. Pan, and S. Cheng, "Power-to-hydrogen by electrolysis in carbon neutrality: Technology overview and future development," *CSEE J. Power Energy Syst.*, vol. 9, no. 4, pp. 1266–1283, Jul. 2023, doi: 10.17775/CSEEJPES.2022.08850.

[5] B. Hernández, A. Alkayas, E. Azar, and A. T. Mayyas, "Mathematical model for the placement of hydrogen refueling stations to support future fuel cell trucks," *IEEE Access*, vol. 9, pp. 148118–148131, 2021, doi: 10.1109/ACCESS.2021.3123901.

[6] C. Campbell-Stanway, V. Becerra, S. Prabhu, and J. Bull, "Investigating the role of byproduct oxygen in UK-based future scenario models for green hydrogen electrolysis," *Energies*, vol. 17, no. 2, p. 281, 2024, doi: 10.3390/en17020281.

[7] A. Elnozahy, M. Sayed, Alaa. F. M. Ali, and M. A. Nayel, "Optimal techno-economic sizing of electrical/green hydrogen generation system for hybrid demand load," in *Proc. 23rd Int. Middle East Power Syst. Conf. (MEPCON)*, Cairo, Egypt, Dec. 2022, pp. 01–08, doi: 10.1109/MEPCON55441.2022.10021775.

[8] I. Chakraborty and A. K. Bohre, "Impact of green hydrogen power generation on HRES for rural area including EV and home loads," in *Proc. IEEE Renew. Energy Sustainable E-Mobility Conf. (RESEM)*, Bhopal, India, May 2023, pp. 1–5, doi: 10.1109/RESEM57584.2023.10236191.

[9] A. Tabandeh, M. J. Hossain, and K. Khalilpour, "A planning framework for integration of distribution systems with grid-connected hydrogen refuelling stations," in *Proc. IEEE PES 14th Asia–Pacific Power Energy Eng. Conf. (APPEEC)*, Nov. 2022, pp. 1–6, doi: 10.1109/APPEEC53445.2022.10072243.

[10] C. Yan, Y. Zou, Z. Wu, and A. Maleki, "Effect of various design configurations and operating conditions for optimization of a wind/solar/hydrogen/fuel cell hybrid microgrid system by a bio-inspired algorithm," *Int. J. Hydrogen Energy*, vol. 60, pp. 378–391, Mar. 2024, doi: 10.1016/j.ijhydene.2024.02.004.

[11] J. Fan and X. Zhou, "Optimization of a hybrid solar/wind/storage system with bio-generator for a household by emerging metaheuristic optimization algorithm," *J. Energy Storage*, vol. 73, Dec. 2023, Art. no. 108967, doi: 10.1016/j.est.2023.108967.

[12] R. Wang and R. Zhang, "Techno-economic analysis and optimization of hybrid energy systems based on hydrogen storage for sustainable energy utilization by a biological-inspired optimization algorithm," *J. Energy Storage*, vol. 66, 2023, Art. no. 107469, doi: 10.1016/j.est.2023.107469.

[13] A. Al Badi and A. Al Wahaibi, "Techno-economic analysis and optimization of solar energy system for power generation and hydrogen production in Al mazyouna area," in *Proc. 3rd Int. Conf. Clean Green Energy Eng. (CGEE)*, Istanbul, Turkey, Aug. 2022, pp. 26–31, doi: 10.1109/CGEE55282.2022.9976768.

[14] R. A. Abdelsalam, Y. S. Abdallah, N. M. Shabar, O. A. Afifi, M. H. Fouda, and A. A. El-Deib, "Energy management and techno-economic optimization of an isolated hybrid AC/DC microgrid with green hydrogen storage system," in *Proc. IEEE Conf. Power Electron. Renew. Energy (CPERE)*, Luxor, Egypt, Feb. 2023, pp. 1–7, doi: 10.1109/CPERE56564.2023.10119587.

[15] N. Pilot and J. Harper, "Bifacial PV fed electrolysis for green hydrogen generation and cofiring hydrogen in an aeroderivative gas turbine," in *Proc. IEEE 50th Photovoltaic Spec. Conf. (PVSC)*, San Juan, PR, USA, Jun. 2023, pp. 1–5, doi: 10.1109/PVSC48320.2023.10359619.

[16] L. Palma, B. Molina, and A. Díaz, "Design and sizing of power conversion system with energy storage for improved PV-electrolyzer energy coupling," in *Proc. Int. Conf. Clean Elect. Power (ICCEP)*, Terrasini, Italy, 2023, pp. 784–788, doi: 10.1109/ICCEP57914.2023.10247422.

[17] I. H. Tawil, M. M. Albarghot, and E. B. Abraheem, "A sizing and dynamic model for a green hydrogen as energy storage technique for the hybrid system 50 KW solar PV with PEM fuel cell," in *Proc. 14th Int. Renew. Energy Congr. (IREC)*, Sousse, Tunisia, 2023, pp. 1–6, doi: 10.1109/IREC59750.2023.10389315.

[18] A. Narmada, A. Jain, M. K. Shukla, and N. K. Mishra, "Evaluation of various controllers in fractional order non-linear systems with actuator fault," *Multimedia Tools Appl.*, vol. 83, pp. 1–18, Jan. 2024, doi: 10.1007/s11042-023-18018-6.

[19] N. K. Mishra, G. Mishra, and M. K. Shukla, "Six-phase DFIG-MPPT synergy: Pioneering approaches for maximising energy yield in wind energy generation system," *Int. J. Power Energy Convers.*, vol. 15, no. 1, pp. 79–98, Jan. 2024, doi: 10.1504/ijpec.2024.10062396.

[20] N. K. Mishra and Z. Husain, "Application of novel six-phase doubly fed induction generator for open phases through modeling and simulation," *IETE J. Res.*, vol. 69, no. 6, pp. 3916–3927, 2023, doi: 10.1080/03772063.2021.1933627.

[21] K. Sayed, M. G. Gronfula, and H. A. Ziedan, "Novel soft-switching integrated boost DC–DC converter for PV power system?" *Energies*, vol. 13, no. 3, p. 749, 2020, doi: 10.3390/en13030749.

[22] K. Sayed and M. Abdel-Salam, "Dynamic performance of wind turbine conversion system using PMSG-based wind simulator," *Electr. Eng. J.*, vol. 99, pp. 431–439, Mar. 2017.

[23] M. Abdel-Salam, K. Sayed, A. Ahmed, M. Amery, and M. Swify, "Design, implementation and operation of a stand-alone residential photovoltaic system," *Int. J. Power Energy Convers.*, vol. 8, no. 1, pp. 47–67, 2017.

[24] *Fuel Cell Store. Education, Science and Fun Since 1999*. Accessed: Nov. 2014. [Online]. Available: https://www.fuelcellstore.com/pem-water-electrolysis-system

[25] *Solar Panel Tilt Angle Calculator*. Accessed: Nov. 28, 2023. [Online]. Available: https://footprinthero.com/solar-panel-tilt-angle-calculator

[26] *Solar Irradiance Database*. Accessed: Jun. 2021. [Online]. Available: https://www.tarcal.uk/solar-radiation.php

[27] *Global Solar Atlas*. Accessed: Sep. 2019. [Online]. Available: https://globalsolaratlas.info/map?s=27.254195,33.134766&m=site&c=21.634147,17.753906,5

[28] I. Marouani, T. Guesmi, B. M. Alshammari, K. Alqunun, A. Alzamil, M. Alturki, and H. H. Abdallah, "Integration of renewable-energy-based green hydrogen into the energy future," *Processes*, vol. 11, p. 2685, Sep. 2023, doi: 10.3390/pr11092685.

[29] S. Hosouli, J. Gomes, A. Loris, I. A. Pazmino, A. Naidoo, G. Lennermo, and H. Mohammadi, "Evaluation of a solar photovoltaic thermal (PVT) system in a dairy farm in Germany," *Sol. Energy Adv.*, vol. 3, Jan. 2023, Art. no. 100035, doi: 10.1016/j.seja.2023.100035.

[30] M. Jesper, F. Pag, K. Vajen, and U. Jordan, "Hybrid solar thermal and heat pump systems in industry: Model based development of globally applicable design guidelines," *Sol. Energy Adv.*, vol. 3, Jan. 2023, Art. no. 100034, doi: 10.1016/j.seja.2023.100034.

• • •