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A Solar Energy System Design for Green Hydrogen Production in South-Western Nigeria, Lagos State, Using HOMER & ASPEN

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Abstract

Solar system design for green hydrogen production has become the most prominent renewable energy research area, and this has also actively fueled the desire to achieve net-zero emissions. Hydrogen is a promising energy carrier because it possesses more energy capacity than fossil fuels and the abundant nature of renewable energy systems can be utilized for green hydrogen production. However, the design of an optimized electrical energy system required for hydrogen production is crucial. Solar energy is indeed beneficial for green hydrogen production and this research designed, discussed, and provided high-level research on HOMER design for green hydrogen production and deployed the energy requirement with ASPEN Plus to optimize the energy system, while also incorporating fuzzy logic and PID control approaches. In addition, a promising technology with a high potential for renewable hydrogen energy is the proton exchange membrane (PEM) electrolyzer. Since its cathode (hydrogen electrode) may be operated over a wide range of pressure, a control process must be added to the system in order for it to work dynamically efficiently. This system can be characterized as an analogous circuit that consists of a resistor, capacitor, and reversible voltage. As a result, this research work also explores the Fuzzy-PID control of the PEM electrolysis system. Both the PID and Fuzzy Logic control systems were simulated using the control simulation program Matlab R2018a, which makes use of Matlab script files and the Simulink environment. Based on the circuit diagram, a transfer function that represents the mathematical model of the plant was created, and the PEM electrolysis control system is determined to be highly significant and applicable to the two control systems. The PI controller, however, has a 30.8% overshoot deficit, but when the fuzzy control system is compared to the PID controller, it is found that the fuzzy control system achieves stability more quickly, demonstrating its benefit over PID.

Keywords

Homer Solar Design, Solar Energy, Renewable Energy, Green Hydrogen Production, Fuzzy Logic, HOMER

1. Introduction

Energy is a fundamental factor in any nation's economic and social development. The reduction of fossil fuel reserves and greater awareness towards global environmental issues such as global warming, climate change, and ozone layer depletion has led to an increase in the research and development of more sustainable, reliable, and affordable energy sources to match our ever-growing population and energy demands. Nigeria, Africa's most populous country with approximately 214 million people [1], mainly relies on fossil fuels for electricity & energy generation. Ruined infrastructure leading to constant rampant blackouts has negatively impacted the populace, consequently, many households and businesses purchase backup generators which are powered by petrol or diesel, increasing greenhouse gas emissions and noise pollution, which are adverse effects. Nigeria has abundant renewable energy resources; and there is a need to harness these resources as the country hopes to develop further its rich potential. Specifically, Lagos state has sufficient solar energy resources for green hydrogen [2].

However, with solar energy being among the reliable sources of renewable energy, it's difficult to comprehend why these energy sources are not fully used in the country. Additionally, Lagos state is the commercial capital of Nigeria with a population of over 24 million, therefore making solar energy generation very pivotal for economic sustainability. By 2019, total electricity generated in Nigeria was recorded at 31,419 GWh, with natural gas contributing about 78%, hydro about 21.47%, and solar about 0.13%, as shown in **Figure 1**. The consumption of natural gas for electricity generation in the country has resulted in a continuous rise in CO_2 emissions, as depicted in **Figure 2**. Nigeria only utilizes a small amount of its renewable energy resources and the utilization of hydro energy, which is currently the country's most used renewable energy source, has declined over the years and has seen about a 15% reduction from 2005 to 2019 [2] [3].

Although the country has a significantly high number of solar and other renewable resources, solar energy for large-scale electricity generation only began in 2015. However, this is still at its infant stage, with solar power generating 41 GWh by 2019 and contributing just 0.13% of total electricity generation in the country [2] [3]. Various studies have been carried out globally to evaluate the

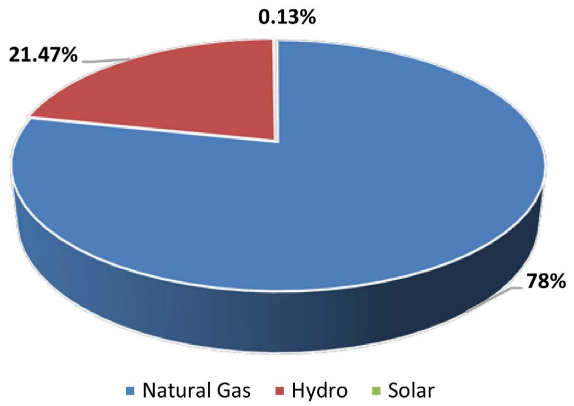

Figure 1. Electricity generation by source in Nigeria in 2019 [2].

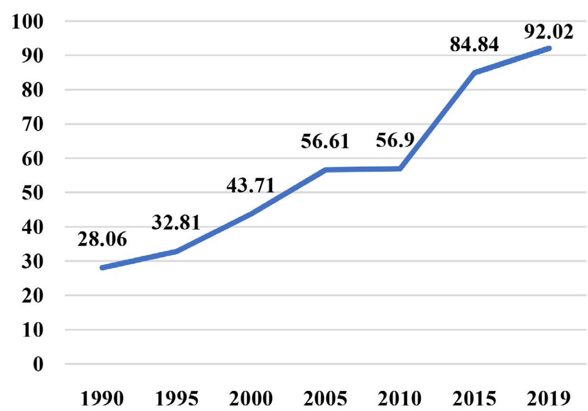

Figure 2. Total CO_2 (Mt of CO_2) emissions in Nigeria [2].

technical and practicality of various solar energy systems. A study in Nigeria shows the utilization of a zero-emission solar system to generate electricity is highly possible. The study investigated economic optimization by using the HOMER software to ascertain the lowest Levelized cost of energy (LCOE) [4].

A study in Rajshahi, Bangladesh, used the hybrid optimization model for electric renewables (HOMER) to develop and analyze a hybrid system for power generation. A PV module and a wind turbine serve as renewable energy sources. A diesel generator serves as an active backup to reduce electrical issues, with a battery serving as a storage medium, and a bi-directional converter. The hybrid PV/Diesel/Battery configuration had a lower LCOE of 0.28 $/kWh when compared to the PV/Wind/Diesel/Battery configuration with an LCOE of 0.29 $/kWh [4].

A comprehensive study on solar energy policies globally indicates how wind and solar energies complement each other and reduce power fluctuations, thereby enhancing grid stability. It also analyzes the economic viability of hybridization of these renewable energies. It shows stipulated policies in place to support the set-up and development of this solar energy to meet energy demand. Finally, the study investigates solar and wind hybrid energy barriers and sets up recommendations for these existing barriers [5].

Solar energy can be utilized to power green hydrogen production processes as a renewable energy source, and as the green hydrogen production processes utilizes electrolyzer which would need to be powered by electricity, and in this regard, the Proton exchange membrane (PEM) electrolyzer is a viable technology with high potential to add substantially to renewable hydrogen energy demand and zero-emission [6] [7]. PEM electrolyzer offers several advantages over alkaline electrolyzer, its hydrogen electrode (cathode) can be operated over wide range of pressure in which case it does not require services of compressor to compress the hydrogen gas to a storage tank [8] the only limitation is the influence of cathodic pressure on the gas cross over [9]. PEM electrolyzer can be operated at quite a low temperature and current density and developments in PEM electrolyzer [4] [5] has heightened the need that numerical modelling is an important tool for simulation and sensitivity analysis of the operating condition of electrolyzer systems, especially for commercial application. Recent developments in PEM electrolyzer have increased the need for numerical modelling as an important tool for numerical simulation and sensitivity analysis of the operating condition of electrolyzer systems. However, the numerical modeling may differ based on the model's level of correctness, which is often adapted to a specific application, as well as its complexity [10] [11]. In a PEM electrolyzer, water is typically decomposed into oxygen molecules and hydrogen ions at the anode electrode, releasing 2 mol of electrons from 1 mol of water. At the cathode, the hydrogen ion and electrons combine to generate hydrogen gas. Over potentials have a significant impact on irreversibility in PEM electrolyzer systems, which increases operating costs [7] [8]; however, there have been several attempts to lessen the excess potentials, which ultimately results in less energy consumption. To analyze the performance of a PEM electrolyzer, a simple model based on thermodynamics and Bulter-Volmer kinetics is frequently deployed; this model may be found in [12]. PEMEL is regarded as a load, and to create effective controllers, a precise model must be taken into account. In fact, the design and tuning of the controller may be influenced by the load modeling. Additionally, modeling is essential for evaluating the efficiency and performance of the controller in simulations, including those DC-DC converters coupled to a PEMEL model [13].

As a result, since an exact model has been taken into account to mimic the operation of the electrolyzer, the results of simulations enable supplying essential information about the dynamic performance of the electrolyzer empirically [14] [15]. Different PEMEL models have been created in the literature. The electrolyzer can be modeled in [11] as a straightforward resistor, but in [16] [17] [18], it is modeled by an equivalent circuit made up of a resistance series coupled to a voltage generator that represents the reversible voltage.

In most solar-enabled green hydrogen production control system applications 90% - 95% of control loops are of PID form [19]. A preferred control system which can give better performance than the PID control system is a properly designed direct Fuzzy control system. PID controllers are the most widely used controllers in process control, the energy industry and green hydrogen production industries, among others, because of their straightforward structure, simple implementation, and low maintenance requirements [20]. The mathematical description of the PEM and the function it plays in effecting control in the electrochemical reactions of an electrolyzer, as well as recent developments in the field of electrochemical reaction in PEM electrolyzer, have improved practical interest in the analysis of PEM systems or voltaic cells using typical transfer function models.

Similarly, recent developments in the field of electrochemical reaction in PEM electrolyzer has directed to a continued interest in the analysis of PEM systems or voltaic cells using typical transfer function models, which is the mathematical description of the PEM and the role it plays in effecting control in the electrochemical reactions of an electrolyzer. Controlling the PEM is another focus of interest. Conventional systems are expected to lose their functions, and humans are not efficient for control systems as there could be biased experience in the control process. PID controllers have a long history in the field of automatic control [20]. PID control employs three modes algorithm, *i.e.*, proportional, integral and derivative. The proportional term incorporates appropriate proportional changes for error (which is the difference between the set-point and process variable) to the control output. The integral term examines the process variable over time and it corrects the output by reducing the offset from process variable. Derivative control mode monitors the rate of change of the process variable and therefore changes the output when there are unusual variations. The user adjusts each parameter of the three control functions to obtain the desired performance from the process. Due to their simple structure, easy implementation, and maintenance, PID controllers are the most extensively used controllers in process control, green hydrogen processes, and manufacturing industries etc. [21].

PID controller delivers good performance with a cost/benefit ratio which is difficult for other types of controllers. They are also utilized in modern applications, like self-driving cars, unmanned aircraft vehicle, and autonomous robots, for the same purpose. In most of the control system applications 90% - 95% of control loops are of PID form [22]. A preferred control system which can give better performance than the PID control system is a properly designed direct Fuzzy control system. As an intelligent control technology, fuzzy logic control (FLC) enables a methodical method to integrate algorithms that are nonlinear, and also characterized by a series of grammatical words, into the controller [22].

Therefore, this project aims to investigate the utilization of renewable energy (solar) for electricity generation to power green hydrogen production in Lagos, Nigeria. This will reduce the over-dependence on natural gas for electricity generation and in addition to this, the fuzzy control also works as well for complex nonlinear multi-dimensional system, which is often described as a system with a keen problem in character variation. It is basically not linear in nature, giving solid and efficient performance under parameter variation and load disturbance effect [21]. Hence, the need for systematic control systems and this paper then focuses on the Fuzzy-PID control of the PEM.

Bases on research [2] and [3], there is a research gap in understanding the reasons for the limited utilization of solar energy in Nigeria, particularly in Lagos state, despite its potential as a reliable source of renewable energy. The fact that solar energy contributed only 0.13% of the total electricity generated in Nigeria in 2019 raises questions about the barriers and challenges hindering the adoption of solar energy.

Further research could focus on exploring the specific factors that limit the adoption of solar energy in Lagos state and Nigeria as a whole. Some potential areas of investigation could include the economic feasibility of solar energy projects, the regulatory and policy environment, technical barriers, and public awareness and acceptance of solar energy. By identifying these factors, policymakers and stakeholders could develop targeted strategies to promote the widespread adoption of solar energy in Nigeria, thereby reducing the country's reliance on fossil fuels and mitigating the negative environmental impacts associated with their use.

Additionally, from the research from [3] and [4], the current state of solar energy adoption in Nigeria presents a notable research gap in terms of understanding the barriers and challenges that hinder the large-scale utilization of this renewable energy source. Despite having a high number of solar and other renewable resources, solar energy for large-scale electricity generation only began in 2015 and currently contributes just 0.13% of the country's total electricity generation. While various studies globally have evaluated the technical and practical aspects of solar energy systems, there is a lack of research on the economic feasibility of large-scale solar energy implementation in Nigeria. To address this research gap, further investigation is needed to explore the economic optimization of solar energy systems in Nigeria. Such research could examine the financial and regulatory frameworks required to incentivize solar energy adoption, as well as explore the technical barriers to large-scale implementation, such as intermittency and storage. In addition, analysis of existing solar energy projects in Nigeria and other similar countries could provide valuable insights into the potential for solar energy to play a more significant role in Nigeria's energy mix, reducing reliance on fossil fuels and mitigating environmental impacts.

In short, the main contribution of this research design project can be summarized as follows;

1) In the past, researchers have used HOMER to design domestic energy systems using a hybrid approach, and then calculated the levelized cost of electricity on the best hybrid systems to be optimally used. In this research solar energy is utilized as the renewable energy source for powering a Green Hydrogen production system in Lagos, Nigeria.

2) Recent developments in PEM electrolyzer used for hydrogen has heightened the need that numerical modelling is an important tool for numerical si-

mulation and sensitivity analysis of the operating condition of electrolyzer systems, however research has consistently shown that there are still many challenges in the design and numerical analysis of PEM electrolyzer especially for commercial application.

3) Energy developments in the field of electrochemical reaction in PEM electrolyzer has led to a renewed interest in the analysis of PEM systems or voltaic cells using typical transfer function models, which is the mathematical description of the PEM and the role it plays in effecting control in the electrochemical reactions of an electrolyzer.

4) In several control system applications majority of the control loops are of PID form. A more preferred control system which can give better performance than the PID control system is a well-designed direct Fuzzy control system. As an intelligent control technology, fuzzy logic control (FLC) enables a systematic method to conduct nonlinear algorithms.

2. Methodology

This research paper studies the solar energy system design for electricity generation which would be utilized for a hydrogen production plant and in the second part process of this research, once the solar energy system produces the required energy for the green hydrogen production through the Hybrid Optimization Model for Electric Renewables (HOMER) which will be the essential software used in this study to determine the economic viability, then to fuzzy logic operations would also be utilized for the hydrogen production process which requires an electrolyzer and the Proton exchange membrane (PEM) electrolyzer is an emerging future technology with high potential to contribute to renewable hydrogen energy demand and zero-emission. And based on that, most of the control system applications 90% - 95% of control loops are of PID form. A preferred control system which can give better performance than the PID control system is a properly designed direct Fuzzy control system. The hydrogen production plant would also be designed using ASPEN Hysys.

2.1. Site Location and Renewable Energy Resources

Lagos is one of Nigeria's major economic cities, located in the southern area of the country. It has a total area of 1171 square kilometers with Ogun state as a border state. The meteorological data for solar resources as given in Table 1 is sourced from the National Aeronautics and Space Administration (NASA) within the hybrid optimization model for electric renewables (HOMER) software tool.

Table 1. Site geographical data.

Latitude	Longitude	DMS Lat	DMS Log
6.465422	3.406448	6˚27'55.19"N	3˚24'23.212"E

The average monthly temperature in the site location is represented in Figure 3. The geographical location of this study has high records of average monthly temperature, with the highest temperature recorded in March (27.22˚C) and the least temperature recorded in August (24.41˚C). A slight difference was seen from the highest and lowest months.

The solar GHI in this geographical location was also seen to be high, as shown in Figure 4. The month of February recorded the highest amount of daily radiation at 5.49 KWh/m^2/day, while July recorded the least daily radiation at 3.95 KWh/m^2/day. The average monthly velocity recorded the highest at 5.86 m/s in August and the least was registered in December at 2.93 m/s. However, it is important to understand the monthly average solar global horizontal irradiation (GHI), as given in Figure 4. The general technical and environmental data for Lagos as a state are also given in the Table 1, and it shows the required geographical data for the area as depicted in Figure 5. However, yearly average of daily sums of GHI in Nigeria is shown in Figure 6.

In addition, Lagos state is located within 714671.72 UTM Northing, 544942.12 UTM Easting.

2.2. Software Utilized

In this section a discussion of the selected software will be conducted, followed by the HOMER simulation a brief explanation of component selection, then Fuzzy Logic System, followed by the ASPEN Design of the green hydrogen

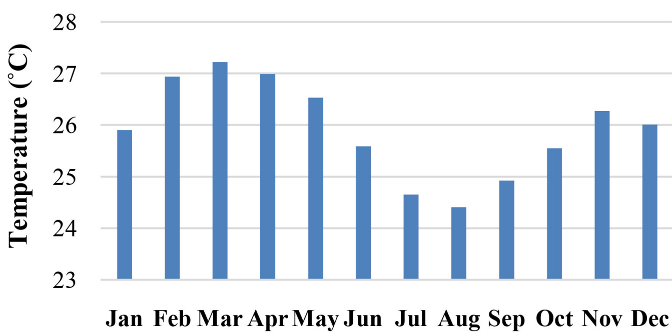

Figure 3. Average monthly temperature in Lagos, Nigeria.

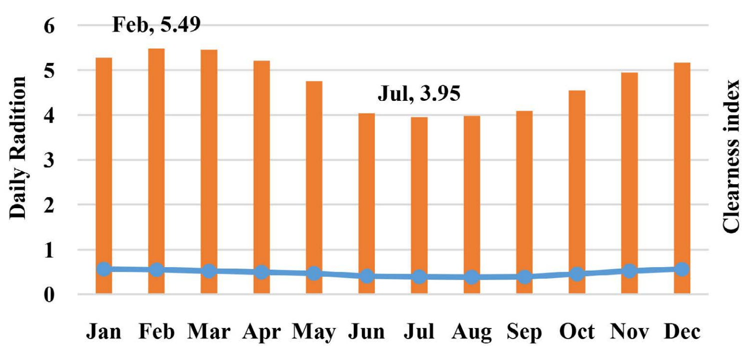

Figure 4. Average monthly solar GHI in Lagos, Nigeria.

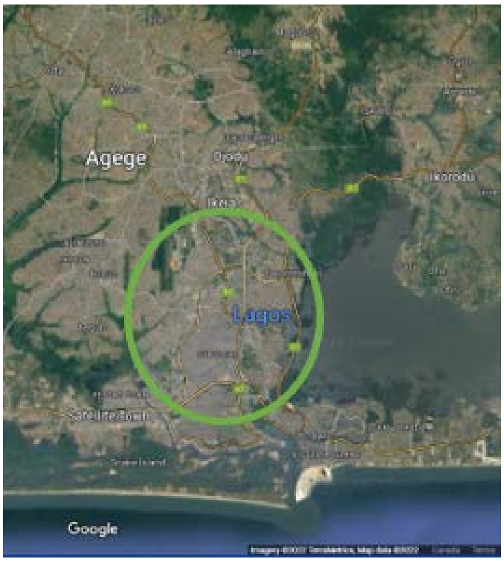

Figure 5. Site Location, Lagos, Nigeria (Google Earth).

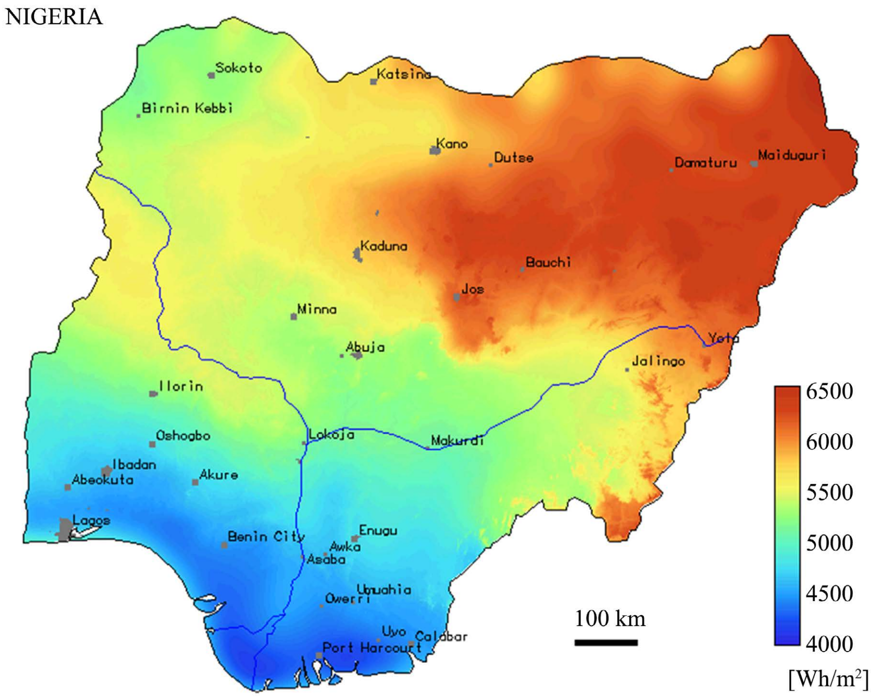

Figure 6. Yearly average of daily sums of GHI in Nigeria [2].

production process a, followed by the Microsoft Visio of the ASPEN design. Summarily the methodology for this research will utilize the approach of the HOMER analysis for developing the Solar system design to serve as the energy requirement for the green hydrogen production process, and the analysis will ensure that the requirement is sufficient enough for deployment in water electrolysis for green hydrogen production and ASPEN. The developed model and feedback controlling strategies will be simulated with MATLAB codes/scripts, and in MATLAB/Simulink environment.

2.2.1. HOMER Optimization Tool

The hybrid optimization model for electric renewables (HOMER) program is a resourceful tool for building and planning energy systems, particularly those based on renewables [23]. By using the HOMER software to do a techno-economic analysis, the optimal component size of the energy system can be determined [23]. Many resources are modeled in HOMER, including wind, solar panel arrays, fuel cells, small hydropower, biomass, converters, batteries, and conventional generators. The software can be used to analyze grid-connected, and off-grid distributed generation systems, as well as perform simulations, optimizations, for hybrid energy systems [24].

Generally, to design a renewable energy system for green hydrogen production, HOMER software can be used for effective clean energy modelling to serve as feed for green hydrogen production, where solar energy is utilized. In performing simulation with HOMER, a systematic flow chart is presented in **Figure 7**.

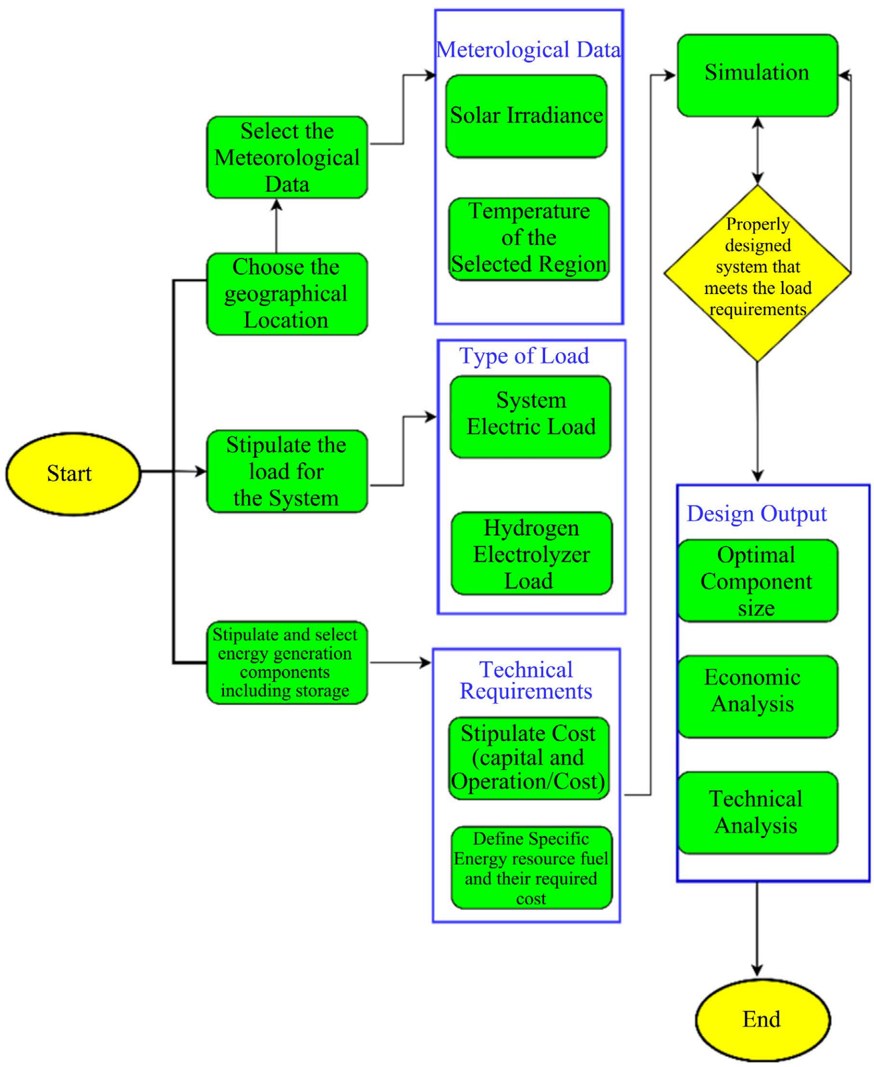

Figure 7. HOMER simulation design flowchart [23].

In contrast to a traditional feedback control algorithm, a fuzzy control algorithm often consists of a collection of heuristic decision rules and can be thought of as an adaptive and control algorithm based on a language process [21]. The software uses input data such as meteorological data, load profiles, equipment characteristics, search space, economic, and technical data [24]. The output energy of the wind turbine, photovoltaic array, and hydropower is calculated using these input values by HOMER. Wind speed, solar radiation, temperature, and streamflow are the meteorological data, which are fed into the software as monthly averages [25].

The design of the solar system for green hydrogen production will involve specific system requirements and components for the design and this would include the following.

1) Photovoltaic (PV) Panels

2) Battery Storage

3) Converter

1) Photovoltaic (PV) Panels

PV panels with a rating for the electrolyzer were used in this investigation. They are monocrystalline N-type 72 cells flat plate panels. The panel has a 25-year lifespan [26]. The panels also feature an 85 percent derating factor and a $10 operating and maintenance cost.

2) Battery Storage

The battery storage system used in this study has an 100 KWh nominal capacity, a $70,000 initial and replacement cost, and a 90 percent roundtrip efficiency. The battery has a 36 V nominal voltage and a 15-year life span [27] [28].

3) Converter

The overall capacity of the converter used in this investigation is 1.55 MW. It has a 15-year lifespan, a $190,000 capital and replacement cost, and a 96.5 percent efficiency [29].

2.2.2. ASPEN HYSYS Process Design Tool

Fuzzy logic is a formal mathematical framework that enables reasoning with uncertain or imprecise data. It utilizes a set of linguistic variables and membership functions to map input values onto fuzzy sets with degrees of membership. The membership functions themselves can be derived from a range of mathematical functions, such as sigmoidal or Gaussian functions, and can be optimized using various techniques. Fuzzy logic is often expressed using a set of fuzzy rules, which are derived from expert knowledge or data-driven learning. These rules describe how the inputs to the system relate to the output variables and are typically expressed in the form of "if-then" statements. For instance, "if the temperature is high and the humidity is low, then increase the air conditioning." Fuzzy logic has found application in a wide range of fields, including control systems, robotics, pattern recognition, decision making, and artificial intelligence. It has proven to be particularly useful in situations where traditional logic fails to capture the imprecision or uncertainty inherent in the data, making it a powerful tool for modeling complex real-world systems.

ASPEN is a powerful tool that can be utilized for optimizing green hydrogen production processes. Green hydrogen is produced via water electrolysis using renewable energy sources, and the ASPEN suite can be utilized to model and optimize this process and its associated equipment. ASPEN's simulation capabilities can be used to model the complex electrochemical reactions that occur during electrolysis, which are influenced by factors such as temperature, pressure, and pH. By accounting for these variables, engineers can identify the optimal operating conditions for the electrolysis process, such as the current density, temperature, and electrolyte composition. Additionally, ASPEN's physical property models can be used to accurately predict the behavior of the chemical systems involved in green hydrogen production, such as the electrolyte solution and gas products. This can help optimize the process, reduce waste, and improve energy efficiency. ASPEN's optimization tools can also be used to evaluate the most effective equipment configurations for green hydrogen production, such as the electrolysis cell design, water treatment system, and power source. By exploring different configurations, engineers can identify the most efficient and cost-effective options, ultimately reducing the energy consumption and environmental impact of green hydrogen production.

In summary, ASPEN provides a comprehensive suite of tools for optimizing green hydrogen production processes by accurately modeling the complex electrochemical reactions, predicting the behavior of chemical systems, and evaluating equipment configurations to improve energy efficiency and environmental impact. Hence, the need for these tools in this research paper.

Aspen Hysys is used to simulate the production of Hydrogen from Seawater by Alkaline Electrolysis. ASPEN Hysys version 11 would be the version used in this simulation. Specifically, Aspen Hysys is modeling environment for conceptual optimization, design and monitoring of process performance of various industrial processes. This software is also used for the Economic Analysis for some process. The Process utilizes the thermodynamic models that govern the equilibrium relations for the reactors simulated and these models are incorporated within the program. The process simulated is assumed to be at steady-state so as to determine the feasibility and the efficiency of the process. The solar system design for the project would serve as the electrical energy that would be utilized for the system to power the green hydrogen production process.

2.2.3. Matlab/Simulink

The developed model and feedback controlling strategies are simulated with Matlab codes/scripts, and in Matlab/Simulink environment. The transfer function representing the resistance model used in the simulation environment as well as PID control tuning with the MATLAB codes will be presented in the work. Continuous tuning would be performed for the simulation as the values of Kp, Ki and Kd will be varied until offset and/or overshoot would be eliminated indicating the system has achieved its stability. Rising time, settling time, overshoot and amplitudes will also be recorded for the various proportional controller, proportional integral controller, and proportional integral derivative controller will be indicated in their respective figures. **Figure 8** is the flow chart showing the order of the performance of the PID control system, as explained earlier in this paper. Hence, revealing the possibility of the control exercise performed by the PID controller on the system or plant. A correctly constructed direct fuzzy control system is a recommended control system that can perform better than the PID control system. Fuzzy logic control (FLC) is an intelligent control technology that offers a methodical way to integrate human experience and implement nonlinear algorithms, which are represented by a number of linguistic assertions, into the controller [21].

Accordingly, it is important to note that some research has been conducted for the evaluation of hydrogen producing methods using fuzzy approach and with regards to risk analysis of the process and feasibility. And further research into the photovoltaic (PV) system with an integrated fuzzy logic controller (FLC) to determine the emergency current compensation for electrolyzer operation to help derive the minimum power for hydrogen production has also been vital.

Figure 9 shows that the fuzzy control is equally effective for complicated nonlinear multidimensional systems, systems with parameter fluctuation issues, and systems with imprecise sensor signals. It performs well under parameter variation and load disruption effects because it is basically nonlinear and adaptable [21]. Fuzzy logic plays a significant role in defect finding, prediction, and control operations.

The flowchart of the fuzzy logic system, from the starting stage of input variable generalization through defuzzification, is schematically represented in **Figure 10**.

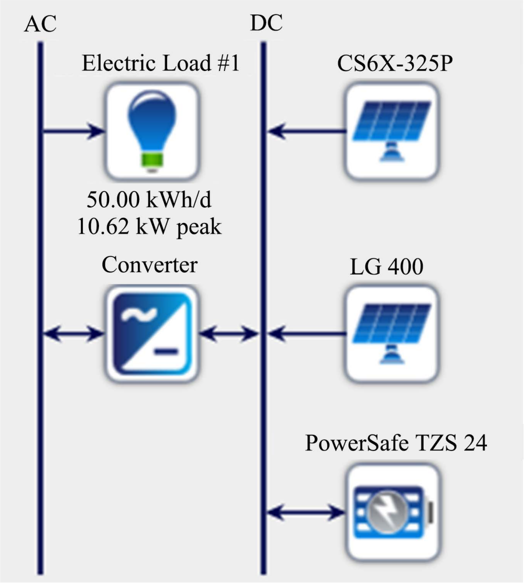

Figure 8. HOMER hybrid optimization simulation design model.

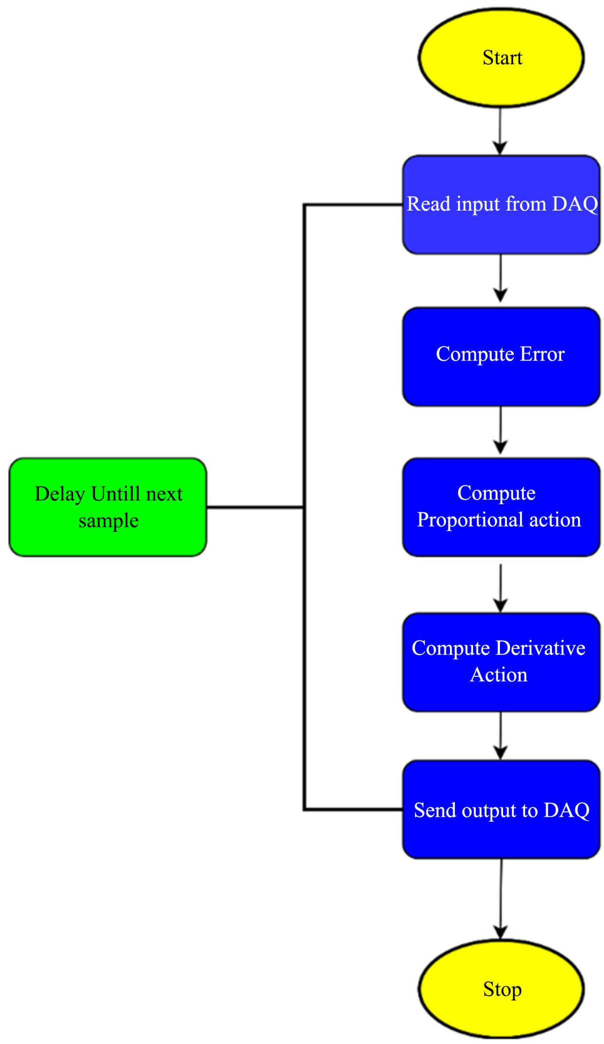

Figure 9. Flow chart for a PID control system.

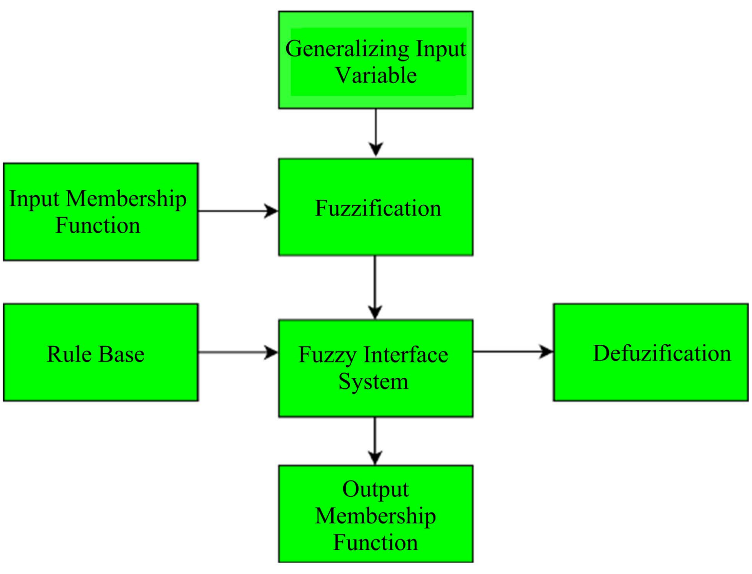

Figure 10. Flow chart for fuzzy logic control system.

In this section of the Methodology, the basic schematic of a circuit diagram for the PEM electrolyzer cell is given in **Figure 10**, it is used in this research work to develop a transfer function. The main component of the PEM electrolyzer cell is a PEM. On which a porous anode and cathode are bound. By sending a DC electric current between the two electrodes, water (H_2O) can be divided into hydrogen and oxygen (*i.e.* the process takes place in the opposite sense of that in a PEM FC). The resulting gases (H_2 and O_2) can be kept in this fashion so they can be used as needed. The following is the whole reaction for splitting water in a PEM electrolyzer

$$\mathrm{H_2O} + \text{Electical energy} \rightarrow \mathrm{H_2}(\text{gas}) + \frac{1}{2}\mathrm{O_2}(\text{gas}) \tag{1}$$

Water is thus supplied to the anode side, where it breaks down into oxygen gas, hydrogen protons, and electrons in an equation. The proton conductive membrane allows the hydrogen protons to be delivered to the cathode side. The external circuit serves as the driving force (or cell potential) for the reaction as the electrons escape the PEM electrolyzer cell at the same time. Meanwhile, at the cathode side, the hydrogen protons and the external circuit electrons recombine to produce the hydrogen gas. At the electrons recombine to produce the hydrogen gas. At the two electrodes, this electrical reaction can be interpreted as follows;

$$\text{Anodic reaction}: \mathrm{H_2O} \rightarrow 2\mathrm{H}^+ + \frac{1}{2}\mathrm{O_2}(\text{gas}) + 2\mathrm{e}^- \tag{2}$$

$$\text{cathodic reaction}: 2\mathrm{H}^+ + 2\mathrm{e}^- \rightarrow \mathrm{H_2}(\text{gas}) \tag{3}$$

According to earlier studies, a PEM electrochemical cell can be described as a straightforward resistor or as an equivalent circuit made up of a series of resistance resistors connected to a voltage generator that represents the reversible voltage, as shown in **Figure 11**. The PEM electrolyzer Fuzzy-PID control is the main topic of this research work.

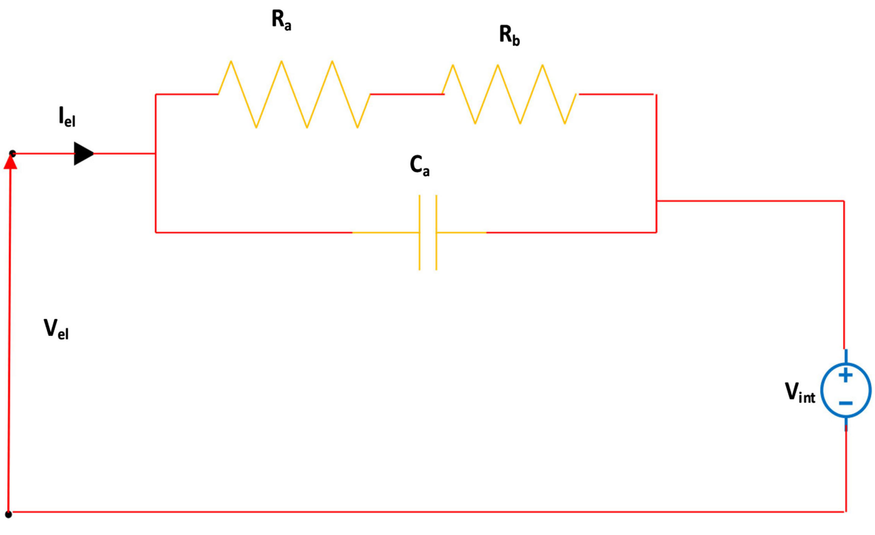

Figure 11. Circuit diagram of the PEM electrolyzer.

$$\dot{x}_h = -R_a C_a x_h + R_a i_{el} \tag{4}$$

$$x_h = x_h + R_b i_{el} \tag{5}$$

Hereby leading to the transfer function below;

$$F_h(S) = \frac{V_{el}(s)}{I_{el}(s)} = \frac{R_a + R_b}{R_a C_a s + 1} \tag{6}$$

Figure 12 gives an ASPEN overview of the green hydrogen process route for hydrogen production. In this process route, the non-gases (which are the ions in formed in the electrolysis process) are directly recycled from the electrolyzers to the product separator instead of being expelled. It is vital to note that Na^+, Cl^-, OH^- and H^+ ions (non-gases) are the ions formed during electrolysis process (water-split process) alongside with H_2 and O_2 which are the only required products, therefore, we have to separate them from O_2 and H_2.

The ASPEN Hysys design of the renewable green hydrogen production process shows the process flow diagram of the solar energy design system that feeds the process with the required electricity for its functioning. The solar energy system is being designed with HOMER software to meet the systems requirements for an effective operation.

The Electrolyzer Model Parameters are well represented in **Table 2**, showing the electrode overvolt coefficient, the feed rate to the hydrogen process plant

Table 2. Electrolyzer model parameters.

Description	Value
Area of electrode	0.25 m^2
Feed rate	1000 kmol/hr
Electrolyzer operation temperature	90˚C
Electrode Overvolt Coefficient	0.185 V
The number of electrons per reaction	2

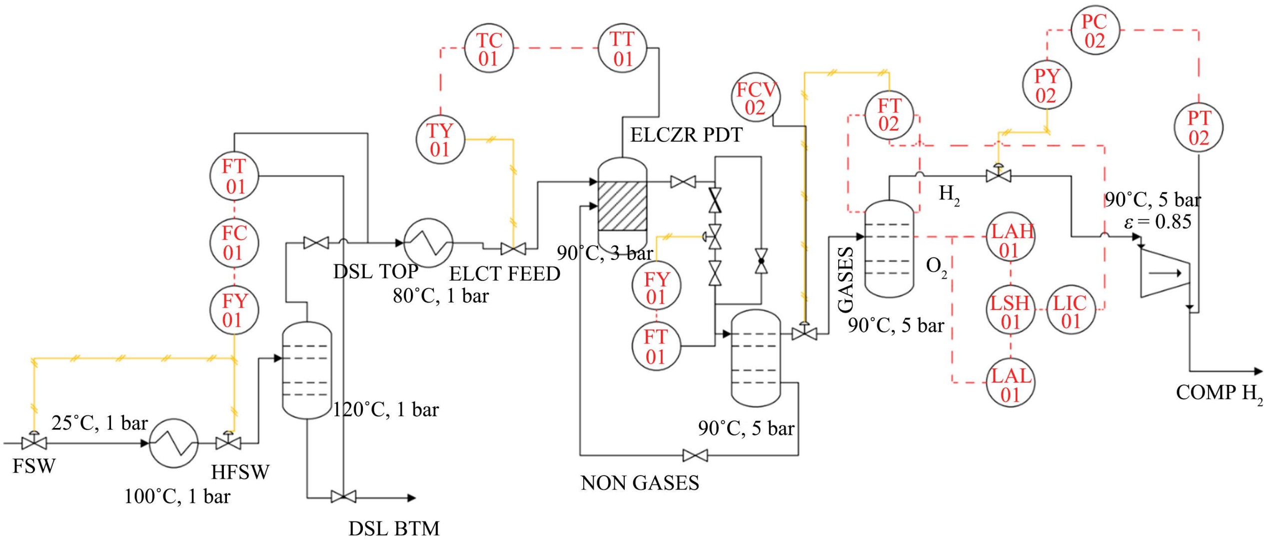

Figure 12. ASPEN process & instrumentation diagram for "*Solar energy based*" *green hydrogen production from water.*

including the area of the electrode. This gives the required framework for the green hydrogen production process.

3. Results and Discussion

3.1. PID and Fuzzy Logic Control Systems

Matlab R2018a codes and scripts are used to simulate the developed model and feedback regulating strategies in the Matlab/Simulink environment. In Equation (6), the transfer function for the resistance model utilized in the simulation environment and for fine-tuning PID control using MATLAB scripts are also presented. As the values of Kp, Ki, and Kd were adjusted, the simulation was continuously tuned until offset and/or overshoot were eliminated, signaling the system had reached stability. As depicted in **Figures 13-15**, rising time, settling time, overshoot, and amplitudes were measured for various proportional controllers, proportional integral controllers, and proportional integral derivative controllers.

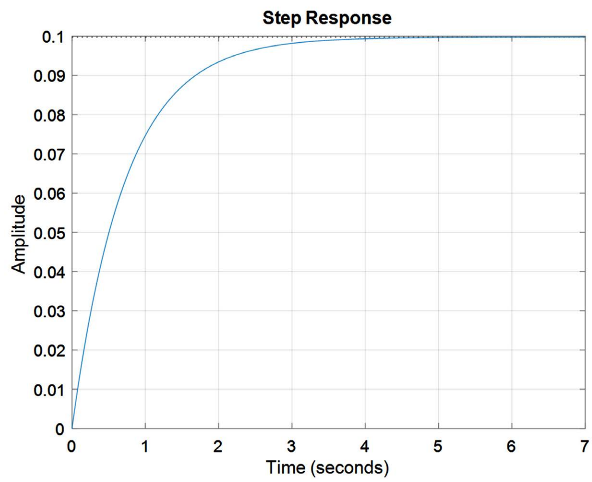

Figure 13. Flow chart for a PID control system.

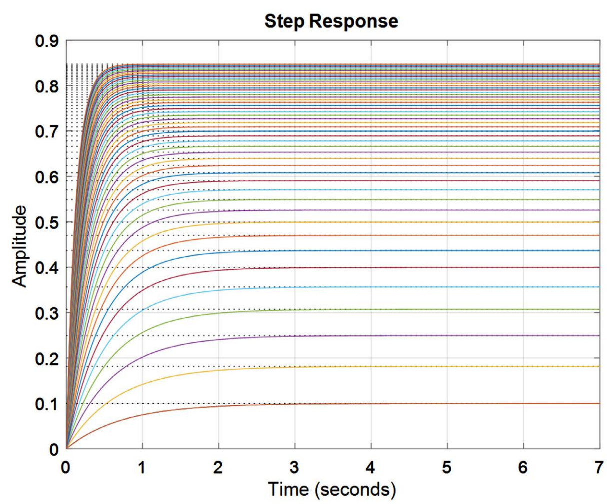

Figure 14. Dynamic response of the proportional controller for Kp = 1 - 50.

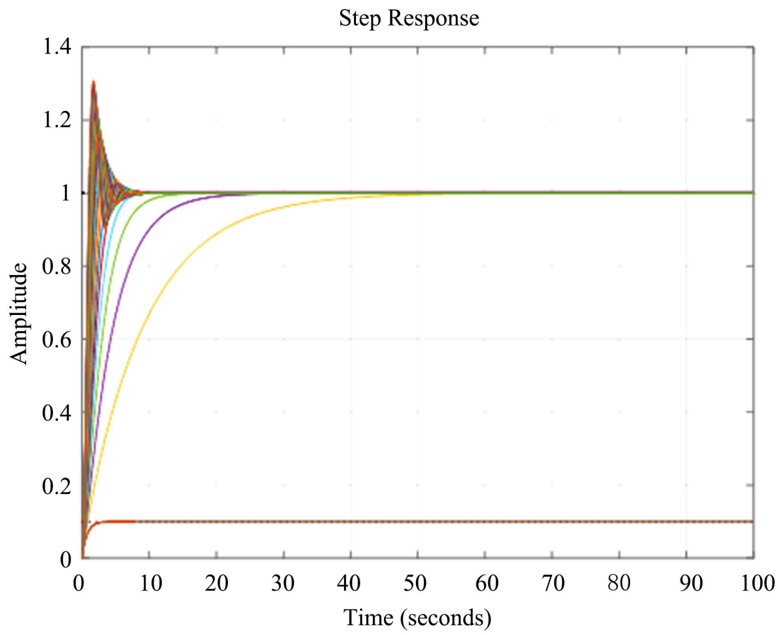

Figure 15. Dynamic response of the proportional integral controller for Kp = 1 - 50, Ki = 1 - 28.

3.1.1. OPEN LOOP

The dynamic reaction of the system without control is shown as the step response of the open loop transfer function.

3.1.2. Proportional Controller

Figure 14 is dynamic response of the system with a proportional controller. The rise time, settling time, amplitude and overshoot of 0.27 sec, 0.481 sec 0.847 and 2.2×10^{-14}, respectively. The proportional controller is found to offer some level of control to the system with negligible overshoot. However, it provides insufficient action, as the amplitude is found to be 0.847.

Hence, the final transfer function for the proportional controller is given as:

$$M_c = \frac{5.54}{0.8048s + 6.54} \quad (7)$$

3.1.3. Proportional Integral Controller

Figure 15 is dynamic response of the system with a proportional integral controller. The rise time, settling time, amplitude and overshoot of 0.486 sec, 3.25 sec, 1.31% and 30.8%, respectively. The proportional integral controller is found to be applicable as it takes the system to the set point, achieving minimal rise time and settling time. However, the PI controller is deficient in terms of overshoot of 30.8 %, thereby making it unsuitable for application as the control system in the PEM electrolysis process. Therefore, the need for derivative action, which eventually results into application of a Proportional Integral Derivative (PID) action.

Hence, the final transfer function for the proportional integral controller is given as:

$$M_c = \frac{0.1108s + 3.102}{0.8048s^2 + 1.111s + 3.102} \tag{8}$$

Equation (8) therefore shows the final transfer function for the proportional integral controller of the system, and more importantly, Figure 15 shows Dynamic response of the proportional integral controller for Kp = 1 - 50, Ki = 1 - 28.

3.1.4. Proportional Integral Derivative Controller (PID)

Figure 16 is dynamic response of the system with a proportional integral derivative controller for Kp = 1 - 50, Ki = 1 - 28, incorporating the effects of a proportional, integral and derivative. The rise time, settling time, amplitude and overshoot of 0.758 sec, 35.09 sec, 1.00% and 30.8%, respectively. The proportional integral derivative controller is found to be of better performance, with the total elimination of overshoot, as well as good rise time, settling time and amplitude as shown in Table 3. Hence, the final transfer function for the proportional controller is given as:

$$M_c = \frac{5.54s^2 + 5.54s + 3.102}{6.345s^2 + 6.54s + 3.102} \tag{9}$$

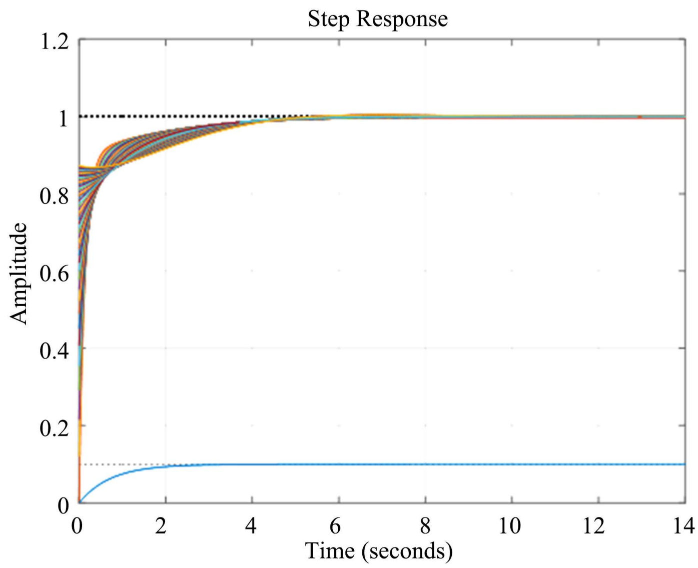

Figure 16. Dynamic response of the proportional integral controller for Kp = 1 - 50, Ki = 1 - 28. Kd = 1 - 50.

Table 3. Parameters for the dynamic response of the simulated control systems.

Controller	Rise time (s)	Settling time (s)	Amplitude	Overshoot (%)
Open loop	1.58	2.83	0.00997	Offset (0.1)
P Controller	0.27	0.481	0.847	2.2×10^{-14}
PI Controller	0.486	3.25	1.31	30.8
PID Controller	0.758	5.09	1.00	0.000

3.1.5. Fuzzy Control

The membership function serves as the foundation for the fuzzy logic control, from which the fuzzy rule for the control system is derived. Since the PEM is believed to work like a resistor, changes in voltage have an impact on the output resistance, which in turn affects the ions produced during the electrochemical reaction. Hence, the fuzzy logic design is based on the variation of voltage, thereby having direct impact on the resistance offered by the PEM. Matlab R2018a was used to perform the fuzzy logic membership design, and the Fuzzy-PID control design was performed in the Simulink environment. **Figure 17** is the fuzzy rule viewer, respectively as applicable in the fuzzy control simulation adopted in this project.

Figure 14 is the dynamic response for the fuzzy control of the plant, using the Simulink environment. Stability of the system is achived with the fuzzy controller. Comparing this with the a PID controller for a period of step seconds as shown in **Figure 18**, reveals the fuzzy control system achieves stability within a shorter period compared to the PID controller, thereby revealing its advantage over PID as earlier stated by Aström, *et al.* [24] and Aissaoui , *et al.* [25]. **Figure 19** reveals the stability of both controllers (PID & Fuzzy), with faster stability achieved by fuzzy controller compared to the PID controller.

3.2. HOMER Optimization Software

The HOMER optimization tool will be used to analyze the economic importance of applying renewable energies (wind and solar) for residential buildings. In comparing economics, the net present cost (NPC), and the Levelized cost of energy (COE), will be used.

3.2.1. Net Present Cost & Levelized Cost of Electricity

The NPC is the current/present value of a component, including all installation and operation costs over a projected lifespan, subtracted from the present values of all earned revenues over the projected lifespan. The NPC is vital and the COE is defined as the average cost per Kwh of effective electrical power generated by the system.

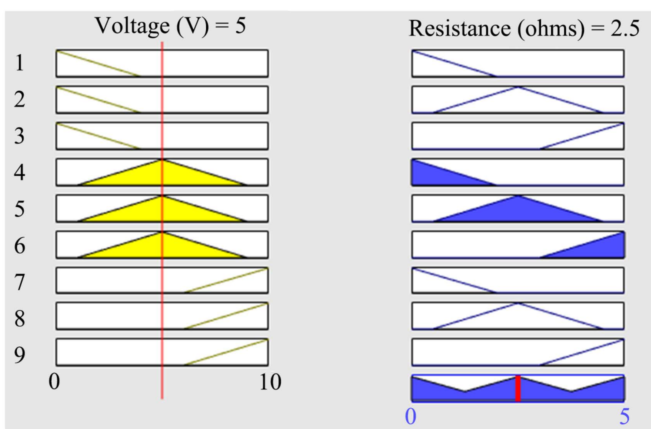

Figure 17. Fuzzy rule viewer.

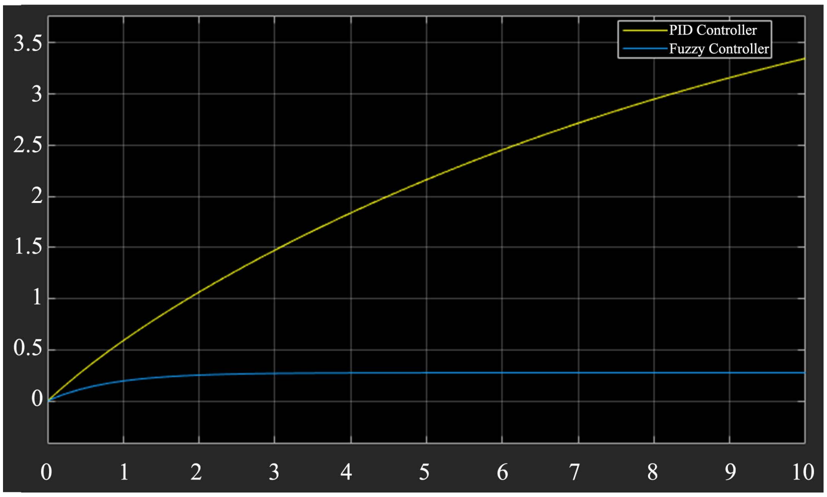

Figure 18. Fuzzy-PID control system with unstable PID controller.

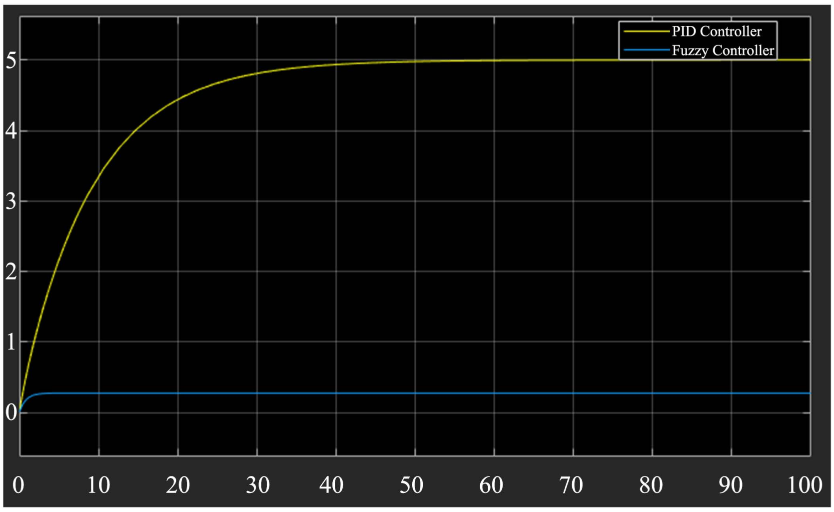

Figure 19. Fuzzy-PID control system with stable PID controller.

3.2.2. Homer Solar Energy System Design Components

Electrical Load: 1 MW alkaline electrolyzer together with a load of 50 KWh/day is considered as the total electrical load of the system. The 50 KWh/day was derived from the average daily power required by the hydrogen equipment.

PV Panels: PV panels with a rating of 200 kW was used in this investigation. They are monocrystalline N-type 72 cells flat plate panels. The panel has a 25-year lifespan and a $640 capital and replacement cost each. The panels also feature an 85 percent derating factor and a $30 operating and maintenance cost.

Battery Storage: Even when PV is combined with wind, there will still be periods when the aggregate yield is not enough to supply the load. During those periods of poor yield, the electrolyzer can operate using a back-up power supply. A battery storage system will be considered for this report as a power supply back-up. The battery storage considered in this study has an 100 KWh nominal capacity, a $70,000 initial and replacement cost each, and a 90 percent roundtrip efficiency. The battery has a 36 V nominal voltage and a 15-year life span.

Converter: The overall capacity of the converter used in this investigation is 1.55 MW. It has a 15-year lifespan, a $19,000 capital and replacement cost each, and a 96.5% efficiency.

Electrolyzer and Hydrogen Tank: A 1 MW alkaline electrolyzer with a 65 percent efficiency was used. 18 kg of hydrogen may be produced by it every hour. Based on a 2-day storage of the hydrogen generated by the electrolyzer, a 1000 kilograms hydrogen tank capacity was selected. Table 4 summarizes the energy system components and their individual technical and economic parameters.

Electricity production for green hydrogen production by the stand-alone solar system for a single green hydrogen plant is represented in Figure 20. From October through May, recorded high values of electricity production, with January being the highest at 0.961 MWh. The least electricity production was recorded in June (0.667 MWh), and therefore green hydrogen production would be at its peak during these specified seasons to give maximum hydrogen produced.

3.2.3. Economic Analysis

LCOE refers to the life-cycle cost of energy, which includes all system costs such as operation, maintenance, construction, taxes, insurance, and other financial requirements. The Equation below is utilized for calculating the LCOE.

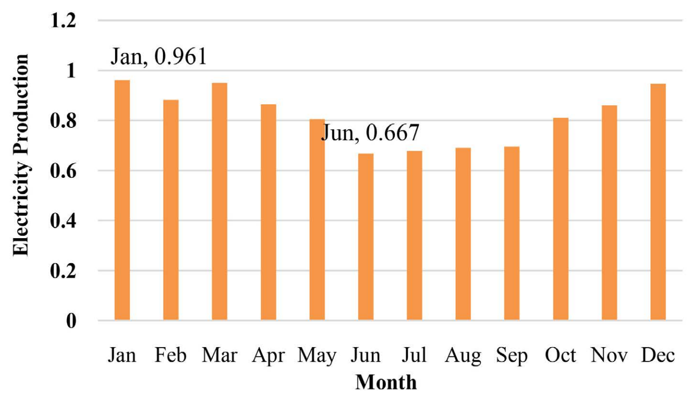

Figure 20. Monthly data of electricity production in MWh by a PV/Battery system.

Table 4. Energy system and economic analysis results.

Component	A	B	C	D	E
PV Panel	35	30	640	640	30
Converter	96.5	15	19,000	19,000	500
Battery	90	15	70,000	70,000	1000
Electrolyzer	65	15	100,000	80,000	5000
Hydrogen Tank	95	10	9000	9000	200
Hydrogen Tank	95	10	9000	9000	200

A = Efficiency (%); B = Lifespan (Years); C = Capital Cost (USD); D = Replacement Cost (USD); E = O & M (USD/Year).

$$\text{COE} = \frac{C_A - C_B H_s}{E_s} \tag{10}$$

From equation above, C_A is the Total annualized cost ($/year), C_B is the Boiler marginal cost ($/KWh), H_S is the Total thermal load served (KWh/year), and E_S is the Total electrical load served (KWh/year). The NPC is defined as the worth of all the costs incurred by the system over the system's lifespan less the worth of the revenues earned during the project's lifespan. The cost incurred includes the initial capital cost, O & M cost, fuel cost, replacement cost, etc. The NPC is mathematically presented in Equation (2) as the ratio of Total annualized cost (C_A) and Capital recovery factor (CRF).

$$\text{NPC} = \frac{C_A}{\text{CRF}} \tag{11}$$

The utilization of the electrolyzer is a key parameter used to evaluate the system's financial viability. The term "utilization" refers to the total amount of hydrogen produced under the specified system parameters (such as PV/wind capacity and battery capacity) expressed as a percentage of the main amount of hydrogen that could be produced if the load was continuously met throughout the simulation period (in this case, one year) at nominal power. The mathematical formula used for calculating the term is given below.

$$\text{Electrolyzer Utilization} = \frac{\text{Actual Hydrogen Gas Prod}}{\text{Ideal Hydrogen Gas Prod}} \tag{12}$$

4. Conclusions

This paper has investigated the utilization of solar energy as a source for green hydrogen production in Lagos state Nigeria, where there is the abundance of solar energy resources. Additionally, this research also demonstrated solar energy's capacity and economic value for green hydrogen generation in Lagos, Nigeria, in an off-grid configuration. The HOMER optimization program utilized a stand-alone solar system (PV/battery) to serve as the electricity energy support for green hydrogen production. Results showed that the stand-alone solar renewable energy system generated the required NPC rating and efficiency. The replacement cost and the capital cost were also generated in comparison to its replacement cost and required lifespan. The Solar systems operated at 100% renewable fraction, thereby eliminating a further increase in GHG emissions. With Nigeria still in a slow transition to renewable energy for power generation, both the PV/battery energy systems are highly recommended for the green hydrogen production to power the electrolyzer and the reverse osmosis process of green hydrogen production. Additionally, ASPEN Hysys was used to simulate and design the process of green hydrogen and Microsoft Visio was used to simulate the instrumentation diagram for the process, and furthermore this research project also investigated Fuzzy-PID control of PEM electrolysis system. The two systems are found to be applicable and of great significance in the PEM electrolysis control system.

Hence, within the limit of this research paper, it can be concluded that:

- A simple resistor can be used to mimic the electrolyzer.
- An analogous circuit made up of a resistance series coupled to a voltage generator that represents the reversible voltage could be used to model an electrolyzer.
- The proportional controller is found to offer some level of control to the system with negligible overshoot. However, it provides insufficient action, as the amplitude is found to be 0.847.
- The proportional integral controller is found to be applicable as it takes the system to the set point, achieving minimal rise time and settling time. However, the PI controller is deficient in terms of overshoot of 30.8%, thereby making it unsuitable for application as the control system in the PEM electrolysis process.
- The proportional integral derivative controller is found to be of better performance with the total elimination of overshoot.
- The fuzzy control system achieves stability within a shorter period compared to the PID controller, thereby revealing its advantage over PID.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Worldometer (2022) Nigeria Population (live). https://www.worldometers.info/world-population/nigeria-population/

[2] IEA (2022) https://www.iea.org/countries/nigeria

[3] U.S. Energy Information Administration (2022) U.S. Energy Information Administration-EIA-Independent Statistics and Analysis. https://www.eia.gov/international/overview/country/nga

[4] Swarnkar, N.M. and Gidwani, L. (2017) Economic and Financial Assessment of Integrated Solar and wind Energy System in Rajasthan. *Proceedings of* 2017 *International Conference on Computation of Power*, *Energy Information and Communication* (ICCPEIC), Melmaruvathur, 22-23 March 2017, 471-476. https://doi.org/10.1109/ICCPEIC.2017.8290413

[5] Shboul, B., AL-Arfi, I., Michailos, S., Ingham, D., AL-Zoubi, O.H., Ma, L., Hughes, K. and Pourkashanian, M. (2021) Design and Techno-Economic Assessment of a New Hybrid System of a Solar Dish Stirling Engine Integrated with a Horizontal Axis Wind Turbine for Microgrid Power Generation. *Energy Conversion and Management*, **245**, Article ID: 114587. https://doi.org/10.1016/j.enconman.2021.114587

[6] Aouali, F., Aouali, F.Z., Becherif, M., Ramadan, S.H., Emziane, M., Khellaf, A. and Mohammedi, K. (2017) Analytical Modelling and Experimental Validation of Proton Exchange Membrane Electrolyser for Hydrogen Production. *International Journal of Hydrogen Energy*, **42**, 1366-1374. https://doi.org/10.1016/j.ijhydene.2016.03.101

[7] Frensch, S.H., Olesen, A.C., Araya, S.S. and Kær, S.K. (2018) Model-Supported

Characterization of a PEM Water Electrolysis Cell for the Effect of Compression. *Electrochimica Acta*, **263**, 228-236. https://doi.org/10.1016/j.electacta.2018.01.040

[8] Ni, M., Leung, M.K. and Leung, D.Y. (2006) Electrochemistry Modeling of Proton Exchange Membrane (PEM) Water Electrolysis for Hydrogen Production. *Proceedings of* 16*th World Hydrogen Energy Conference* 2006 (*WHEC* 2006), Lyon, 13-16 June 2006, 33-39.

[9] Islam, M.S., Das, B.K., Das, P. and Rahaman, M.H. (2021) Techno-Economic Optimization of a Zero-Emission Energy System for a Coastal Community in Newfoundland, Canada. *Energy*, **220**, Article ID: 119709. https://doi.org/10.1016/j.energy.2020.119709

[10] Al-Buraiki, A.S. and Al-Sharafi, A. (2021) Technoeconomic Analysis and Optimization of Hybrid Solar/Wind/Battery Systems for a Stand-Alone House Integrated with an Electric Vehicle in Saudi Arabia. *Energy Conversion and Management*, **250**, Article ID: 114899. https://doi.org/10.1016/j.enconman.2021.114899

[11] Das,, B.K., Alotaibi, M.A., Das, P., Islam, M.S., Das, S.K. and Hossain, M.A. (2021). Feasibility and Techno-Economic Analysis of Stand-Alone and Grid-Connected PV/Wind/Diesel/Batt Hybrid Energy System: A Case Study. *Energy Strategy Reviews*, **37**, Article ID: 100673. https://doi.org/10.1016/j.esr.2021.100673

[12] Tijani, A.S., Abdul Ghani, M.F., Abdol Rahim, A.H., Muritala, K.M. and Mazlan, F.A.B. (2019) Electrochemical Characteristics of (PEM) Electrolyzer under Influence of Charge Transfer Coefficient. *International Journal of Hydrogen Energy*, **44**, 27177-27189. https://doi.org/10.1016/j.ijhydene.2019.08.188

[13] Maamouri, R., Guilbert, D., Zasadzinski, M. and Rafaralahy, H. (2021) Proton Exchange Membrane Water Electrolysis: Modeling for Hydrogen Flow Rate Control. *International Journal of Hydrogen Energy*, **46**, 7676-7700.

[14] Sahin, M. (2020) A Photovoltaic Powered Electrolysis Converter System with Maximum Power Point Tracking Control. *International Journal of Hydrogen Energy*, **45**, 9293-9304. https://doi.org/10.1016/j.ijhydene.2020.01.162

[15] Sahin, M. (2019) An Effcient Solar-Hydrogen DC-DC Buck Converter System with Sliding Mode Control. *El-Cezeri Journal of Science and Engineering*, **6**, 558-570. https://doi.org/10.31202/ecjse.558383

[16] Yodwong, B., Guilbert, D., Kaewmanee, W. and Phattanasak, M. (2019) Energy Efficiency Based Control Strategy of a Three-Level Interleaved DC-DC Buck Converter Supplying a Proton Exchange Membrane Electrolyzer. *Electronics*, **8**, Article 933. https://doi.org/10.3390/electronics8090933

[17] Albarghot, M. and Rolland, L. (2017) Comparison of Experimental Results with Simulation of a PEM Electrolyzer Powered by a Horizontal Wind Turbine. *Proceedings of* 2017 *International Conference of Electrical and Electronic Technologies for Automotive*, Turin, 15-16 June 2017, 1-6. https://doi.org/10.23919/EETA.2017.7993232

[18] Atlam, O. and Kolhe, M. (2011) Equivalent Electrical Model for a Proton Exchange Membrane (PEM) Electrolyser. *Energy Conversion and Management*, **52**, 2952-2957. https://doi.org/10.1016/j.enconman.2011.04.007

[19] USGS (2022) Why Is the Ocean Salty? USGS. http://www.usgs.gov/faqs/why-ocean-salty

[20] Aström, K.J. and Hägglund, T. (2001) The Future of PID Control. *Control Engineering Practice*, **9**, 1163-1175.

[21] Aissaoui, A.G. and Tahour, A. (2012) Application of Fuzzy Logic in Control of Electrical Machines. IntechOpen, London.

[22] Yager, R.R. (1997) Fuzzy Logics and Artificial Intelligence. *Fuzzy Sets and Systems*, **90**, 193-198. https://doi.org/10.1016/S0165-0114(97)00086-9

[23] Salisu, S., Mustafa, M.W., Olatomiwa, L. and Mohammed, O.O. (2019) Assessment of Technical and Economic Feasibility for a Hybrid PV-Wind-Diesel-Battery Energy System in a Remote Community of North Central Nigeria. *Alexandria Engineering Journal*, **58**, 1103-1118. https://doi.org/10.1016/j.aej.2019.09.013

[24] Bahramara, S., Moghaddam, M.P. and Haghifam, M.R. (2016) Optimal Planning of Hybrid Renewable Energy Systems Using Homer: A Review. *Renewable and Sustainable Energy Reviews*, **62**, 609-620. https://doi.org/10.1016/j.rser.2016.05.039

[25] Cekirge, H.M. (2019) Modified Levelized Cost of Electricity or Energy, MLOCE and Modified Levelized Avoidable Cost of Electricity or Energy, MLACE and Decision Making. *American Journal of Modern Energy*, **5**, 1-4. https://doi.org/10.11648/j.ajme.20190501.11

[26] Modern Outpost (2020) LG400N2W-A5: 400W LG Neon2 Solar Module. Modern Outpost.

[27] Bergey Windpower Co (2022) Retail Price List. Bergey Windpower Co, Norman.

[28] Bergey Price List (2022) https://criticaltowers.com/Bergey%20Windpower%20Co/Web%20Pages/Bergey%20Wind%20Tur

[29] HOMER (2021) Optimize the Value of Your Hybrid Power System-From Utility-Scale and Distributed Generation to Stand-Alone Microgrids. HOMER. https://www.homerenergy.com/