



Evaluation of Solar and Wind Energy Potential for Alkaline Water Electrolysis-Based Green Hydrogen Production

¹Kamepalli Lakshmi Teja, ²P.Chaithanyakumar

^{1,2}Department of Electrical and Electronics Engineering

^{1,2}Gokula Krishna College of Engineering

ABSTRACT: Numerous industrial uses for hydrogen are being investigated in order to create a variety of chemical compounds, such as methanol and ammonia. Conventional hydrogen generation, on the other hand, is mostly dependent on finite fossil fuels and is linked to hazardous pollutants. In order to secure a sustainable energy transition, renewable energy sources have been proposed as alternative energy sources to reduce the use of fossil fuels and guarantee reduced emission levels. For the creation of green hydrogen, renewable energy sources like wind turbines (WT) and solar photovoltaics (PV) are receiving a lot of attention. The storage of renewable energy generation to improve the green hydrogen production process is the main topic of this essay. The requirement for low-cost, extremely effective energy storage is one of the primary barriers to the quick development of renewable energy. One promising way to address this issue is to incorporate renewable energy sources into the creation of green hydrogen. The purpose of this effort is to assess the possibilities for electrolysis of solar PV and wind energy to produce hydrogen. A theoretical model of a caustic electrolyser coupled to a solar PV panel and a wind generator serves as the implemented methodology. To highlight the effectiveness of the MPPT controller and renewable-based hydrogen production systems, the study evaluated the input/output power of solar and wind energy and computed the green hydrogen production rate. The MATLAB/Simulink environment simulation results show that the hydrogen generation system operates well, particularly in terms of energy efficiency. Based on the final results, wind energy performs better than solar photovoltaics, which have an efficiency of 82% and a rate of 0.66 Nm³/h, respectively. Wind energy achieves 90% efficiency and 1.2 Nm³/h.

Index terms: solar energy, wind energy, green hydrogen, and alkaline electrolyzer

I.INTRODUCTION

Fossil fuel combustion engines contribute significantly to greenhouse gas emissions, making climate change one of the century's most urgent issues. Being the most prevalent element in the universe, hydrogen has a large amount of energy potential and is a clean and environmentally beneficial energy source because it burns without emitting carbon dioxide or other dangerous greenhouse gases [1-2]. Many scholars have suggested replacing fossil fuels with renewable energy [3]. Renewable energy sources, as opposed to fossil fuels, are limitless and emit no pollutants when in use [1]. Renewable energy sources are a strong contender to replace fossil fuels because they are endless and emit no pollutants when in use. However, there are significant obstacles to employing renewable energy, including its high reliance on weather, the high cost of energy transportation, the need for huge energy storage systems, and limited grid integrations [3].

Additionally, there are serious drawbacks to using alternative energy sources in conjunction with power grid generation, such as large upfront costs, significant land demands, significant governmental hurdles, and increased wildlife problems. Some of these renewable energy sources, like solar and wind, are sporadic and can't deliver energy continuously.

To address these issues, systems that use renewable energy sources ought to be enhanced in some manner. The best remedy for all of these issues is increasingly hydrogen [4]. To get over these problems, hydrogen manufacturing devices could be combined with renewable energy sources.

Using green energy to increase the efficiency of green hydrogen production has been the subject of numerous research investigations. The best technology for producing hydrogen using solar energy is the combination of photovoltaic (PV) systems with water electrolysis. Water can be separated into hydrogen and oxygen by using an electrolyzer powered by electricity from photovoltaic panels [5–8]. Currently, the green hydrogen manufacturing process with the lowest lifecycle greenhouse gas emissions is wind-powered water electrolysis. Among renewable energy sources, wind energy has the second-lowest electricity cost, only exceeded by hydropower. Significantly higher than comparable wind turbine (WT) systems, solar PV energy generation is usually 6–18 times more expensive. Worldwide, wind energy-based hydrogen synthesis has been the subject of numerous studies [9].

By turning surplus energy into hydrogen gas, green hydrogen energy storage makes it possible to store it. The hydrogen that has been stored can subsequently be utilized to power industrial operations, produce energy, or fuel automobiles.

This study examines a system that generates green hydrogen by combining PV and WT energy sources. For electrolysis, an alkaline electrolyzer is employed, and the proper voltage is ensured by a buck converter. To optimize power extraction, the Maximum Power Point Tracking (MPPT) algorithm's Perturb and Observe (P&O) approach is used. This method involves assessing the system's economic performance and efficiency [10].

By fusing the best features of both algorithms, the PSO-GA hybrid algorithm provides a number of advantages over regular PSO. Whether the objective is to refine a local solution or locate the global optimum, this hybridization produces faster convergence and better optimization quality, making it a more useful tool for exploring complex search spaces [11]. Static voltage stability in power grids has been the subject of much research. Hussan et al., for example, created an energy management system for microgrids that operate independently. Their method optimizes renewable inputs, mostly from wind turbines and photovoltaics, using an intelligent Lyapunov adaptive fuzzy controller. According to simulation studies, this control system successfully maintains the microgrid's global asymptotic stability, improving the power grid's overall dependability and efficiency [12].

By analyzing the performance of alkaline electrolyzer driven by solar and wind energy via a DC-DC converter, this work contributes to our understanding of green hydrogen production. Significant learning effects are seen in the analysis, especially when wind turbine power is combined with electrolyzer efficiency.

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The alkaline electrolyzer technique for hydrogen production using solar PV panels and WT is the main topic of this study. This study's primary contributions are many. In order to power an alkaline electrolyzer, it first describes the design and installation of a stand-alone PV and WT system. Second, it concentrates on the efficient application of the P&O MPPT algorithm for the PV and WT systems, using a low incremental step to guarantee maximum power capture and quick response times. The system's performance was also meticulously measured and analyzed as part of the research. At a constant temperature of 25°C, the study examined the MPPT controller's input, output, and efficiency for the standalone PV system under various irradiance levels (ranging from 600 to 1000 W/m²). The input, output, and efficiency of the MPPT controller were measured for the WT system under varying wind speeds (ranging from 10 to 14 m/s) with a fixed pitch angle of zero. Importantly, the article also quantifies each system's voltage and current characteristics as well as the rate at which hydrogen is produced. The direct comparison of the PV and WT system outputs when feeding the identical PEMEL, exposing their various efficiency and disparities, is an important component of our work. Additionally, the performance of the PV system is contextualized by comparing its output with previous studies in the field. In the end, this document provides a useful manual for creating workable PV or WT systems meant to supply electricity to electrolyzer in actual settings.

II. HYDROGEN PRODUCTION USING RENEWABLE ENERGY

Based on the information in the previous section and some literature [13–16], it can be said that depending on non-renewable resources has a number of disadvantages and difficulties in addition to the fact that fossil fuels are depleting quickly and are processed in a way that harms the environment, making them unsustainable [17]. The following are some of the disadvantages: Greenhouse gas emissions from natural gas reforming are considerable [18]. Furthermore, while it is feasible to reduce greenhouse gas emissions when taking coal into account, this necessitates expensive processing [19]. Moreover, using nuclear energy requires a lot of energy and emits harmful gasses [17]. Specifically, steam-methane reforming requires an expensive high temperature for a thermochemical splitting process [19].

In the meantime, one of the operational challenges of natural gas reforming is the requirement for high temperatures (700–800 °C) [19]. The need to remove moisture and clean coal of impurities, especially low-quality coal, is another challenge in using coal to generate hydrogen [20–21]. The use of nuclear energy to generate hydrogen is limited by the challenge of containing dangerous gasses inside the reactor [15]. Specifically, the solution employed in a thermochemical splitting process needs to have a certain content and concentration, which could make the method less useful [19]. In light of this, recent research in a number of fields, including the creation of green hydrogen, has focused more on ecologically benign renewable energy sources including solar, wind, biomass, geothermal, etc. Renewable energy sources are also widely recognized and reasonably priced. The primary techniques for producing green hydrogen using hydropower, solar and wind energy, and electrolysis are covered in this section. A brief mention is made of a few more emerging techniques for producing hydrogen from renewable resources [19].

A viable option for a variety of stationary and mobile applications is to store hydrogen as metal hydrides, particularly to mitigate the volatility of solar and wind energy generation [22]. Because they provide high-density and secure storage, metal hydrides are especially well-suited for long-term hydrogen storage in applications such as power grids, buildings, and industrial operations [20]. From automobiles and buses to trucks and trains, hydrogen is used in fuel cell vehicles to provide a longer range and quicker refilling than conventional batteries. Because metal hydrides are safer and have a higher density than gaseous or liquid hydrogen, they are essential for effective hydrogen storage [19]. However, problems including sluggish hydrogen release, high weight, and cost must be resolved before widespread use may occur [23]. An overview of water electrolysis applications for renewable energy is presented in Fig. 1.

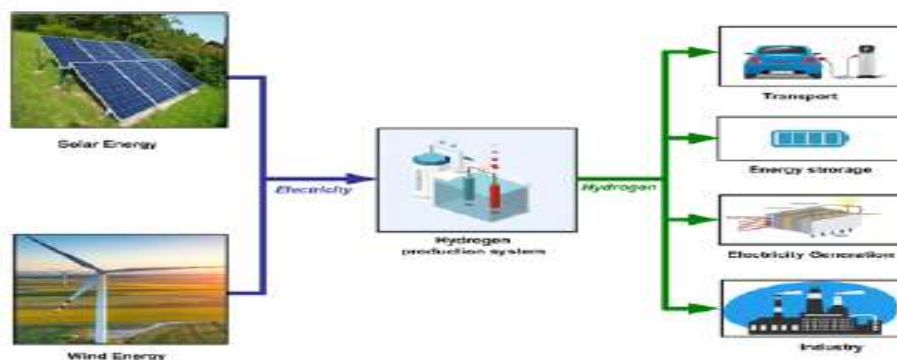
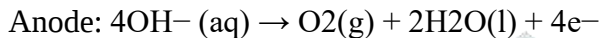
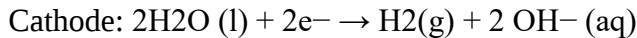
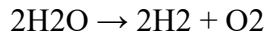


Figure 1. Overview Of Renewable Energy Water Electrolysis Applications

A. SOLAR ENERGY-GENERATED HYDROGEN

Solar energy is regarded as the most reliable option for meeting global energy demand when compared to other renewable energy sources [23]. Fortunately, solar energy can be inexpensively converted into electrical power [23]. Solar-powered electricity can be produced using two different technologies. These consist of photo-thermal and solar PV techniques. In the first approach, solar energy is directly converted into electrical power while being influenced by photovoltaics. In the second technique, solar energy is captured and concentrated using a network of reflective mirrors; heat exchangers help to generate heat. After that, this heat is used to power a steam turbine, which produces electricity [24]. One of the technologies of thermal water electrolysis

(disassociation), an endothermic process [25], such as alkaline water electrolysis, anion exchange membrane, solid oxide electrolysis cells, and proton exchange membrane electrolysis, can then be used to produce hydrogen using this solar-powered electricity. Solid oxide electrolyzers are superior than proton exchange membrane electrolyzers because they generate hydrogen at faster electrochemical reaction rates and need less energy and temperature [26–27]. Of these technologies, proton exchange membrane electrolysis for hydrogen production is the most applied technology today as it is considered among renewable energy [28–29]. It operates by filling a divided electrolytic cell into two chambers with pure water. In each chamber, an electrode (anode/cathode) is placed to interact with an electrical current of a predetermined voltage. Once applied, the electrical current passes through the two electrodes, with oxygen generated at the anode and remains with water. In contrast, hydrogen is generated at the cathode [30], concerning the following chemical reaction, with the governing mechanism can be explained by the other two chemical reactions [30]:



About 12% of electricity can be converted into hydrogen using photovoltaic techniques, while about 25% can be converted using photo-thermal techniques [30]. A photovoltaic system's low conversion efficiency has prevented it from finding widespread commercial use [23]. The intermittent nature of daylight and radiation intensity is another issue with solar-powered hydrogen synthesis [7]. Additionally, the thermal electrolysis of water requires high temperatures, which makes it difficult to implement and lowers solar panel efficiency [7,23]. Efforts are being made to investigate the impact of substituting multi-junction solar cell systems for traditional photovoltaic systems in order to increase the efficiency of hydrogen conversion by capturing more electricity [6–7]. By increasing solar irradiation, reflecting mirrors added to the PV system can also increase conversion efficiency [23]. Both methods are beneficial in terms of the environment because the hydrogen they produce is clean and emits no emissions [24].

Electrochemical splitting technologies for hydrogen creation have also been powered by renewable solar energy, much as non-renewable nuclear power. However, in a solar-powered thermochemical splitting process, water is split using effective cycles, the UT-3 cycle and S-I cycle, as opposed to the troublesome nuclear-powered thermochemical splitting process that uses steam-methane reforming [2]. In the latter cycle, a three-closed-loop chemical reaction system uses the Bunsen reaction to produce sulfuric acid and hydroiodic acid. After being purified and concentrated, the two produced acids are then broken down in a special way into H_2 and I_2 and O_2 and SO_2 , respectively [31]. Figure 2 shows how a solar photovoltaic system produces hydrogen.

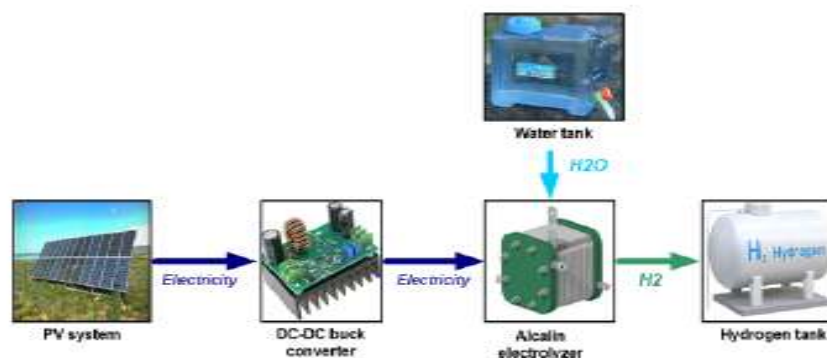


FIGURE 2. PV-Electrolyzer hydrogen production system

B. WIND ENERGY-GENERATED HYDROGEN:

Wind energy has been widely used to generate power, much like other renewable sources for sustainable energy. For the energy industry, wind energy provides a sustainable way to produce clean hydrogen [10]. From an alkaline electrolyzer in conjunction with a wind farm or turbine, an AC/DC converter or regulated rectifier, and a power controller, hydrogen can be produced from wind energy by breaking down water molecules into hydrogen and oxygen.

Even when fossil fuels are used in a hybrid system, an effective strategy can be used to produce hydrogen and cut or eliminate greenhouse gas emissions. The procedure is as follows: an alkaline electrolyzer receives electrical energy produced by a wind turbine or wind farm. This electrolyzer uses two electrodes to divide water into hydrogen and oxygen, allowing for the manufacture of pure hydrogen using only renewable energy [30]. The process's efficiency is mostly determined by the electricity produced by the wind turbine or turbines [29]. Both the electrolyzer's energy usage and the rectifier's efficiency have a significant impact on the amount of hydrogen generated [10]. The location, speed, and size of the wind all affect how efficient the operation is overall [10]. Wind-powered hydrogen has a number of uses in fuel-cell automobiles and, to a lesser degree, in industry as a cleaner fuel [31].

Wind-powered hydrogen generation outperforms photovoltaic systems [10]. Although the manufacturing of hydrogen with wind energy produces greenhouse gas emissions for the environment, these emissions are not seen as critical [27]. Additionally, the project of producing hydrogen using wind energy is often lucrative [9].

Nevertheless, this method of producing hydrogen has certain drawbacks, such as the erratic supply of wind energy and problems with the storage and transportation of the generated hydrogen [4]. Wind energy's unpredictability is equivalent to giving up electricity, which could irritate investors and power producers. To maintain a steady supply of electricity, it is advised to combine an energy storage system with a wind farm or turbine as a cure [25]. Lithium-ion battery systems and energy conversion (electricity to gas/hydrogen) are examples of energy storage devices generated by wind energy [17]. A typical wind-powered hydrogen manufacturing process is depicted in Fig. 3.

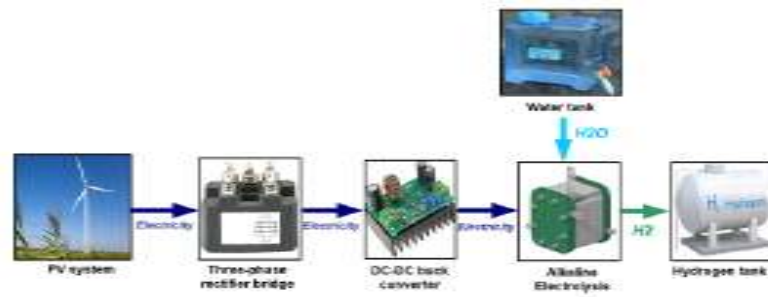


FIGURE 3. Wind-Electrolyzer hydrogen production system

III. MODELLING OF THE HYDROGEN PRODUCTION SYSTEM COMPONENTS

A. Sources of Renewable Energy

- The PV system

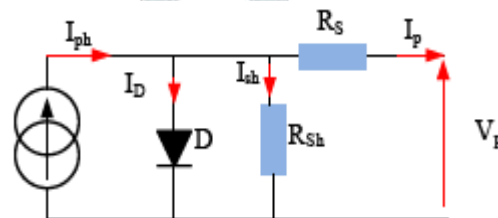


FIGURE 4. Equivalent circuit of the PV cell.

Eq.(1) represents the output current according to Kirchhoff's current law (KCL).

A basic physical process in the PV panel immediately transforms solar energy into electrical energy. A solar cell's physical performance is quite similar to that of a traditional P-N junction diode. As illustrated in Fig. 4, the one-diode equivalent circuit serves as the foundation for the equivalent circuit (PV) generator

$$I_{ph} = I_{ph} - I_D - I_P \quad (1)$$

The diode is a non-linear component, and its I-V characteristic is expressed by the following relationship:

$$ID=IS[\exp(q \frac{V_d}{\gamma kT}) - 1] \quad (2)$$

According to the law of Kirchhoff:

$$VD=VP+RSIP \quad (3)$$

$$I_{sh} = \frac{V_p + R_s I_p}{R_{sh}} \quad (4)$$

The relationship (1) becomes:

$$I_p = I_{ph} - I_s$$

$$I_p = I_{ph} - I_s [\exp(q \frac{V_p + R_s I_p}{\gamma kT}) - 1] - (\frac{V_p + R_s I_p}{R_{sh}}) \quad (5)$$

The photovoltaic cell's output power can be found as follows:

$$P_m = I_{mp} V_{mp} \quad (6)$$

System of Wind:

The power coefficient determines the aerodynamic power that a wind turbine converts [25].

$$P_t = \frac{1}{2} C_P(\lambda, \beta) \rho R^3 \pi V_w^3 \quad (7)$$

where V_m is the wind speed (m/sec), R is the blade radius, β is the pitch angle, λ is the tip speed ratio, and ρ is the air density (kg/m³).

Only a portion of the total wind power captured can be converted by a wind turbine. Each wind turbine's power coefficient, C_p , fluctuates according on the tip-speed ratio (λ) and blade pitch angle (β), and it cannot be greater than 0.592. The following relationship [23] represents the power coefficient C_p :

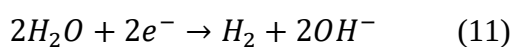
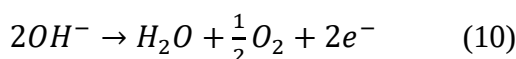
$$C_p(\lambda, \beta) = A_1 \left[\left(\frac{A_1}{\lambda_i} \right) - A_3 \beta - A_4 \right] e^{\frac{A_5}{\lambda_i}} + A_6 \lambda \quad (8)$$

B. Electrolyzes that Are Alkaline

The most developed technique, alkaline electrolysis, uses an ion-conducting medium consisting of 20% to 30% aqueous potassium hydroxide (KOH) or sodium hydroxide (NaOH). Dihydrogen (H₂) and hydroxyl ions (OH⁻) are created at the cathode when molecules in the alkaline solution are reduced; these ions then cross the membrane and reach the anode. [15, 16].

An electrolyzer is a device that, when a minimum electrical voltage is applied, enables the water molecule, H₂O, to split into the hydrogen gas, H₂, and oxygen, O₂. The voltage across the electrolysis cell should ideally match this minimal value, also referred to as the reversible voltage [1], [6], [33], and [34].

The following lists the anode and cathode-related reactions in alkaline electrolysis:



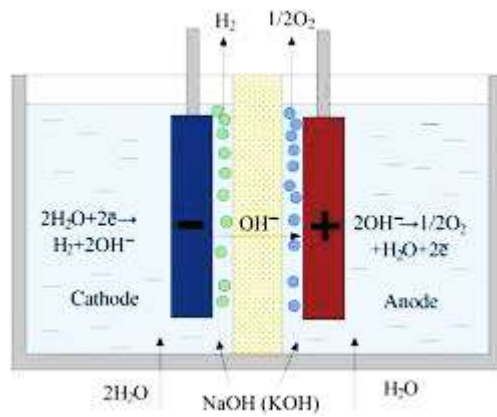


FIGURE 5. Alkaline Electrolyzer

One can determine the electrical operation voltage as follows:

$$V = V_{\text{rev}} + V_{\text{act}} + V_{\text{ohm}} \quad (12)$$

Where:

$$V = V_{\text{rev}} + \frac{r_1 + r_2 T}{A} I + s \cdot \log \left(\left(t_1 + \frac{t_2}{T} + \frac{t_3}{T^2} \right) \frac{I}{A} + 1 \right) \quad (13)$$

Under typical conditions, the thermodynamic stress ($T=298\text{K}/p=1\text{atm}$) is:

$$V_{\text{rev}} = \frac{\Delta G}{ZF} = 1.229\text{V} \quad (14)$$

In typical situations:

$$\Delta H = 285,83\text{kJ/mol} \text{ and } \Delta G = 237\text{ kJ/mol}.$$

The following is an empirical expression for the Faraday efficiency:

$$\eta_F = \frac{\left(\frac{1}{A}\right)^2}{f_1 + \left(\frac{1}{A}\right)^2} f_2 \quad (15)$$

The Faraday efficiency's parameters are:

$$f_1 = 2.5T + 50 \quad (16)$$

$$f_2 = 1 - 6.25 \cdot 10^{-6} T \quad (17)$$

When several cells are connected in series, the rate at which hydrogen is created is represented as follows:

$$\text{NH}_2 = \eta_F \frac{ncI}{nF} \quad (18)$$

C. Storage of Hydrogen

Here, the physical hydrogen storage method and the hydrogen flow rate are used to calculate the storage tank's pressure.

The following formula is used to determine the flow rate of hydrogen production:

$$Q = \frac{nc \cdot R \cdot I_F \cdot T}{Z \cdot F \cdot P} = \frac{nc \cdot R \cdot I_f \cdot T}{2 \cdot 96485 \cdot P} \quad (19)$$

The tank pressure is determined using the physical hydrogen storage method

$$P_b - P_{bi} = \frac{n_{H_2} R T_b}{M_{H_2} V_b} \quad (20)$$

P_b is the actual tank pressure, P_{bi} is the beginning tank pressure, T_b is the working temperature, R is the general gas constant, V_b is the hydrogen storage tank's volume, M_{H_2} is the molar mass of, and I_f is the electrolyzer's operating current. The hydrogen atom (H_2).

A high-pressure composite cylinder intended for effective and safe hydrogen containment serves as the model for the hydrogen storage tank in this study. Safety elements including strengthened materials to withstand high pressures, pressure release valves to prevent over-pressurization, and compliance with pertinent industry standards were all part of the design process. By taking these precautions, the hazards connected with storing hydrogen are reduced and dependable functioning is guaranteed

D. MPPT Control and Dc-Dc Buck Converter

Buck Converter DC-DC:

The DC-DC buck converter, which is the primary part of this green hydrogen production system, raises the output current in order to maximize matching to the electrolysis load by decreasing the output voltage of the CPV system. Fig.6 displays the buck converter's structure.

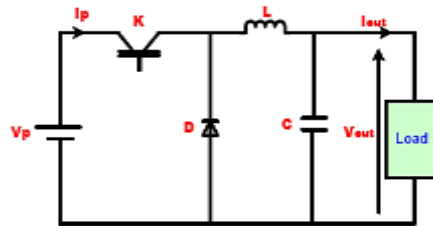


FIGURE 6. DC-DC buck converter

Depending on the duty cycle of the signal regulating the converter, the electrical properties of the buck converter (V_{out}, I_{out}) are connected to those of the PV system (V_p, I_p).

$$D = \frac{V_{out}}{V_p} = \frac{I_p}{I_{out}} \quad (21)$$

Both the inductor and the capacitor are essential for smoothing the current that is supplied to the electrolyzer; the inductor reduces current ripple and the capacitor maintains a steady voltage based on the duty cycle (D), which together give the electrolyzer a constant and steady current. The values of the inductor (L) and capacitor (C) are determined using the following formulas: $C = \frac{(1-D)V_{out}}{2Lf^2\Delta V}$ (22)

$$C = \frac{(1-D)V_{out}}{2LfI_{out}} \quad (23)$$

MPPT Control

This control examines the effects of duty cycle variations on the power output of wind turbines or solar systems. if a specific direction is indicated by the power at time k . The P&O approach is frequently used to achieve the MPPT [31]. The operating voltage is more disturbed when the power at time k is in a certain direction ($\Delta V > 0$) than when it is at time $(k-1)$ ($\Delta P > 0$), and the disturbance is in the direction of the MPP operating point. Until the P&O algorithm reaches the operational point, or MPP, when the power oscillation is zero ($\Delta P = 0$), it keeps perturbing the voltage in the same direction. After that, the power drops ($\Delta P < 0$).

Because of its simplicity and convenience of use, the Perturb and Observe (P&O) algorithm is one of the most often used techniques for Maximum Power Point Tracking (MPPT) in photovoltaic systems. It works by varying the solar

panel's working voltage on a regular basis and tracking the power change that results; if the power rises, the disturbance continues in the same direction; if not, it reverses. The P&O algorithm has certain intrinsic drawbacks despite being widely used. Overall efficiency may be lowered since it frequently results in steady-state fluctuations around the maximum power point. Additionally, it is susceptible to abrupt variations in temperature and irradiance, which can cause tracking errors and slower reaction times. Adaptive step size modifications and filtering approaches are two tactics that can be used to address these problems. These strategies help reduce oscillations and enhance the algorithm's responsiveness in dynamic operating situations. The P&O technique flowchart is displayed in Fig. 7. A realistic and thorough evaluation of system performance is ensured by considering changes in renewable energy inputs as well as other external disruptions

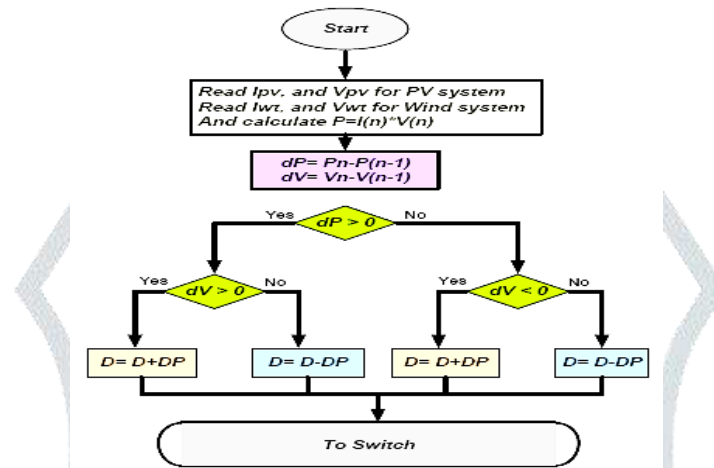


FIGURE 7. Flowchart of the P&O technique

Variations in irradiance, temperature, and wind speed were considered to assess the system's capacity to sustain steady operation, given the intrinsic unpredictability of renewable energy sources such as sun and wind. To further test the robustness and flexibility of the suggested model, possible disturbances such load changes, component aging, and environmental conditions were taken into account. By including these dynamic conditions, the system's behavior in the real world is better understood and opportunities for more control and optimization are highlighted

IV. SIMULATION RESULTS

Electrolysis of Alkali Utilizing a Photovoltaic Generator

As solar irradiation increases, the electrolyzer's input current rises steadily over time, as seen in Fig. 8. The concurrent increase in the electrolyzer's output power is directly correlated with this rise in current. In essence, the input current serves as a trustworthy gauge of solar intensity; higher current indicates better sunshine, which increases power production. The system's reliable operation is highlighted by the tight correlation between the input current, sun irradiation, and output power.

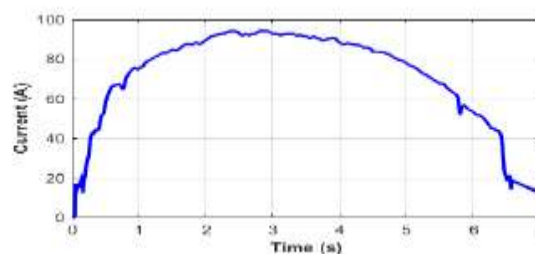


FIGURE 8. Variation of electrolyzer current with time.

The direct correlation between sun irradiance (W/m^2) and the rate of green hydrogen production (Nm^3/h) at a constant temperature of 25°C is shown in Fig. 9. In particular, a peak irradiation of 950 W/m^2 is equivalent to a rate of hydrogen generation of roughly $0.66 \text{ Nm}^3/\text{h}$.

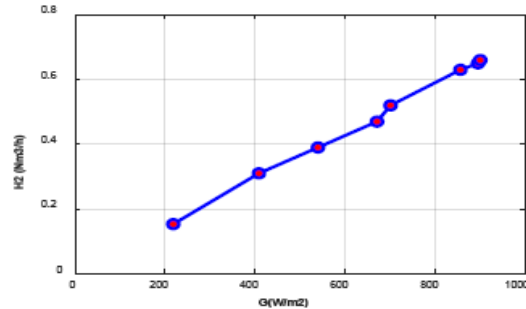


FIGURE 9. Green hydrogen production rate as a function of variable solar irradiance.

The system's efficiency, which peaks at 82% at 2.8 seconds, fluctuates with hydrogen mass and volume. Hydrogen output is directly impacted by these variations, which are caused by variations in sunlight; poor efficiency lowers production, while high efficiency increases the danger of electrolyzer damage. To maintain maximum efficiency, a buck DC-DC converter with P&O MPPT control is therefore necessary.

A. ELECTROLYSIS OF ALKALI UTILIZING A WIND TURBINE FOR POWER

With their 130V peak amplitude, the sinusoidal line voltages (V_{ab} , V_{bc} , and V_{ca}) shown in Figure 10 illustrate a synchronous generator's efficient energy conversion. To achieve balanced power output and reduce energy losses, these voltages must oscillate between $+130\text{V}$ and -130V , with a 120° phase shift between them.

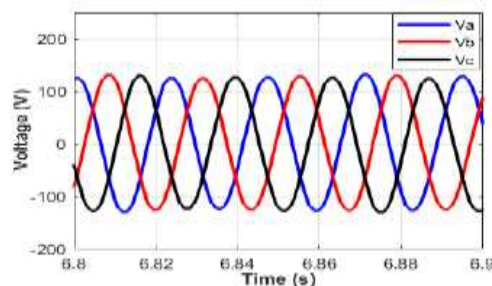


Figure 10. Evolution of PMSG Three-Phase Stator Voltages.

To evaluate the economic feasibility of producing green hydrogen with solar and wind energy, a thorough techno-economic analysis was conducted. Along with balance of plant expenses, the analysis considered capital expenditures (CAPEX), which included the expected \$1,200 per kW cost of the electrolyzer, \$800 per kW cost of the solar PV system, and \$1,300 per kW cost of the wind turbine. Maintenance and electricity expenses were anticipated to be \$0.02/kWh and \$0.05/kWh, respectively, as operational expenditures (OPEX). Based on these factors, the levelized cost of hydrogen (LCOH) for solar-powered systems was estimated to be around \$4.5/kg, whereas for wind-powered systems, it was \$3.8/kg. Sensitivity analysis showed that the most important factors influencing cost are electricity price and electrolyzer efficiency, with a 10% increase in efficiency lowering LCOH by as much as 15%. According to these findings, increasing system capacity and enhancing efficiency are essential for making green hydrogen generation sustainable and competitive. They also emphasize economic drivers.

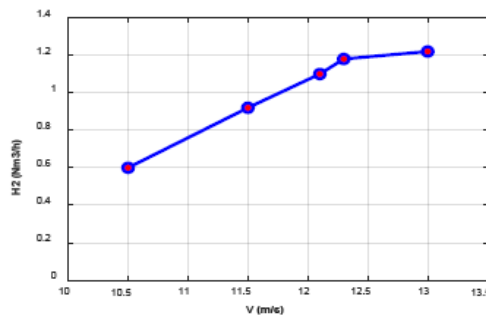


FIGURE 11. Hydrogen production rate as a function of variable wind speed

A quantitative lifecycle assessment (LCA) was carried out to give a thorough analysis of the environmental advantages of wind and photovoltaic systems used in green hydrogen production. This study measured the greenhouse gas (GHG) emissions from the production process as a whole, from the creation of hydrogen to the generation of renewable energy. In comparison to the 9–12 kg CO₂-equivalent per kg released by traditional steam methane reforming techniques, the LCA calculations show that green hydrogen production emits roughly 1.5–2.0 kg CO₂-equivalent per kilogram of hydrogen. In addition, other environmental effects like water use and land footprint were evaluated to guarantee a comprehensive comprehension of sustainability. The electrolysis process alone was found to have a water footprint of about 9 liters per kilogram of hydrogen produced, which is substantially less than that of conventional hydrogen generation techniques. According to the evaluation, the land use requirements for solar PV and wind turbines were 3–5 m² per kW and 0.3–0.5 m² per kW, respectively. This highlights the importance of effective site planning in order to reduce ecological disturbance. These evaluations show that renewable-powered hydrogen generation maintains relatively low environmental impacts in important places while reducing greenhouse gas emissions by up to 85%, so bolstering its feasibility as a sustainable energy alternative.

V.CONCLUSION:

A comprehensive investigation into the production of green hydrogen via alkaline water electrolysis powered by hybrid solar–wind renewable energy systems. The alkaline electrolyzer is selected for its rapid response and suitability under fluctuating irradiance and wind conditions. A perturb-and-observe (P&O) MPPT algorithm integrated with a buck converter ensures optimal power tracking and fast dynamic response. The hybrid configuration employs a photovoltaic array operating between 200–1000 W/m² and a wind turbine functioning at 8–13 m/s, effectively enhancing electrolyzer capacity. Comparative analysis indicates wind energy achieves 90% efficiency and 1.2 Nm³/h hydrogen production, outperforming solar PV at 82% and 0.66 Nm³/h. The study highlights each source's operational merits—solar's low maintenance and daytime stability versus wind's higher capacity factor and continuous availability. Despite individual limitations, the hybrid approach demonstrates superior stability, reliability, and energy utilization. The findings underscore the practical feasibility of integrating wind and solar resources for efficient, sustainable hydrogen generation and provide valuable design insights for future renewable-powered electrolysis systems aiming at large-scale green hydrogen deployment.

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