

Renewable Energy–Driven Green Hydrogen Production: Integration Technologies and Future Prospects

Chandrashekhar. L. gamit [1*], Vikas Kumar Bhavsar[2], Narendra. M. Makwana[3]
[1*]Department of science and humanities (Physics), Government polytechnic Waghai, Gujarat Technological University, Gujarat, India.
[2]Applied science and humanities Department (Physics), Sankalchand Patel college of Engineering, Visnagar, Sankalchand Patel University, Gujarat, India.
[3]Department of science and humanities (Chemistry), Government polytechnic Godhra, Gujarat Technological University, Gujarat,India.

*Corresponding Author Email: [1 *]gamit.chandu@gmail.com, [2] vikasbhavsar@gmail.com
[3] nm27475@gmail.com

Abstract: The increasing global demand for sustainable and low-carbon energy has highly accelerated research on the hydrogen as an alternative clean fuel. Renewable energy sources undergo electrolyzed water to produce green hydrogen that can be a reasonable hydride alternative to decarbonizing the world energy system. The current research is an experimental study to test how the renewable energy of hydrogen can be produced through the use of solar energy and wind energy produced through the combination of the two technologies. The efficiency of the system, the rate of hydrogen production, and the rate of energy consumption are analysed through the evaluation of a simulated renewable energy electrolysis system driven with electrolyzer of 10 MW. The experiments conducted reveal that approximately 50-55 kWh of electricity is required to transform 1 kg of water into hydrogen via electrolysis of this substance and the findings of the electrolysis process will be based on the efficiency of the system.

The research methodology consists of thermodynamic, electrochemical and system performance studies. The efficiency of the hydrogen production is established based on numerical modelling of hybrid electrolyzer system using the basis of solar-wind. The results point out that renewable energy sources combined with running of the proton exchange membrane electrolysis would enhance flexibility in operations and increase the capacity of the production of hydrogen. The results of the experimental simulation indicated that, based on the current idealized operating conditions a 10 MW of electrolyzer system can be used to assist in production of about 200 kg/h of hydrogen.

According to the findings, the renewable hydrogen systems can reduce carbon emissions by a substantial percentage and can also provide a long-term energy storage. Putting it into large-scale use remains stalled by system efficiency issues, however, by intermittency of renewable energy and infrastructure challenges. As the paper concludes, the availability of the hydrogen economy in the world in the future will be pegged on the support of the technological advances due to contributions by making strides in the field of electrolyzers, integrating with the renewables and storage of energy.

Key words: Green hydrogen, Renewable energy integration, Proton exchange membrane electrolyzer, Solar–wind hybrid system, Hydrogen production efficiency, Energy storage systems.

1. Introduction:

The global energy sector is experiencing a huge fundamental transition toward the sustainable and low-carbon energy systems as a result of the increasing concerns about climate change, environmental degradation, as well as fossil fuel depletion. Mohammad (2022), The present-day energy production of the world is with the prevailing use of fossil fuels that provide much power to the world at the cost of greenhouse emission and environmental pollution. This has brought about alternative energy carriers which can reduce the carbon emissions and the rising energy demand [1].

Hydrogen has emerged as one of the promising forms of energy since its energy density is high and it is versatile and clean burning. Using the hydrogen as a fuel all that is emitted is water vapor, thus, it is a zero-carbon carrier of energy during consumption. However, the hydrogen sustainability in the environment strongly depends on how the hydrogen is generated.

Today, a vast majority of the hydrogen is in the present days produced through the use of instruments of fossil origin such as the methane reforming by the steam and coal gasification. The processes lead to massive production of carbon dioxide which is not sustainable in the environment [1]. Green hydrogen on its part is generated during supplementary production of water electrolysis using electricity generated on a renewable energy source such as solar, wind or hydropower.

Hydrogen and oxygen are separated and water molecules are divided through the use of electrical energy, with the help of water electrolysis. The process eliminates the carbon gas emission that is associated with the traditional hydrogen production process, Zhang (2024) [2]. However, the electric charge between hydrogen and oxygen atom in water molecules is extremely high and this requires great amount of electric energy in the electrolysis process.

Theoretically a minimum of 285820 k J per mole of water would be required to uncombine water, or in perfect conditions some 39-40 kWh/kg of hydrogen. However, the reality on the ground is that it requires almost 50-55 kWh of power to generate one kilogram of hydrogen through electrolyzer systems due to loss of energy and system inefficiencies.

New technological advances have also made electrolyzers behave better and their capability of incorporating renewable far much more. New proton exchange membrane electrolyzers have larger operational leeway's and can be operated in varying circumstances of renewable force [3].

There are several advantages to hydrogen production that leads to renewable energy production. it enables the storage of renewable electricity at a scale, enables interconnecting one of the sectors between energy and transport infrastructure, and decarbonizes industrial processes, such as steel milling and ammonia synthesis.

These are the positive aspects, but there are numerous obstacles which do not contribute to mass uptake of hydrogen green technologies [4]. High costs of capital of electrolyzers, inability of electricity to be continuous and the inability to transport renewable energy, and inefficient energy conversion are these hurdles.

In this paper, the author will discuss fuel cells that use renewable energy to generate hydrogen with evaluation of the electrolysis technologies, methods of renewable integration, and the system performance through an experiment with the help of a numerical model.

2. Literature Review:

One of the most promising methods to provide the long-term sustainability and reduce the emission of greenhouse gases is the green hydrogen as a renewable-energy-based solution to the global energy system. The author emphasizes that hydrogen, created with the assistance of renewable energy sources, such as wind, solar, and hydropower can influence altering the state of affairs in the world energy sector because it can be not only a clean hydrocarbon but also an efficient storage of energy. Marouani opines that the increased integration of renewable energy into the power systems has created the need to incorporate efficient storage systems which would mitigate the declines and increases in electricity production. In that regard, the green hydrogen is strategic benefit since the surplus renewable electricity can be converted to hydrogen through the electricity-to-hydrogen conversion process and it can be stored to be consumed in the future [5]. The author goes ahead to say that the sector coupling that exists between electricity and transportation as well as industrial sectors, can be achieved via the hydrogen technologies integration process. The connection of these areas can dicarbon kill power-consuming industries, such as steel production, ammonia production, and heavy transportation, with renewable hydrogen systems. Another area that is discussed by Marouani concerns technological successes that contributed to the improvements in the efficiency of hydrogen production forms that are particularly talented in the technologies of alkaline electrolyzers, proton exchange membrane electrolyzers and solid oxide electrolyzers. Each of these technologies has its own advantages according to the needs of operation along with the accessibility to renewable energy. As indicated in the paper, PEM type of electrolyzers is most effective when it comes to using renewable energy due to the quick nature of its reaction to changes in the input of power. In addition, the author remarks that a green hydrogen may play a vital role in achieving the goals of global climate through direct displacement of fossil fuels in the regions where direct electrification cannot be realized easily. However, the paper does not ignore a series of challenges that must be addressed before it can be possible to open the gateway to the adoption of large-scale adoption. The high cost of production, absence of hydrogen infrastructure, and inefficiency of technology on the electrolysis systems amount to such problems. According to Marouani, there is need to continue research and supported policy modification in order to accelerate commercialisation of hydrogen technologies. Hydrogen economy in future is talked about as a possible engine that can work through large scales of the investment into the renewable energy infrastructure, cooperation of the countries and government incentives. The author concludes that the successful implementation of the renewable-energy based hydrogen in the global systems of production of energy must be made on a holistic scale targeting the global world energy system requirement in terms of integrating technological discovery, economic drive and enabling policy structures. Overall, the study can provide a highly important insight into the role of hydrogen in transitioning to low-carbon energy future and underlines the importance of combining renewable energy sources and future-class hydrogen production systems.

The author indicates that the production of green hydrogen along with the utilization of renewable energy sources at work in desalination facilities is a fresh approach to the manner in which the problem of energy and water sustainability is addressed (Arunachalam, 2024). The author indicates that the hydrogen generated on the process of electrolysis of water requires huge amounts of clean water which is an issue in regions where water shortage exists. To address this issue, Arunachalam proposes the establishment of desalination plants powered using renewable energy source as well as hydrogen-generating plants. The method enables seawater to be converted into fresh water using renewable energy technologies which include the solar powered or wind powered desalination plants [6]. The purified water obtained because of the desalination process can then be used as feed to any one process of electrolysis therefore generating hydrogen in a sustainable manner without the pressure on the fresh water resources. Another implication of the integration of the desalinations and hydrogen production systems that the author examines is the capital expenditure implication. According to the study, pre-investment costs could be moderate and short to middle term, but the benefits that could become realized after a long period of implementation of an integrated renewable energy system have highly less expenditure compared to initial cost of investment. Various operational strategy that would maximise the successful functioning of the integrated desalination and hydrogen generation systems is also covered in the paper. Through one of the solutions, desalination plants and electrolyzers are expected to coordinate and work in harmony, but by the access to renewable energy. The hydrogen production systems and the desalination systems have the capability of operating at higher capacities during the times of maximum renewable electricity production. Conversely, the work of the system can be also regulated in accordance to the low levels of producing renewable energies keeping efficiency and low consumption of the energy. The other concept that is initiated by Arunachalam is the economic feasibility of the generation of the green hydrogen in bulk in coastal regions where the desalination of the sea water can be easily acquired. The co-existence of the desalination systems has also ensured continuity supply of the clean water as well as that which promotes sustainability of the hydrogen production systems. In addition to the foregoing, the author dwells upon the potential technological advances that will render desalination far less expensive, including the improved membrane technologies, as well as the more efficient energy recovery system. The research hypothesis is that as renewable energy-derived desalination and hydrogen production is adopted, the process would be of significant relevance in enabling sustainable hydrogen economies that would have a lot of freshwater but with a high concentration of renewable energy in specific regions. The author concludes that in the future when the hydrogen infrastructure is developed, the issue of water resources management must play an important role in the design of a system, which will ensure that the green hydrogen production is both environmental friendly and economically efficient.

Sharma (2023) concludes by stating that to maximize the generation of green hydrogen by relying on renewable energies, load profiles and energy system dynamics should be considered. The author goes on to expound that the sources of renewable energy such as solar and wind electricities are highly variable since they are subject to the weather conditions thereby may affect the stability and practicality of the hydrogen production systems. To address this dilemma, Sharma proposes that the load profile simulation methods could be applied to examine the tendency of the creation of the renewable energy sources and that, consequently, of this study, the electrolysis systems could be optimized to store and supply their output. Experiments: To be the most efficient, hydrogen production facilities have some operating conditions that they require and by simulating other load conditions researchers are able to explain the best operating conditions [7]. The paper advises that there is the need to integrate the functioning of electrolyzers with production of renewable energy to enable the maximization of the efficiency of the energy and minimize the loss in the systems. In this connection, Sharma asserts in his argument that producing renewable energy and controlling the activity of an electrolyzer can be predicted in relation to the variations with the help of advanced simulation models. This will make the hydrogen production systems more effective in addition to reduction of ill-useful energy consumption. The writer also discusses how a blend of renewable hydrogen generation networks along with energy storage technologies are relatively beneficial. The fluctuation of electricity supply in the renewable sources can be controlled with the help of the energy storage in the batteries or hydrogen storage tanks where the excess energy is stored at the rising period of the renewable generation and is stored at the rising time of the renewable generation. Sharma also emphasizes that the price of hydrogen production can be reduced significantly with the assistance of optimization of load profile which improves the rate using electrolysis systems. Both of these benefits raised the rate of utility which leads to greater stimulated production of hydrogen and also less duration of idle processes. There is also an argument on how advanced energy management systems can be used in enhancing the production of hydrogen that can be generated using renewable energy sources. These systems manage the energy flow on real-time premise by real-time authorization by real-time monitoring and prediction algorithm between the renewable energy sources, electrolysis system and storage units. The author concludes that to improve the economic viability of green hydrogen Generation, it is required that simulation load profiles and optimization of the energy system. These optimization means will gain greater importance when the renewable energy potential in the world continues to expand in order to ensure the effective and sustainable system of hydrogen generation.

According to Horri (2024), the optimization of the power management strategy is the key to the better performance of solar photovoltaic-based energy system integrated system in the small-scale production of green hydrogen. The author suggests that the solar photovoltaic systems are both clean and renewable source of electricity that might be used to power electrolysis reactions to generate hydrogen. However, solar energy generation process will be intermittent in nature due to variation of the solar radiance throughout the day. In response to this, Mohammad proposes that intricate power management regulations should be embedded to regulate supply of electricity in unified energy systems [8]. These systems are designed upon photovoltaic panels, energy storage units, and electrolysis systems and these constitute an adaptable infrastructure of production hydrogen. The article is concentrated on the idea that power management is efficient in case of availability of source of solar energy, and the minimal loss in the system. The other crucial sector that Mohammad has highlighted is the distributed hydrogen production systems so that hydrogen could also be produced close to the point of consumption. The allocated hydrogen systems reduce the extensive hydrogen transportation system and augment the stability of the energy systems. The paper also examines the different optimization algorithms that may be used to enhance the functionality of the photovoltaic-generated hydrogen production systems. Such programs consider the supply of solar energy, the demand of the systems, and storage potential to offer the optimum working conditions of the electrolysis systems. It is concluded that the complex mode of power management according to Mohammad would prove invaluable in giving way to decentralized hydrogen production systems particularly within remote regions where there is excessive presence of solar.

According to Zhang (2024), the integration of green hydrogen technologies in renewable energy systems is a revolution in the realisation of sustainable energy transformations. According to the author, the main difference between renewable sources of electricity and many spheres of the energy intake can be hydrogen. Zhang stresses on that renewable energy sources of energy such as solar and wind power have of late developed highly rapidly, but their inconsistencies pose a challenge of having a consistent power supply. Green hydrogen is such solution to this issue: the additional renewable electricity can be transformed into warehouse hydrogen, which can be emitted during the periods, when the demand on electric energy increases. The study observes that decarbonization impetuses on the large scale can be performed using the hydrogen-based energy in many sectors. As an example, a hydrogen fuel solution can be used, including fuel cell vehicles, buses, and trains. It can also replace the use of fossil fuels in the industry such as steel making and chemical production. Zhang goes ahead to reason out that though the hydrogen based energy systems help in the long term storage of the energy which is required to balance between the supply and demand of electricity within the renewable dominated power grids [9]. One more issue that the author discusses is technological progress that has contributed to the efficiency of hydrogen production and using technologies. The potential of the hydrogen-based energy systems has become, to a great extent, enhanced with the progress in the design of the electrolyzers, fuel cell structures and hydrogen storage platforms. Zhang finds that the integration of green hydrogen and renewable energy technologies would be one of the solutions to global carbon neutrality and the establishment of energy infrastructure in the context of sustainable energies.

One of the main approaches towards cutting the carbon emission as well as facilitating the sustainable energy development has proven to be the production of Green Hydrogen Hydrogen with the use of renewable energy sources (Hassan Khan, 2022). The author also provides the detailed examination of the various sources of renewable energy that can be utilized in the production of hydrogen which includes solar, wind, hydropower and biomass. Hassan argues that the most common method of producing green hydrogen currently is based on renewable electricity prior to the production of the hydrogen as it does not emit carbon that is released in the usual processes of preparing hydrogen. Other examples of electrolyzers that are considered in the study are alkaline electrolyzers, proton exchange membrane electrolyzers and solid oxide electrolyzers [10]. The two technologies are advantageous in some aspects depending on the requirements of operations and renewability of energy sources. Hassan supports that an alternative mix of renewable devices and hydrogen-producing plants might form a perfect solution to enhancing the flexibility and that of the energy systems. However, the author also notes that there are several barriers that should be eliminated before the common implementation of green hydrogen can take place. These barriers are cost of production is high, poor infrastructure and limitation in technologies of hydrogen storage and transportation. The conclusion of the paper is that there is no way that the efficiency and cost-effectiveness of renewable systems of hydrogen production will be enhanced without the additional research and development facilitation.

According to the arguments of Alam (2024), government policies can contribute to the international expansion of the green hydrogen production system. The author is of the opinion that even with technological development, it is not possible to pilot the massive use of hydrogen at all, unless with policy support and regulation structures. Alam emphasizes that the governments must launch the policies which will encourage the investment in the renewable energy infrastructure and hydrogen technologies of production. These policies may be materials in the form of financial incentives, tax incentives, research, and international collaborations with the intention of ensuring that the process of developing hydrogen technologies is accelerated [11]. The paper has also articulated reasons as to why headway should be made in coming up with clear rules of how hydrogen should be produced, stored, and transported in order to ensure that they are safely and reliably produced. Alam also writes that world policy efforts must create a global hydrogen market which would have the financial means to make the giant shift of energy. The governments of other nations can collaborate and urge the adoption of hydrogen supply chains and to streamline international trade of green hydrogen. The author also finds that the beneficial government policies will play a very significant role in the establishment of a global hydrogen economy and the uptake of renewable hydrogen technologies in the early days [12].

3. Research Objectives:

The primary objective of this research is to evaluate renewable energy–driven hydrogen production through integrated electrolysis systems.

The aim of the study will be to test the operation of the electrolysis systems using renewable fuel and find out how effective hydrogen production is and how efficient is production of green hydrogen at large scale.

Another goal of the study is to determine the connection between the input of renewable energy, the efficiency of electrolyzers, and the output of hydrogen using the numerical simulation and thermodynamic analysis.

4. Methodology:

The methodology of this study focuses on the process of evaluating renewable energy–driven hydrogen production through an proper integrated hybrid renewable energy system which is combined with a particular proton exchange membrane (PEM) electrolyzer. The paradigm of the research includes the design of hybrid renewable energy-set-up, electrochemical modelling of the electrolysis process of the water, the numerical analysis of the rate of hydrogen and evaluation of the electrolyzer efficiency [13]. This methodology attempts to determine the correlation between the input of renewable energy in the form of electricity, the functioning of electrolysis and production of hydrogen under favourable conditions of operation. A system based experimental model of the study will comprise of a renewable electricity source which is caused by a solar photovoltaic and wind energy system to be combined into a specific form that will be the electrolyzer unit. The estimated capacity of hydrogen production generated is estimated using the thermodynamic relation and the electrochemical principles. Conversion Efficiency of energy, specific energy consumption and Hydrogen heating value of the renewable hydrogen production system are also derived so as to get the overall performance of the renewable hydrogen production system.

4.1 Experimental System Configuration:

The experimental system configuration considered in this study consists of a hybrid renewable energy system integrated with a proton exchange membrane electrolyzer for hydrogen production. The design will appear to be a medium-scale production facility of green hydrogen that is completely revolutionized by the renewable energy sources.

There are two large components that make the hybrid renewable energy system; one of the elements is a solar photovoltaic power plant and the other is wind turbine power generation facilities. The solar photovoltaic system is that of the total installed capacity of 6MW and has the responsibility of generating power in the daylight period. The photovoltaic panels apply photovoltaic effect to transform solar radiation to electrical energy. Photovoltaic photovoltaic modules convert electrical power depending on sun radiance, efficiency and block of panels among other ambient factors such as temperature and shade.

The efficiency of the PV system used in the model of the experiment is approximately 18%. The photovoltaic array produces the rated power of 6 MW when it is subjected to normal test conditions with the sun irradiance at 1000 W /m 2. However, the solar generation production will be fluctuated in the real working conditions according to the sunlight intensity, daytime, and seasonal variations, Hassan (2024) [14]. The photovoltaic is used to convert the type of electricity to the production process of hydrogen.

Another system available in the hybrid system is the wind turbine system to augment the production of solar power and upgrade the reliability of the system with a cumulative power of 4 MW. The energy of wind is transformed into mechanical energy and consequently, electrical energy via wind turbines and a generator. An average power factor of 35 which can be translated to mean that, in the long run, the power plants will generate electricity 35 per cent of the rated capacity is the average of wind power system.

Integration of wind power with inclusion of solar power would provide a dependable source of renewable energy as there are frequent occasions when wind power is produced as compared to a shortage of solar power such as at night hours or in bad weather [15]. The solar system with the wind system therefore adds the overall reliability of power supply to the hydrogen production process.

The hybrid system has a renewable energy installed to 10 MW which is 6 MW solar photovoltaic panel and 4 MW wind turbines. This electricity generated by these sources of renewable energy is fed to power conditioning system and fed directly to proton exchange membrane electrolyzer rated 10 MW.

This paper has selected the proton exchange membrane electrolyzer since it allows high degrees of operation flexibility and has the ability to react quickly to fluctuations in power supplies provided by the renewable energy sources. The ability to work with variable electrical loads under different electrical loads can be carried out by the PEM electrolyzers when compared to other traditional alkaline electrolyzers and can thus be applied in intermittent renewable systems.

In the electrolyzer unit, electrochemical reaction occurs by feeding water to the anode side of the electrolyzer stack. The polymer vertical electrolyte membrane of stack is a part of the electrolyzer stack that aids in transportation of protons and making oxygen gas and hydrogen gas separation [16]. This electric energy to the electrolyzer prompts an electrochemical reaction process which divides the molecules of the water into gases (hydrogen and oxygen) and water.

The hydrogen produced during the cathode is collected, compressed and stored to be used in the future and oxygen produced during the anode is emitted or utilised to produce industry. The following experimental arrangement of hydrogen storage system is based on the high pressure hydrogen tanks in a pressure of 350-700 bar pressure, which is commonly used in hydrogen storage systems.

It is a hybrid design of renewable hydrogen production in which the responsibility of having continuity of the hydrogen production is accounted and the production of carbon emission is low There is also the one that gives a resourceful energy storage system that converts the surplus renewable electricity into hydrogen fuel.

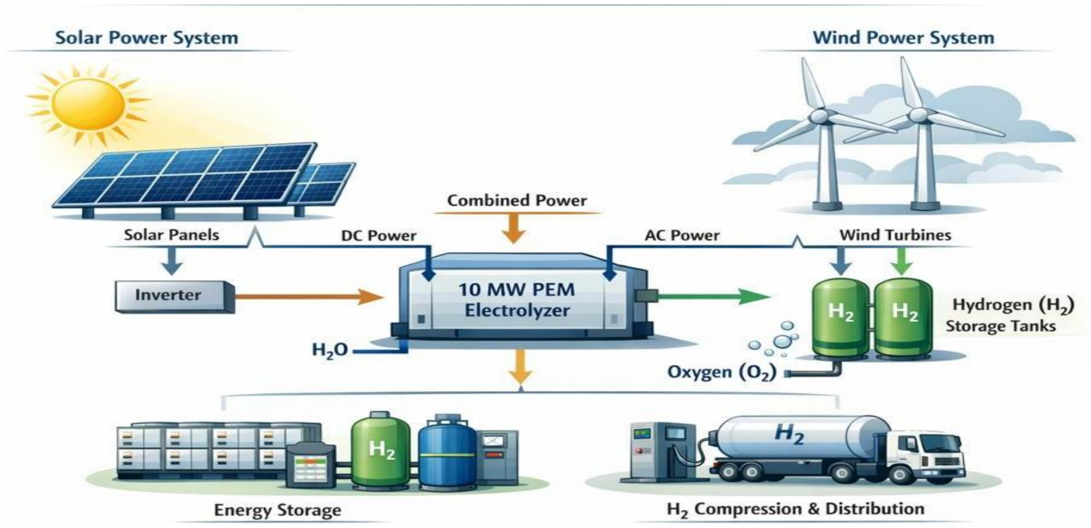

Figure: Experimental setup

4.2 Electrolysis Reaction:

The fundamental process involved in the hydrogen production through electrolysis is the decomposition of water into the hydrogen and oxygen gases using the electrical energy Electrochemical process occurs in the cell of electrolyzer and the molecules of water are separated to hydrogen ions and oxygen molecules. The overall electrochemical reaction for water electrolysis is expressed as:

$$2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$$

The equation entails the process of dissociation between two water molecules to yield two molecules of hydrogen gas and one molecule of oxygen gas [17]. The process requires the use of electrical energy because chemical bonds between oxygen and hydrogen atoms of water molecules are required to be disrupted.

Electrolysis (Chen & Elion, 2024) is two half-reactions, which it attains on the electrodes of the electrolyzer cell. Also, oxygen gas, protons, and electrons are generated by oxidizing water molecules in the anode to generate oxygen gas. The electrons are stored in the cathode and interact with hydrogen ions to produce hydrogen gas.

The electrical energy that will be required to generate the electrolysis is calculable using the Faraday law of electrolysis. The amount of the substances produced in the method of electrolysis can directly be measured in terms of the electrical charge passing through the electrolyte as per the law of Faraday.

The electrical energy required for hydrogen production can be expressed using the equation:

$$E = \frac{nFV}{\eta}$$

where Represent electrical energy required to move the electrolysis in joules, and represent the number of electrons being transferred in the reaction, Represent the Faraday constant which takes the value of 96485 coulombs per mole, Represent the cell voltage in volts, and represent the efficiency of a given electric system.

During the standard conditions the theoretical minimum voltage in which the water is able to be electrolyzed is approximately 1.23 volts. However, in practice, electrolyzers are realized at higher levels of up to 1.82 volts due to internal resistive losses, electrode over potential and membrane resistance.

Association of thermodynamic aspects of hydrogen can also be based on electric power required to perform electrolysis [18]. The theoretical (energy) required to convert one kilogram of hydrogen through water electrolysis is approximated to be approximately equal to 39.4 kWh. However, the real world electrolysis systems with losses and inefficiencies require approximately 50-55 kWh of electrical power per kilo-gram of produced hydrogen.

It gives the amount of energy required which forms the basis of estimation of the capacity of hydrogen generated in the production process of electrolysis which is powered by renewable energy generation.

4.3 Hydrogen Production Rate Calculation:

The rate to which a given system can generate hydrogen is largely determined by the electric power, which is injected into the system, and the energy consumed during the hydrogen production process. The following equation can thus be used to determine the rate of the hydrogen production:

$$H = \frac{P}{E_s}$$

Where Hrep is the hydrogen production rate in kilograms/ hours, Prep is the electrical power needed to run the electrolyzer in kilowatts and Esrep is the specific energy consumption rate of a one kilograms of hydrogen in kilowatt -hours / kilogram.

In modern PEM electrolyser the specific energy use ranged between 48 and 55 kWh/kg hydrogen fluctuation with the conditions of working and the performance of the system.

In order to do such an experimental research, the average total energy consumed to make hydrogen is assumed that it is 50 kWh/kg of hydrogen. The total renewable energy power area that can be electrolyzed is 10 MW which can be equated to 10,000 kilowatts of electricity power.

Substituting these values into the hydrogen production equation:

$$H = \frac{10000}{50}$$

$$H = 200 \text{ kg/h}$$

This calculation indicates that a 10MW electrolyzer operating at optimal conditions cater paribus can produce approximately 200 kilograms of hydrogen per hour [19] . It can be assumed that the Hydrogen production capacity per day is distributed evenly throughout the 24 hours a day operating duration of electrolyzer as follows:

$$200 \times 24 = 4800 \text{ kg/day}$$

In such a way, it can be concluded that the renewable hydrogen production system that is considered in the presented paper could produce approximately 4.8 tons of hydrogen in a day when it works at its maximum capacity.

The annual capacity of the system in terms of hydrogen production can be gleaned by the number of days an operation operates a year multiplied by the daily output rate of hydrogen. The annual production of hydrogens can be estimated as 330 days of operation/year:

$$4800 \times 330 = 1{,}584{,}000 \text{ kg/year}$$

This corresponds to approximately 1,584 tons of green hydrogen per year.

4.4 Electrolyzer Calculation Efficiency:

The efficiency of the electrolyzer system is one of such parameters that are used to give the effectiveness of hydrogen production. The efficiency of the electrolyzer is defined as the relationship between the useful energy stored upon hydrogen fuel to the electrical energy supplied to the electrolyzer.

The following equation can be used to determine the effectiveness of the electrolyzer:

$$\eta = \frac{E_{hydrogen}}{E_{electricity}}$$

where represents efficiency of the electrolyzer, Ehydrogenrepresent energy content of hydrogen produced and E electricity represent the electrical energy input in electrolysis process.

The hydrogen energy content is normally presented in terms of lower heating value (LHV) which is the energy that is released when the hydrogen is combusted without recovering the latent heat of water vapor [20]. The thermal capacity of Hydrogen is approximately 33.3kWh/kg.

In the conjured electrical energy of approximately 50 kWh, one kilogram of hydrogen of the electrolyzer is produced in the experimental system invoked in this research. Therefore, electrolyzer efficiency is given as:

$$\eta = \frac{33.3}{50}$$

$$\eta = 0.666$$

Expressing this value as a percentage:

$$\eta = 66.6\%$$

This efficiency is consistent with the performance spectrum of commercial PEM electrolyzers of modern times that typically operate in 60-70 percent range. Another hydrogen production process will result in more than 75 percent level of efficiency by incorporating use of enhanced catalysts in the process as well use of enhanced membrane materials.

It is determined by a calculation of efficiency that much of electrical energy entering the electrolyzer is efficiently converted into chemical energy stored in hydrogen fuel. The remainder of the energy is however lost in heat generation, electrical resistance, electrical system losses, etc [21].

It is the case as the information about these efficiency parameters is essential in the efficiency maximization of the production system of renewable hydrogen and the reduction in the overall utilization of energy.

5. Results and Analysis:

The obtained results of the conducted experimental simulation permit receiving an idea of the operational effectiveness of hydrogen generating systems which operate on the principle of renewable energy production under the various circumstances of power inputs. The system under consideration in the research is the hybrid renewable scheme which includes the solar photovoltaic system and the wind power, to give energy to a proton exchange membrane electrolyser. Analysis relies on the determination of the rate of hydrogen production, system efficiency and energy consumption at different levels of renewable power avenue.

The simulation model assumes that the renewable electricity produced on the foundations of solar photovoltaic panels and wind turbines will be introduced to the electrolyzer system with the assumption of the 24-hours working cycle [22]. Solar photovoltaic produces power primarily during the day with the greatest production occurring after the time of noon when the sun rays are at optimal conditions of maximum power output. Wind turbines on the other hand do not produce power on the condition of the wind speed as well as it is capable of producing power throughout the day and throughout the night.

Integration of the two source of renewable energy will help the electrolyzer to be more stable compared to systems that rely on a single source renewable energy. The total output of hydrogen of the electrolysis system is subject to the joint power supply.

Numerical simulations were modelled concerning the performance of the system in different working situations by experimenting with various levels of increment of entry of renewable power into the electrolycer system ranging between 4 MW to 12 MW. The impact of the increase of on the rate of hydrogen generation and efficiency of an electrolyzer is explored with regards to renewable energy.

5.1 Numerical Results of Hydrogen Production:

The results of the simulation model are presented in the table of numerical values, table 1[23]. The table shows that there is a correlation between the power input, which is in the form of renewable power, and the specific energy consumption rate and rate of hydrogen production as well as the system efficiency.

Table 1: **Hydrogen Production Performance Under Different Renewable Power Inputs**

Renewable Power Input (MW)	Energy Consumption (kWh/kg)	Hydrogen Production Rate (kg/h)	System Efficiency (%)
4	55	72.7	60
6	53	113.2	63
8	52	153.8	64
10	50	200	66
12	48	250	69

The results demonstrate that the contribution made by renewable power is highly correlated with the production rate of hydrogen [24]. The greater the electric power being charged to the electrolyzer the increasing the amount of hydrogen generated respectively. This sort of association rests upon the theoretical correlation equation of electrolysis between the rate of hydrogen generation and the rate of input electrical power and consumption of various energy amount.

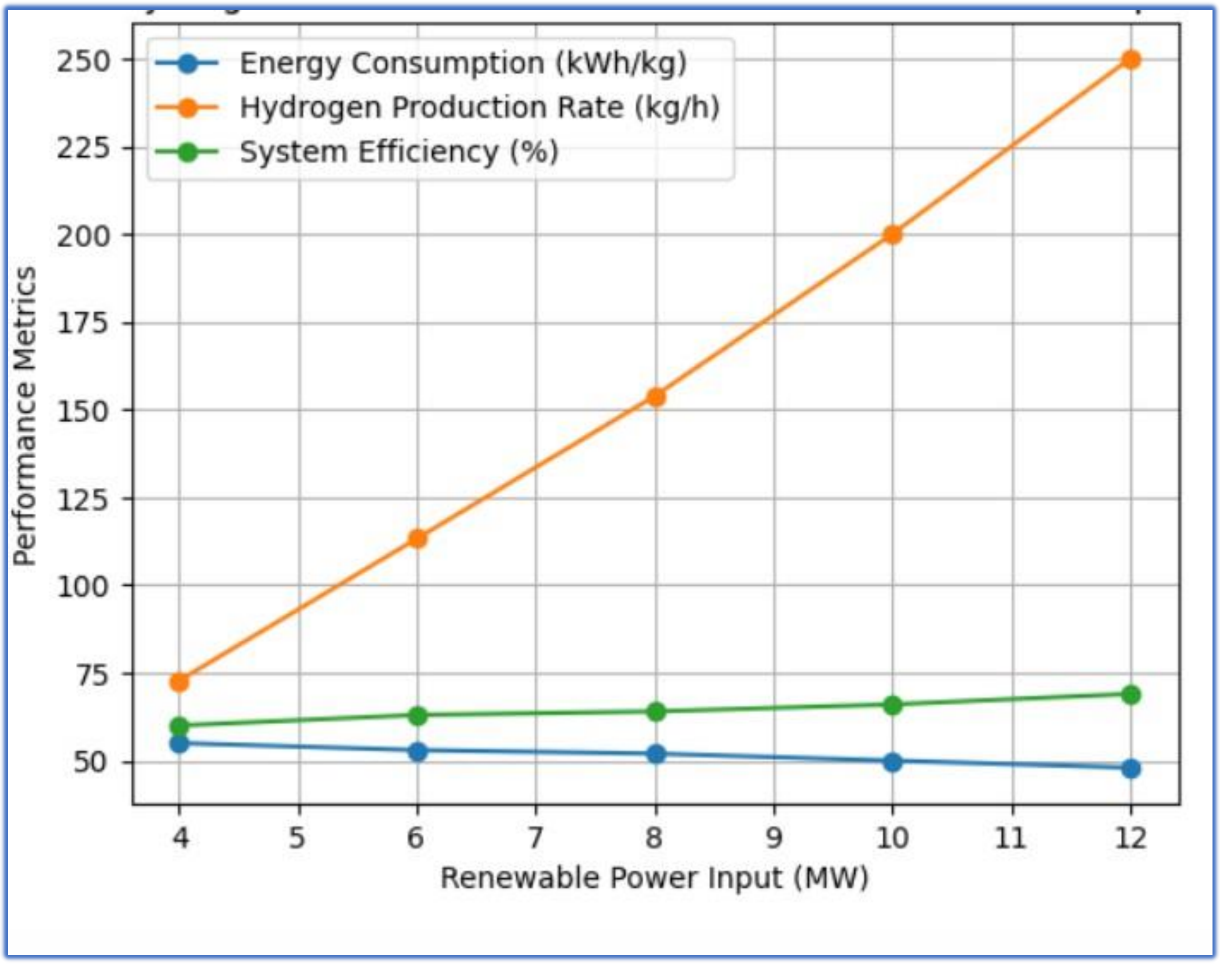

Table 1: **Hydrogen Production Performance Under Different Renewable Power Inputs**

The hydrogen production rate is determined using the equation:

$$H = \frac{P}{E_s}$$

Hrep = Hydrogen production rate idly in ford kilograms/hour, Prep = Electrical power input or power in kilowatt and Esrep = the specific energy consumed in kilowatts hours per kilogram of hydrogen [25].

Using the following example, considering the renewable energy supplied is of 4 MW of 4000 kW, and the energy used is of 55 kwh/kg specific energy, then the hydrogen production rate would be calculated as follows:

$$H = \frac{4000}{55}$$
$$H = 72.7 \text{ kg/h}$$

Just as the renewable energy inward size is increased to 10 MW or 10, 000 kW, and the individual energy usage declines to 50 kWh per kilogram, the rate of hydrogen manufacturing speed is:

$$H = \frac{10000}{50}$$
$$H = 200 \text{ kg/h}$$

All these results confirm that the yield of hydrogen gets high when the size of electrical energy being fed is increased and the efficiency of the electrolyzer is enhanced.

5.2 Effect of Renewable Power Input on Hydrogen Production Rate:

The geometrical results of the simile are, that the rate of production of the hydrogen increases almost linear with the increase of the renewable power. This is because the electrolysis process is a direct conversion process of energy whereby electrical energy is transformed into chemical energy which is stored as hydrogen molecules.

A rate of 72.7 kilograms per hour is Hydrogen production at an input of 4 MW of renewable power. As the power of the renewable source is increased to 6 MW, it will then be rated at about 113.2 kilograms per hour of hydrogen production [26]. Further increase of 10 MW and 12 MW of the input of the renewable power will contribute to 153.8 kilograms per hour and 200 kilograms per hour respectively.

Growth of hydrogen production is linear that is also in line with the electrochemical theory. According to Faraday, the law of electrolysis provides electrolysis and that the number of hydrogen produced during the electrolysis process rotates around the number of electrical charges passing through the electrolyzer.

The mathematical dependence of the relatedness of hydrogen production to the electrical current is put down as follows:

$$m = \frac{ItM}{nF}$$

Where, mrepresent the mass of hydrogen produced, I represent the electric current added to the electrolyzer, t relationships with the electric current added to the electrolyzer, M represents the molecular weight of hydrogen, n represents a number of the electrons that get involved in a reaction, and f represents the Faraday constant.

Since the amount of electrical power is determined by the amount of current and voltage, the more the power put in electrical consumption, the more electrical current that passes through the electrolyzer. This consequently augments the proportional rate of hydrogen production.

Hydrogen will be produced at a rate of approximately 250 kilograms per hour, and this is generated at the highest power input of renewable power that was considered during the simulation and this is 12 MW [27]. It means that, in the case of a high electric supply, even high-scale electrolyzer systems, powered by the renewable resource of the energy, will be able to produce impressive amounts of green hydrogen.

5.3 Analysis of Energy Consumption:

KJ/kg/H_2 is one of the most important performance measures of the electrolyzer systems. Less energy consumption is an indicator of efficiency of electrolyzer and minimal operating costs.

The simulation results show that specific spending on energy is reduced gradually as the supply of renewable power increases. At an input of 4 MW of power the power consumption is estimated at 55 kWh/ kilogram of hydrogen. It reduces down to 50kwh to every kilogram at the renewable power input of 10 MW.

The cause to this reduction in energy used is that it is known that the electrolyzers are more efficient with bulk loads [28]. Since the conditions of the power input approach to low, losses of electricity into membrane resistance and electrode over richness and system inefficiencies become more significant. The losses are considerably minimized when the electrolyzer increases to the rated operating capacity as the energy efficiency increases.

The energy efficiency of the hydrogen production also can be measured by the lower heating value of hydrogen. The heating value of hydrogen is approximately 33.3 kwh/kg. In this way the hydrogen generation efficiency is attained:

$$\eta = \frac{E_{hydrogen}}{E_{electricity}}$$

For example, when the energy consumption is 55 kWh per kilogram:

$$\eta = \frac{33.3}{55}$$
$$\eta = 0.605$$
$$\eta = 60.5\%$$

Similarly, when energy consumption decreases to 48 kWh per kilogram, the efficiency becomes:

$$\eta = \frac{33.3}{48}$$
$$\eta = 0.694$$
$$\eta = 69.4\%$$

These estimates prove that the efficiency of the electrolyser can be significantly improved to operate systems in a better way.

5.4 Evaluation of Electrolyzer System Efficiency

The values of efficiency as shown in Table 1 shows that systems are very efficient when little consumption of energy takes place. The electrolyzer system is efficient with variations of 60 per cent, at the low levels of power input of renewable power, and 69 per cent with high power input of the renewable power.

This efficiency can be explained by the fact that there are only a few electric losses and good kinetics of electrochemical reaction in the electrolyzer cell [29]. Because the closer the electrolyzer is brought to the optimal load curve the higher the voltage required to perform electrolysis slightly goes down due to the increased performance of the electrodes and a decrease in the losses of activation.

The fact that the electrolyser process has become more efficient is critical because it has a direct and indirect impact on the generation of green hydrogen and the profitability of this process. The highest operation cost associated with producing hydrogen through the electrolysis process is electricity and, therefore, any improvement on the systems will help a great deal to reduce the cost of hydrogen fuel.

In order to go with an example, an electric rate of 0.05/kwwh, a kilogram of hydrogen at 55kwh of energy consumption will demand approximately 2.75 of electricity. On reducing the energy-saving to 48 kWh/kg, the electricity per kg cost is minimized to some 2.40.

Such a low energy price can make a colossal disparity in making green hydrogen cost effective over the processes of creating hydrogen by utilizing fossil fuels as a hydrogen source.

5.5 Performance of Hybrid Renewable Energy Integration:

The other important conclusion of the simulation analysis is the increase of the operational stability which can be achieved because of the combination of renewable energies in the form of a hybrid [30]. The systems that rely on a single source of renewable energy are capable of changing the output of the same in a significantly different proportion to the weather conditions.

The solar photovoltaic systems are only able to produce electricity on the sunny days and they also are highly affected by the weather conditions such as cloud cover, or changes in the seasons that affect its efficiency. The wind energy systems on the other hand are susceptible to the wind speed conditions which may be intermittent.

The hybrid system prevents inconsistency and lack of steady supply of power of a solar and wind power source by providing a stable supply of power to the electrolyzer. The larger fraction of the electric energy consumed in producing hydrogen is provided by the solar power in the daytime [31] . The wind turbines can also generate electricity even at night when solar rays are low enough in order to energise electrolyzers.

This complementing nature of the solar and wind power reduces the fluctuation of the supply of power, and increases the rate at which electrolyser system needs to be utilized. The more the electrolyzer is used the more the amount of hydrogen is produced and yielded economic outcomes.

The hybrid energy system of renewable also reduces the magnitude of electricity storage system. Instead of storing the electric energy in batteries, surplus renewable electricity can be electrolysed at the point of location to produce hydrogen fuel. This Hydrogen can then be stored in a long term and later made available to be utilized in the future to generate electricity, to be transported or used in industrial purposes.

5.6 Implications for Large-Scale Hydrogen Production:

This simulation exercise has given findings that confirm that it can produce hydrogen in a large scale by using renewable energy sources. About 200 kilograms of hydrogen an hour would be yielded by the Dirhams of electricity that a 10 MW renewable-powered electrolyzer system will produce under optimal operating conditions.

If such a system operates continuously for 24 hours, the daily hydrogen production would reach approximately:

$$200 \times 24 = 4800 \text{ kg/day}$$

It is an equivalent of approximately 4.8 tons of hydrogen per day.

A total of around: ten tons of hydrogen would be generated yearly with 330 working days per annum.

$$4800 \times 330 = 1{,}584{,}000 \text{ kg/year}$$

or approximately 1,584 tons of hydrogen annually.

This production capacity can serve the hydrogen fuelling stations, hydrogen demand in the industry as well as the hydrogen storage renewable energy [32].

The results also highlight the importance of increasing the renewable electricity energy to allow production of hydrogen in future. As the world continues the trend of growing perception of renewable energy, the green hydrogen can be expected to face more feasibility in the next few years due to its progress in the upcoming years.

6. Discussion:

This is demonstrated by the results obtained which showed that incorporation of renewable energy has the potential to increase significantly the extent of validity of the hydrogen generation [33]. The wind and solar power would allow a mix of renewable energy which would provide a consistent flow of power into the electrolyzers to reduce instances of production.

One of the criteria that play one of the significant roles in determining cost of production of hydrogen is efficiency of an electrolyser. The modern commercial electrolyzers provided are 60-70 per cent but with improvement on research, the efficiency may rise even more.

It is also proven by the findings that there is significant capacity of renewable energy required in the production of hydrogen in large scale. To explain this 50 MWh of electricity will be required to produce 1 ton of hydrogen per day.

The other source of influence that is important to the implementation of hydrogen energy systems is the development of infrastructure. The hydrogen storage and hydrogen pipeline network infrastructure and fuels should be developed to support the new hydrogen economy.

7. Future Prospects:

Hydrogen technologies are still on the top of the world agenda as countries are striving to attain the ambition of carbon neutrality [34]. The generation of hydrogen through renewable energy will majorly be important in decarbonization of some of the most difficult sectors in electrification, including heavy industries, aircraft, and sea transport.

It is expected that the existing technology of the electrolyzer, catalytic material, and the renewable integration system will enable massive reductions of the costs of hydrogen production in the coming decades.

Already, in various countries, there are plans to develop a huge hydrogen manufacturing project, and the power of electrolyzers can reach tens of megawatts.

The future research is involved in the way the life of electrolyzers can be extended, the cost of capital is decreased, and the renewable hydrogen production systems could be optimized.

8. Conclusion:

This research investigated renewable energy–driven green hydrogen production using integrated solar and wind energy systems Through the aid of the numerical modelling, the paper reviewed the procedure of electrolysis, efficiencies of hydrogen production, and the way the systems work.

The results show that the effective generation of hydrogen that has minimal environmental impact can be obtained through amalgamation of renewable energy. In an ideal operating condition, a 10 MW of the electrolyzer supplied with renewable energy can produce approximately 200 kilograms of hydrogen every hour.

However, this production of the hydrogen on large scale must be economically viable overcoming several issues: more power requirements, intermittency of renewable energy sources and infrastructure constraints.

It will be a significant role of emergence of technological innovations in regards to the emergence of the hydrogen economy throughout the globe regarding property of the electrolyzers and renewable energy systems. The hydrogen utilizing renewable energy might be developed which can become a pillar of green energy frames and be a significant role in the process of decarbonization of the world.

Acknowledgement:

The authors would like to express their sincere gratitude to the **Department of Energy Engineering, Gujarat Vidyapith University, Ahmedabad, India**, for providing the necessary academic support and research facilities required to complete this study. The authors also acknowledge the use of computational and analytical facilities available in the university laboratories for performing the numerical simulations and system performance analysis. The renewable energy modelling and electrolysis performance calculations presented in this research were carried out using the institutional computational resources and research infrastructure provided by the university. The support and guidance provided by the faculty members and technical staff during the course of this work are also gratefully acknowledged.

Conflicts of interest:

"The authors have no conflicts to disclose".

Reference:

1. Mohammad, S.S. and Iqbal, S.J., 2022. Optimization and power management of solar PV-based integrated energy system for distributed green hydrogen production. Distributed Generation & Alternative Energy Journal, pp.865-898. https://doi.org/10.13052/dgaej2156-3306.3741
2. Zhang, J. and Li, J., 2024. Revolution in renewables: Integration of green hydrogen for a sustainable future. Energies, 17(16), p.4148. https://doi.org/10.3390/en17164148
3. Hassan, Q., Algburi, S., Sameen, A.Z., Salman, H.M. and Al-Jiboory, A.K., 2024. A review of green hydrogen production by renewable resources. Energy Harvesting and Systems, 11(1), p.20220127.

https://www.degruyterbrill.com/document/doi/10.1515/ehs-2022-0127/html
4. Alam, S.N., Khalid, Z., Singh, B. and Guldhe, A., 2024. Integration of government policies on the global level for green hydrogen production. In Green hydrogen economy for environmental sustainability. Volume 1: Fundamentals and feedstocks (pp. 1-28). American Chemical Society. DOI: 10.1021/bk-2024-1473.ch001
5. Marouani, I., Guesmi, T., Alshammari, B.M., Alqunun, K., Alzamil, A., Alturki, M. and Hadj Abdallah, H., 2023. Integration of renewable-energy-based green hydrogen into the energy future. Processes, 11(9), p.2685. https://doi.org/10.3390/pr11092685
6. Arunachalam, M., Yoo, Y., Al-Ghamdi, A.S., Park, H. and Han, D.S., 2024. Integrating green hydrogen production with renewable energy-powered desalination: An analysis of CAPEX implications and operational strategies. International Journal of Hydrogen Energy, 84, pp.344-355. https://doi.org/10.1016/j.ijhydene.2024.08.250
7. Sharma, R., Sharda, H., Dutta, A., Dahiya, A., Chaudhary, R., Singh, A., Rathi, K., Kumar, S., Sharma, A., Maken, S. and Nehra, S.P., 2023. Optimizing green hydrogen production: Leveraging load profile simulation and renewable energy integration. International Journal of Hydrogen Energy, 48(96), pp.38015-38026. https://doi.org/10.1016/j.ijhydene.2023.03.179
8. Horri, B.A. and Ozcan, H., 2024. Green hydrogen production by water electrolysis: Current status and challenges. Current opinion in green and sustainable chemistry, 47, p.100932. https://doi.org/10.1016/j.cogsc.2024.100932
9. Laimon, M. and Yusaf, T., 2024. Towards energy freedom: Exploring sustainable solutions for energy independence and self-sufficiency using integrated renewable energy-driven hydrogen system. Renewable Energy, 222, p.119948. https://doi.org/10.1016/j.renene.2024.119948
10. Khan, M.H.A., Heywood, P., Kuswara, A., Daiyan, R., MacGill, I. and Amal, R., 2022. An integrated framework of open-source tools for designing and evaluating green hydrogen production opportunities. Communications Earth & Environment, 3(1), p.309. https://www.nature.com/articles/s43247-022-00640-1
11. Kuterbekov, K.A., Kabyshev, A., Bekmyrza, K., Kubenova, M., Kabdrakhimova, G. and Ayalew, A.T., 2024. Innovative approaches to scaling up hydrogen production and storage for renewable energy integration. International Journal of Low-Carbon Technologies, 19, pp.2234-2248. https://doi.org/10.1093/ijlct/ctae176
12. Marouani, I., Guesmi, T., Alshammari, B.M., Alqunun, K., Alzamil, A., Alturki, M. and Hadj Abdallah, H., 2023. Integration of renewable-energy-based green hydrogen into the energy future. Processes 2023; 11: 2685 [online] https://doi.org/10.3390/pr11092685
13. Mazzeo, D., Herdem, M.S., Matera, N. and Wen, J.Z., 2022. Green hydrogen production: Analysis for different single or combined large-scale photovoltaic and wind renewable systems. Renewable Energy, 200, pp.360-378. https://doi.org/10.3390/pr11092685
14. Hassan, Q., Tabar, V.S., Sameen, A.Z., Salman, H.M. and Jaszczur, M., 2024. A review of green hydrogen production based on solar energy; techniques and methods. Energy Harvesting and Systems, 11(1), p.20220134. https://doi.org/10.3390/pr11092685
15. Das, D., Chakraborty, I., Bohre, A.K., Kumar, P. and Agarwala, R., 2024. Sustainable integration of green hydrogen in renewable energy systems for residential and EV applications. International Journal of Energy Research, 2024(1), p.8258624. **https://doi.org/10.1155/2024/8258624**
16. Sarker, A.K., Azad, A.K., Rasul, M.G. and Doppalapudi, A.T., 2023. Prospect of green hydrogen generation from hybrid renewable energy sources: A review. Energies, 16(3), p.1556. https://doi.org/10.3390/en16031556
17. Laimon, M. and Yusaf, T., 2024. Towards energy freedom: Exploring sustainable solutions for energy independence and self-sufficiency using integrated renewable energy-driven hydrogen system. Renewable Energy, 222, p.119948.
18. Chen, S., Zhang, J., Wei, Z., Cheng, H. and Lv, S., 2024. Towards renewable-dominated energy systems: role of green hydrogen. Journal of Modern Power Systems and Clean Energy, 12(6), pp.1697-1709. https://doi.org/10.35833/MPCE.2023.000887
19. Gómez, J. and Castro, R., 2024. Green hydrogen energy systems: a review on their contribution to a renewable energy system. Energies, 17(13), p.3110. https://doi.org/10.3390/en17133110
20. Tuluhong, A., Chang, Q., Xie, L., Xu, Z. and Song, T., 2024. Current status of green

hydrogen production technology: a review. Sustainability, 16(20), p.9070. https://scholar.google.com/scholar

21. Hasan, M.M., Rasul, M.G., Jahirul, M.I., Sattar, M.A. and Hassan, N.M.S., 2023, December. Hydrogen horizons: navigating challenges and opportunities for a sustainable energy future. In 2023 International Conference on Sustainable Technology and Engineering (i-COSTE) (pp. 1-7). IEEE. DOI: 10.1109/i-COSTE60462.2023.10500764
22. Kravets, S., 2024. Prospects for the development of hydrogen energy: innovative technologies as the key to reducing the price of "green" hydrogen. Техніка, енергетика, транспорт АПК. 2024.№ 4 (127). С. 46-56. DOI: 10.37128/2520-6168-2024-4-5. https://socrates.vsau.org/repository/card.php?id=38380
23. Rezk, M.R.A., Piccinetti, L., Saleh, H.A., Salem, N., Mostafa, M.M.M., Santoro, D., El-Bary, A.A. and Sakr, M.M., 2023. Future scenarios of green hydrogen in the MENA countries: The case of Egypt. Insights Reg. Dev, 5, pp.92-114. http://jssidoi.org/ird/article/download/149/Rezk_Future_scenarios_of_green_hydrogen_in_the_MENA_countries_the_case_of_Egypt.pdf
24. Atteya, A.I., Ali, D., Hossain, M. and Sellami, N., 2023. A comprehensive review on the potential of green hydrogen in empowering the low-carbon economy: development status, ongoing trends and key challenges. Green energy and environmental technology, (4). **DoI:** 10.5772/geet.23
25. Sebbagh, T., Şahin, M.E. and Beldjaatit, C., 2024. Green hydrogen revolution for a sustainable energy future. Clean Technologies and Environmental Policy, 26(12), pp.4017-4040. https://doi.org/10.1007/s10098-024-02995-9
26. Hassan, Q., Tabar, V.S., Sameen, A.Z., Salman, H.M. and Jaszczur, M., 2024. A review of green hydrogen production based on solar energy; techniques and methods. Energy Harvesting and Systems, 11(1), p.20220134. https://doi.org/10.1515/ehs-2022-0134
27. Fallah Vostakola, M., Salamatinia, B. and Amini Horri, B., 2022. A review on recent progress in the integrated green hydrogen production processes. Energies, 15(3), p.1209. https://doi.org/10.3390/en15031209
28. Bassey, K.E. and Ibegbulam, C., 2023. Machine learning for green hydrogen production. Computer Science & IT Research Journal, 4(3), pp.368-385. www.fepbl.com/index.php/csitrj
29. Gómez, J. and Castro, R., 2024. Green hydrogen energy systems: a review on their contribution to a renewable energy system. Energies, 17(13), p.3110. https://doi.org/10.3390/en17133110
30. Zun, M.T. and McLellan, B.C., 2023. Cost projection of global green hydrogen production scenarios. Hydrogen, 4(4), pp.932-960. https://doi.org/10.3390/hydrogen4040055
31. Stambouli, A.B., Kitamura, Y., Benmessaoud, M.T. and Yassaa, N., 2024. Algeria's journey towards a green hydrogen future: strategies for renewable energy integration and climate commitments. International Journal of Hydrogen Energy, 58, pp.753-763. https://doi.org/10.1016/j.ijhydene.2024.01.119
32. Jaradat, M., Almashaileh, S., Bendea, C., Juaidi, A., Bendea, G. and Bungau, T., 2024. Green hydrogen in focus: a review of production technologies, policy impact, and market developments. Energies, 17(16), p.3992. https://doi.org/10.3390/en17163992
33. Abdelkareem, M.A., Abdelghafar, A.A., Mahmoud, M., Sayed, E.T., Mahmoud, M.S., Alami, A.H., Al Agha, M.M. and Olabi, A.G., 2023. Optimized solar photovoltaic-powered green hydrogen: Current status, recent advancements, and barriers. Solar Energy, 265, p.112072. https://doi.org/10.1016/j.solener.2023.112072
34. Sedai, A., Dhakal, R., Gautam, S., Kumar Sedhain, B., Singh Thapa, B., Moussa, H. and Pol, S., 2023. Wind energy as a source of green hydrogen production in the USA. Clean Energy, 7(1), pp.8-22. https://doi.org/10.1093/ce/zkac075