Review

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A review of green hydrogen production based on solar energy; techniques and methods

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Abstract: The study examines the methods for producing hydrogen using solar energy as a catalyst. The two commonly recognised categories of processes are direct and indirect. Due to the indirect processes low efficiency, excessive heat dissipation, and dearth of readily available heat-resistant materials, they are ranked lower than the direct procedures despite the direct procedures superior thermal performance. Electrolysis, bio photosynthesis, and thermoelectric photodegradation are a few examples of indirect approaches. It appears that indirect approaches have certain advantages. The heterogeneous photocatalytic process minimises the quantity of emissions released into the environment; thermochemical reactions stand out for having low energy requirements due to the high temperatures generated; and electrolysis is efficient while having very little pollution created. Electrolysis has the highest exergy and energy efficiency when compared to other methods of creating hydrogen, according to the evaluation.

Keywords: electrolysis; green hydrogen production; hydrogen energy; solar energy.

1 Introduction

Over the past few decades, the impact of environmental deterioration and global warming on life on Earth has grown. Thus, there is a compelling need to embrace clean energy alternatives. Renewable energy sources have received a lot of interest since they can provide ecologically beneficial electricity. The solar and wind power producing choices are the most enticing (Schrotenboer et al. 2022; Zaik and Werle 2022). The electricity generated by these resources is influenced by meteorological factors such as sun radiation, wind speed, ambient temperature, etc (Malik et al. 2022; Zhang et al. 2022). Energy storage remains the weak link in the generation of clean power, notwithstanding the expansion of renewable energy production (Olabi et al. 2022; Hassan et al. 2022a). To supply a 100% off-grid power source using renewable energy sources, a storage system is necessary, which greatly raises the overall cost. Solar energy power generation systems require substantial storage systems since there is insufficient solar irradiation at night or during periods of bad weather and clouded sky. The energy that the sun generates during the day should be stored and used at night, when there is frequently a high demand for power. The power generated by a wind turbine of this type, however, is inversely proportional to the cube of the local wind speed. If the local wind speed at the installation location is less than the wind turbine cut-in wind speed, which will prohibit electricity from being generated, using the storage system becomes required. When numerous renewable energy sources are employed, a hybrid system is enhanced and the size of the storage device is decreased. An energy storage battery bank is frequently used in renewable energy systems (Yang et al. 2022). Battery banks need to be replaced frequently over the lifetime of a project since they last less time than other components of renewable energy systems. It also contributes significantly to the overall cost of stand-alone systems.

1.1 Hydrogen

Today, the manufacturing of ammonia fertilizers which is extremely polluting and whose demand is always rising and the oil refinery sector are the two primary uses of hydrogen. However, the development of electrolysis in the early nineteenth century opened the possibility of getting hydrogen

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while producing almost no harmful byproducts. The electrical energy necessary for this system functioning must originate from non-polluting resources for it to be considered fully clean. Nowadays, this could be done by using renewable sources of energy like wind and solar energy. Thus, produced hydrogen is referred to as "green hydrogen."

Green hydrogen is developing into a competitive source of energy and is able to abide by the need for lowering greenhouse gases as a result of the ongoing cost decrease of these renewable energy installations. However, as electricity represents a significant portion of the total cost of the hydrogen generated, its pricing and source may have a significant impact on how competitively priced the hydrogen is. The cost of producing green hydrogen is being investigated in order to ascertain how it could be made more affordable in the market.

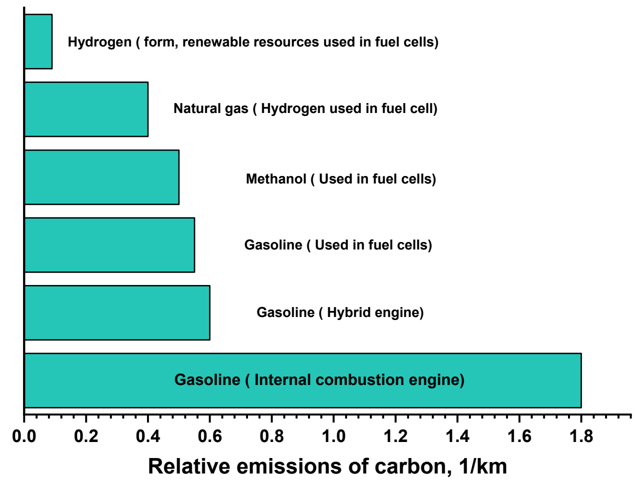

Figure 1: Compares the relative emissions of greenhouse gases from gasoline-powered cars today with those powered by fuel cells (represented in carbon units per kilometre) (Liu et al. 2021).

1.2 Is the hydrogen future's dependent fuel?

The future main fuel source is largely believed to be hydrogen. In light of the following factors, there have been significant efforts made to develop multiple techniques based on the implementation of hydrogen as an energy source rather than fossil fuels:

- Fossil energy deposits are limited (Akçaba and Eminer 2022; Hassan et al. 2022b);
- Climate change is caused by the use of fossil fuels (Abbasi et al. 2022; Gunderson and Fyock 2022; Perera and Nadeau 2022);
- There is a requirement for a fuel produced from the feedstock (Li et al. 2022; Shenbagamuthuraman et al. 2022);
- The price of fossil fuels is rising (Borzuei et al. 2022; Moosavian et al. 2022);
- There is a requirement for a fuel produced from the raw resources which are readily available (Deora et al. 2022);

Various potential uses for hydrogen exist, such as the propulsion of non-polluting automobiles, heating, and aviation. Consequently, it is projected that hydrogen will join solar energy as the main energy source in a sustainable energy future (Hassan 2020; Hassan et al. 2022c; Hunt et al. 2022). How near we are to the hydrogen era may be gauged by recent attempts to construct cars that run on hydrogen, whether directly or via hydrogen fuel cells. The graphic in Figure 1 demonstrates that although the use of fuel cell technology will result in a significant decrease in the emission of greenhouse gases (represented in carbon units per kilometre), the use of fuel cells driven by hydrogen produced from solar energy would result in practically zero emissions (Liu et al. 2021). Gaseous forms of hydrogen do not exist in nature. However, it is widely distributed in plants and in a number of substances, including methanol, ethanol, and higher hydrocarbons. It is most easily accessible by water. Consequently, these molecules must be processed to get hydrogen.

Until now, steam reforming has mostly been used to create hydrogen from methane (Wang et al. 2022a). However, CO_2 is nonetheless released as a consequence of this technique. For this same reason, hydrogen produced by water electrolysis with power generated from the burning of fossil fuels can indeed be regarded as ecologically good. On the other hand, the creation of hydrogen by photoelectricity is thought to be the safest method. This hydrogen also stands for a fuel that can be stored and is made from a source of energy that cannot be stored: photoelectricity.

1.3 Fundamentals of green hydrogen production based on solar energy

Solar energy is a key source of power for green hydrogen production, which involves the electrolysis of water. The electrolysis process uses electricity to split water molecules into hydrogen and oxygen. The hydrogen can then be used as a clean-burning fuel, while the oxygen is released back into the atmosphere.

- The production of green hydrogen from solar energy involves the use of photovoltaic systems. Photovoltaic systems convert sunlight into electricity, which is then used to power the electrolysis process. The electricity does not require any additional fossil fuels, so it produces no emissions. Solar energy is a renewable and sustainable source of energy, making it the preferred choice for green hydrogen production.

- The cost of producing green hydrogen from solar energy is currently high. This is mainly due to the cost of the photovoltaic systems, which are relatively expensive. However, as the technology continues to improve, the cost of green hydrogen production from solar energy is expected to decrease significantly.
- In addition to being a clean source of energy, green hydrogen production from solar energy also has the advantage of being modular and scalable. This means that it can be deployed anywhere and the power output can be adjusted depending on the demand.

The green hydrogen production based on solar energy is a promising solution for reducing carbon dioxide emissions. This process is currently expensive and there are still many challenges to overcome, but with continued technological advancement it is likely to become a viable option for producing clean, renewable energy in the future.

1.4 Hydrogen prices

Hydrogen is the final applications are quite varied, since they rely significantly on whether it is utilised directly as an energy resource, or as a raw ingredient in a production. In particular, the utilisation of hydrogen in its natural state has several uses, which it could be used directly as a fuel, an energy carrier, or an industrial feedstock (Peng and Jin 2022).

The formation of the green hydrogen economy in the upcoming decades and its potential to compete with blue hydrogen, grey hydrogen, and fossil fuel extraction will occur as soon as the cost of producing green hydrogen becomes more affordable. It is commonly assumed that the cost of producing renewable energy would drop over time, mostly owing to the economies of scale, research, completed projects, and technological advancements.

According to the most recent hydrogen commission research, the price of hydrogen-based solutions will fall over the next decades. Because of their increasing scale, it is expected that the cost of hydrogen technologies and component production will have dropped by half by 2030. Specifically, forecasts indicate that renewable hydrogen production prices might decrease to between $1.5 – $2.5/kg by 2030 (Wang et al. 2021). This indicates that additional renewable and grey hydrogen supply might approach cost parity in some places by 2028–2035, making hydrogen cheap and competitive not just with other low-carbon alternatives but also with conventional solutions (Hassan et al. 2022d). It is highlighted that hydrogen generation from renewable energy may be less expensive in economies with superior renewable energy facilities. In addition, an adequate water supply is required for water electrolysis, even though water desalination expenses represent just a tiny portion of the overall hydrogen cost of production. In southern European nations, solar photovoltaics are the least expensive choice. But in northern European countries, onshore wind power has the lowest production costs, except in Belgium and Germany, where offshore wind tends to be the least expensive (Manesh et al. 2022).

Currently briefly go over the fundamental concepts of the multiple core parts of solar energy harvesting and the production of hydrogen using the latest technology along with overarching theories so that our readers can follow the development of the technology solutions that have resulted in today integrated solar water splitting technology solutions for hydrogen production. Given that solar-hydrogen is a well-established issue, we just provide a very quick overview to let readers know how different solar-hydrogen technologies have developed over time, along with a summary of the key concepts. We then go into great depth about the numerous solar-hydrogen methods, including their working principles, development timeline, and relative benefits, as the review aim is to green hydrogen using many of the most commonly used methods for hydrogen production. The primary objective of this study is to illustrate and summarise the potential of solar energy for hydrogen production. In addition, the future viability of green hydrogen was assessed.

1.5 Motivation of the study

Green hydrogen production based on solar energy has become an increasingly attractive option for producing hydrogen in a manner that is both cost-effective and environmentally friendly. Solar energy has the potential to provide an abundant and renewable source of energy for the production of hydrogen, and the process of producing hydrogen from water through electrolysis is relatively simple. This makes solar-based hydrogen production an attractive option for countries and industries looking to reduce their carbon footprint while also taking advantage of the cost savings associated with renewable energy sources. Moreover, solar-based hydrogen production can be paired with other renewable energy sources, such as wind and geothermal, to produce a more secure and reliable energy supply. This review discussed the potential benefits of solar-based hydrogen production, the challenges associated with the implementation of such technologies, and the current state of research and development in this area.

The authors of this review believe that green hydrogen production is a promising field with great potential. It has the potential to revolutionize the energy sector, and its low cost and low environmental impact make it attractive to many countries. The green hydrogen production based on solar energy requires a significant capital investment, as well as an understanding of the technology and its limitations. The authors recommend that governments provide incentives and support to encourage investment in the field. Additionally, research into the economics of green hydrogen production should be conducted to ensure that it is economically viable. The authors also suggest that green hydrogen production should be integrated into the existing energy systems, such as electricity grids, to ensure maximum efficiency, which they believe that more research is needed to understand the potential for green hydrogen production, as well as the potential risks associated with it.

This study points out the directions:

- A focus on the development of low-cost, efficient and reliable technologies for the production of green hydrogen from solar energy.
- Exploring the potential for using renewable energy in combination with electrolysis for green hydrogen production.
- Investigating methods for maximizing the efficiency of solar energy conversion into green hydrogen.
- Exploring opportunities for creating effective energy storage models for green hydrogen produced from solar energy.
- Investigating the economic feasibility of green hydrogen production from solar energy and the factors influencing its competitiveness.
- Investigating the potential for integrating green hydrogen production from solar energy into existing energy systems.
- Exploring the potential for using green hydrogen as a transport fuel.
- Investigating the potential for using green hydrogen in various industrial applications.
- Exploring the potential for using green hydrogen as a feedstock for chemical manufacturing.

1.6 Green hydrogen potential benefits

Hydrogen production based on solar energy is a promising alternative. It has the potential to provide a clean, renewable, and cost-efficient source of hydrogen energy. The potential benefits can summarised as:

- The most common method of green hydrogen production is through electrolysis. This process uses electricity generated from solar energy to split water molecules into hydrogen and oxygen. This hydrogen can then be used as a fuel source for vehicles, electricity generation, or other applications. This method of hydrogen production does not release any emissions into the atmosphere, making it one of the most environmentally friendly sources of energy available.
- Green hydrogen production based on solar energy can also provide numerous economic benefits. It can help reduce energy costs, create new jobs in the energy sector, and increase energy security by reducing dependence on imported fuels. Additionally, solar energy-based hydrogen production can help reduce greenhouse gas emissions and improve air quality.
- Green hydrogen production based on solar energy is a promising technology with many potential benefits. It has the potential to revolutionize the way we produce hydrogen fuel and provide an environmentally friendly and economically viable source of energy.

2 Producing hydrogen by solar energy

Both non-renewable resource methods such as the reformation or combustion of fossil fuels, and renewable resource-based methods such as electrolysis of water, that can be employed to produce hydrogen (Jendar et al. 2022). The final strategy is considered environmentally friendly and carbon-free (Farajollahi et al. 2022). Whenever combined with a source of renewable energy, this strategy may also be seen as a popular strategy for attaining sustainable development because of the decreased reliance on non-renewable resources (Hassan et al. 2022e). Wind and solar sources are given a greater priority than other renewable sources due to their high reliability (Rostami et al. 2022). Furthermore, due to its availability in all parts of the planet at varying intensities, solar energy may be preferable to wind power (Hassan 2019; Jaszczur and Hassan 2020). Direct conversion of solar light energy into electrical and heat energy is possible using SPV and thermal collector techniques (Abdulateef et al. 2021; Ceran et al. 2021). On the other extreme, when an electric current is provided during the electrolysis of water, water undergoes dissociation into hydrogen and oxygen. Figure 2 displays the flowchart for water electrolysis utilising solar power.

Green hydrogen production based on solar energy principles is a process that uses solar energy to generate electricity that is then used to split water molecules into hydrogen and oxygen (Mehrpooya et al. 2021). This process is

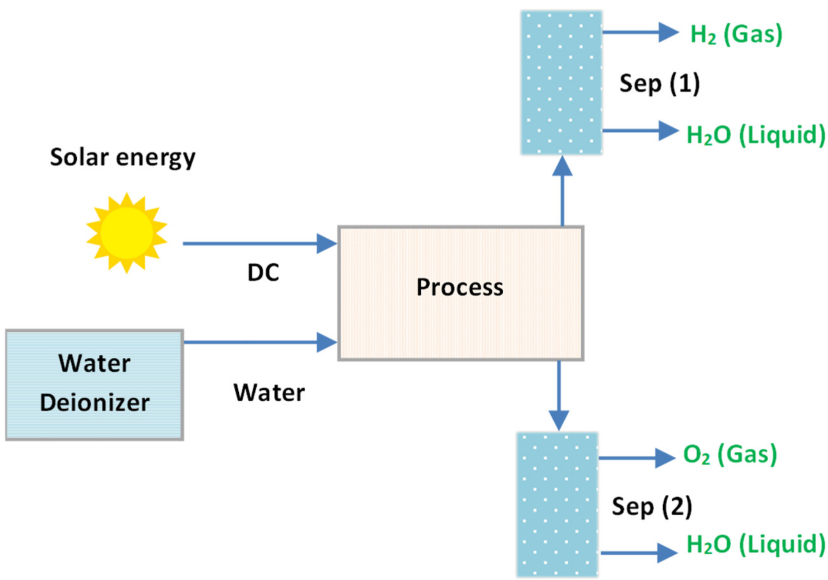

Figure 2: Schematic of water electrolysis utilising solar energy.

known as water electrolysis and is one of the most efficient ways to produce hydrogen. To produce green hydrogen, renewable energy sources such as solar, wind, and hydropower are used to power the electrolysis process. By using renewable energy sources, green hydrogen can be produced without any emissions or any other pollutants (Burton et al. 2021). Additionally, the process of electrolysis is highly efficient, making it a cost-effective method of producing green hydrogen. The principles of design such system can summarised as:

- **Maximize Efficiency:** Solar energy can be harnessed to produce green hydrogen with very high efficiency. To maximize efficiency, the solar energy should be used in tandem with cutting-edge techno design principles logy such as photovoltaic systems, electrolysers, and fuel cells.
- **Minimize Losses:** All renewable energy sources have associated losses due to inefficiency and the need for infrastructure. When producing green hydrogen, minimize losses by installing the appropriate equipment and taking into account the location and environment.
- **Reduce Environmental Impact:** Green hydrogen production should be done in ways that minimize its environmental impact. This includes using renewable energy sources, such as solar, and avoiding materials that produce hazardous emissions during the production process.
- **Utilize Local Resources:** Green hydrogen production should utilize local resources whenever possible. This includes using local energy sources and materials to produce hydrogen and transport it to the point of use.
- **Reuse and Recycle**: The materials used to produce green hydrogen should be reused and recycled whenever possible. This is an important part of reducing the environmental impact of green hydrogen production.
- **Educate and Engage**: Educating people about green hydrogen production is an important part of creating a sustainable future. This includes engaging with stakeholders and providing them with the necessary information to make informed decisions.

As a result, this technique of producing hydrogen may be roughly divided into two approaches, as seen in Figure 3.

(1) Direct approach is a thermal analysis.
(2) Indirect approaches for solar-based water splitting are electrolysis, thermochemical, photolysis, and, biophotolysis.

2.1 Direct thermal approaches

In recent years, many theories for the production of solar thermal hydrogen have been established. The main thermochemical ideas include methane splitting, solar natural gas steam reformation, and solar thermo-chemical processes. Additionally, pure hydrogen can be created utilising solar heat and renewable power via the electrochemical technique of high-temperature electrolysis. Over the last several years, significant progress has been made in the development of solar thermal techniques for the creation of hydrogen. Different process models were examined, and design ideas and test facilities may be realised. Le Naour

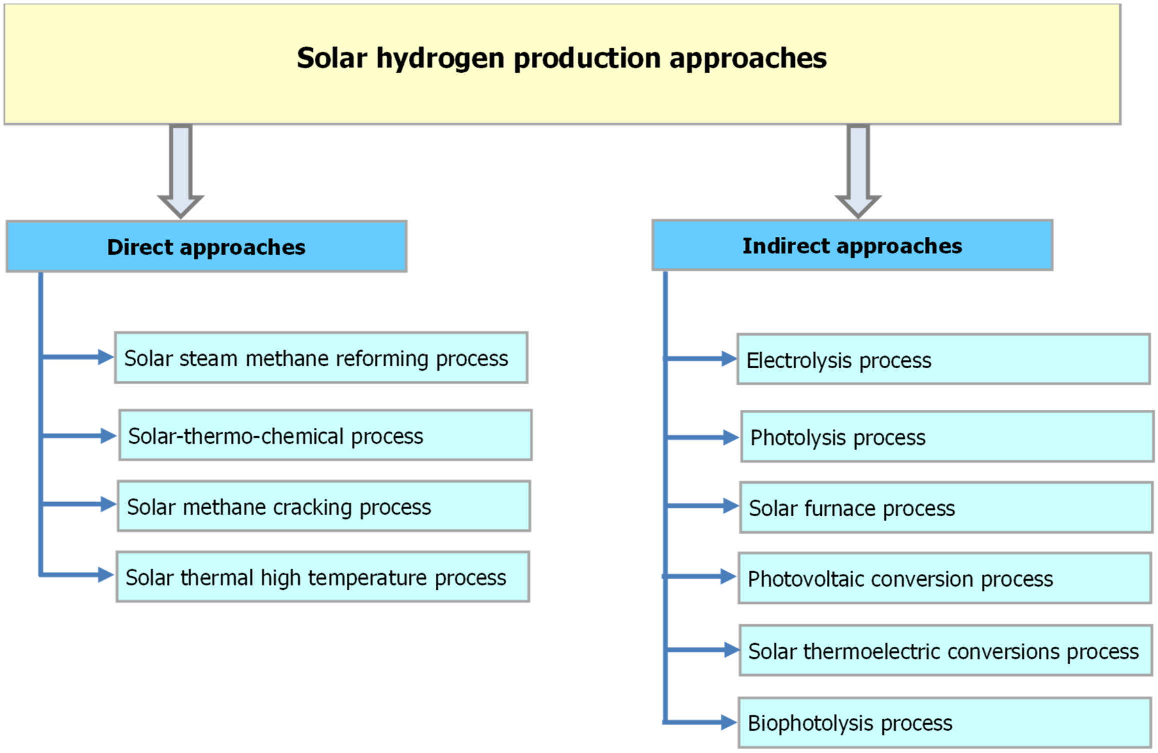

Figure 3: Solar water splitting approaches.

et al. (2005), Zhang et al. (2014) provides a summary of the current state of the art and research problems in high-temperature hydrogen generation. Technologies as the primary or only source of high-temperature thermal applications. A concentrator system for a solar thermal plant includes a circular solar collector that directs solar energy onto a receiver located on a tower. The receiver includes a heat-exchanging mechanism or a chemical reactor. The fundamental ideas behind the processes under consideration are shown in Figure 4.

2.1.1 Solar steam methane reforming process

Currently, steam methane reforming is the best technique for producing high quantities of hydrogen, with the global use of hydrogen being over 70 Mton/year (van Hulst 2019). The three catalysed chemical processes form the basis of the procedure:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 = +206\,\text{kJ/mol} \tag{1}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 = -41\text{kJ/mol} \tag{2}$$

Whereas the water gas transfer process is mildly exergonic, the steam methane reforming reaction (1) is significantly endothermic. The overall response is the whole endothermic (3):

$$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2 = 165\ \ \text{kJ/mol} \tag{3}$$

In order to attain high conversions of the hydrocarbon feedstock, the steam methane reforming process needs a lot of energy and operates at high temperatures. The mainstream method is basically carried out in batch reactors, where heat duty is provided by burning a methane-rich gas fuel at temperature changes between 750 and 950 °C. In addition to the CO_2 involved in chemical reaction according to stoichiometric ratio, the combustion of methane results in significant atmospheric carbon dioxide emission levels: the CO_2 emissions for a large-scale plant range from 8.3 to 10.1 $kgCO_2/kg/H_2$ depending on the process power conversion efficiency (De Falco et al. 2010). It is feasible to move away from fossil fuels with an external, carbon-free, and sustainable energy source, such as solar energy (De Falco and Piemonte 2011; Giaconia et al. 2010; Giaconia et al. 2015). When compared to a typical plant, a steam methane reform powered by solar energy may reduce carbon dioxide emissions by 34–53% and methane consumption by at least 34% (Giaconia et al. 2008). Relative emissions in solar hydrothermal that are due entirely to reaction composition are 5.5 $kgCO_2/kgH_2$ (Giaconia et al. 2008).

De Falco et al. (2021) established a computational formula consisting of partially differential equations that has been solved by numerical simulation for hydrogen synthesis by

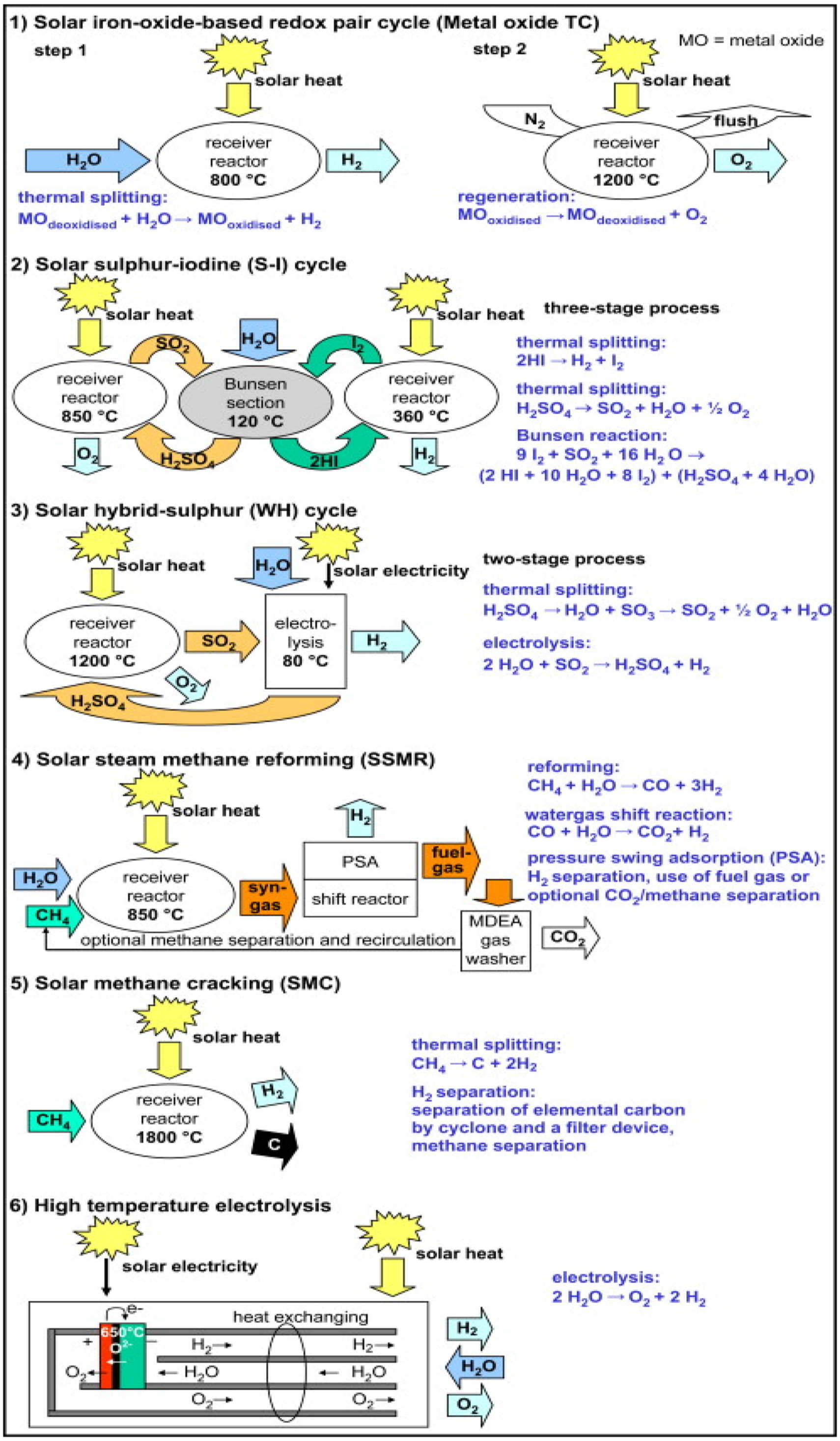

Figure 4: The fundamentals of solar thermal hydrogen production systems (Pregger et al. 2009).

solar steam methane reformation. The influences of steam-to-carbon ratio, molten salt intake temperature, and sweeping gas rate on the operation of a production plant have been explored. The use of concentrated solar energy as an external heat source for the reformation of methane steam has been investigated by Bruni et al. (2019). At temperatures up to 550 °C, molten salts may be employed as a solar heat transporter and storage system, while at temperatures below 550 °C, a hydrogen selective membrane can be used to drive conventional reforming operations, purifying hydrogen.

The incorporation of modern technologies, such as membranes and membrane reactors, concentrating solar

Table 1: A summary of solar steam methane reforming process.

Hydrogen production rate	Used temperature	Energy efficiency	Other prospective	Ref.
82.9 mmol/gh	300 °C	70–80%	Provide an example of the direct use of solar energy to produce hydrogen using water and natural gas resources that are available on earth.	Wang et al. (2022b)
63.1 mmol/gh	310 °C	70–80%	When compared to the fresh materials, the substance employed for the reaction had less crystallinity, a smaller smooth surface area, and a lower Brnsted acid site concentration.	Bajec et al. (2023)
Large scale	–	72–75%	An efficient way to convert methane into an oxide of carbon-free hydrogen gas, a blend of light aromatic and aliphatic hydrocarbons, and significant carbon dioxide.	Liu et al. (2023)
Large scale	773.15 K.	71–78%	It is highly desirable to minimise the radial thickness of the membrane process to sub-millimeter scale and develop the catalysts with considerably greater activity in order to substantially accelerate the membrane generator for high-efficiency hydrogen generation through methane hydrogen production.	Yan and Cheng (2022)
Large scale	–	83%	Global warming, a methane production shortage, a carbon dioxide byproduct, and a reliance on fossil fuels	Bundhoo et al. (2013)

power systems, and molten salt heat carriers, permits the partial decarbonization of fossil fuels and the transfer of solar energy via the existing natural gas infrastructure. Kim et al. (2018) offer a cost-effective method for producing hydrogen and capturing emissions centred on a methane hydrogen production pathway using a composite membrane reactor. To adequately recover hydrogen and concentrate carbon dioxide, a membrane that was both highly permeable and moderately selective was used. Further the above literature review, Table 1 shows a summary of solar steam methane reforming process.

To enhance the productivity and optimise the processing parameters of steam methane reforming, the incorporation of artificial intelligence into steam methane reforming was discussed in order to increase the conversion efficiency and facilitate the prediction of steam methane reforming performance using machine learning algorithms.

The future of steam methane reformation combined with carbon dioxide capture for the creation of hydrogen as a clean fuel is undoubtedly bright. Currently, the most significant obstacles to practical hydrogen generation from the steam methane reforming method are as follows:

(1) Production of cost-effective, stable, and efficient catalysts to enhance conversion efficiency.
(2) Optimisation of the process related energy consumption.
(3) Design and installation of strong heat and energy recovery systems.
(4) Chemical configuration optimization using techno-economic and exergy analyses to optimize overall costs of production.

Future research is anticipated to place a significant emphasis on the creation of strong and machine learning approaches in an effort to overcome some of these obstacles. Although these approaches are widely used, the predictions must be empirically tested to ensure their viability. The use of biofuels as fuels is also being researched in an effort to lower related costs; nevertheless, heat loss in the system is still believed to be substantial, necessitating the development of sophisticated heat recovery technologies. Prior to the deployment of large-scale steam methane reforming technologies, extensive techno-economic and thermal efficiency studies are thought crucial for optimising overall production costs.

2.1.2 Solar-thermo-chemical process

For large-scale production of hydrogen exceeding 500 t/day, water electrolysis and the thermo-chemical water-splitting cycle are both regarded as viable options (Safari and Dincer 2020). Although photovoltaic-electrolysis is rather mature technologically, its overall performance is constrained by the significant quantity of power it consumes. Thermal energy dominates the solar thermo-chemical water-splitting process. As a result, the photovoltaic-electrolyte cycle is potentially less efficient than the solar thermo-chemical process. Due to its economy of scale, the solar thermo-chemical water-splitting process is indeed appropriate for producing massive amounts of hydrogen (Funk 2001).

A wide range of chemical processes are used in the solar thermo-chemical water-splitting process to separate water into hydrogen and oxygen (Diver et al. 2008). All other materials, save water, hydrogen, and oxygen, could well be recycled throughout the process. Using evaluation, Dincer and Acar (2015) assessed the environmental effects of hydrogen-generating techniques. They discovered that compared to electrolysis-based hydrogen generation technologies, the solar thermo-chemical water-splitting process had reduced global warming potential, acidification potential, and cost. The solar thermo-chemical water-splitting process can be divided into pure solar thermo-chemical water-splitting cycles that require only heat and hybrid solar thermo-chemical water-splitting cycles that necessitate heat and a comparatively tiny amount of energy (Boretti 2022). The pure solar thermo-chemical water-splitting process requires only heat. Future-oriented large-scale hydrogen production requires a primary source of energy that can simultaneously produce a significant amount of high-temperature heat and a little bit of energy. This is necessary to retain the solar thermo-chemical water-splitting process advantage of zero carbon emissions. As a result, it is believed that solar and nuclear energy are the best sources of energy for the solar thermo-chemical water-splitting process (Abbasi and Abbasi 2011).

The implementation of nuclear power to produce hydrogen on a wide scale is nonetheless constrained by the location, volume, safety, and disposal of radioactive waste (Armaroli and Balzani 2011). Additionally, the option of a solar thermo-chemical water-splitting process and the size of producing hydrogen are constrained since the heat source for nuclear producing hydrogen is excess heat, and its temperature is often a set value. However, adaptability is increased when solar energy and the solar thermo-chemical water-splitting process are combined. The solar thermo-chemical water-splitting process system is shown schematically in Figure 5. The solar collecting system transforms the solar energy it has captured into heat, which it then transmits to the thermal energy storage system heat storage medium. While a portion of the heat storage devices can be provided to the systemic circulation working substance of the energy production part to produce electricity for the solar hybrid thermo-chemical water-splitting process or the energy infrastructure, someone else can flow and transfer heat within the system to satisfy the heat requirement of the solar thermo-chemical water-splitting process. The power grid could also supply energy during severe weather to maintain steady hydrogen production. The production of hydrogen approach is dynamic, effective, and ecologically benign (Oruc and Dincer 2021) because of the integration of solar energy and the solar thermo-chemical water-splitting process. This large-scale hydrogen production method is a step toward decarbonisation.

A review article for hydrogen production by solar-thermo-chemical process presented by Steinfeld, A (Steinfeld 2005). Having used non-dominated sorting evolutionary algorithms, Sadeghi et al. (2020) constructed an integrated thermo-chemical system powered by a solar power tower and a pressurised transmitter. Using air and fluid flow materials as those of the heat and mass transfer fluid and thermal energy storage materials. The results showed that the optioned hydrogen cost of the proposed system was \$1.7/kg. Sadeghi et al. (Sadeghi et al. 2021) suggested a solar-based thermochemical integrated with the steam Rankine cycle, heat recovery, and thermal energy storage systems that use high-temperature phases for hydrogen production.

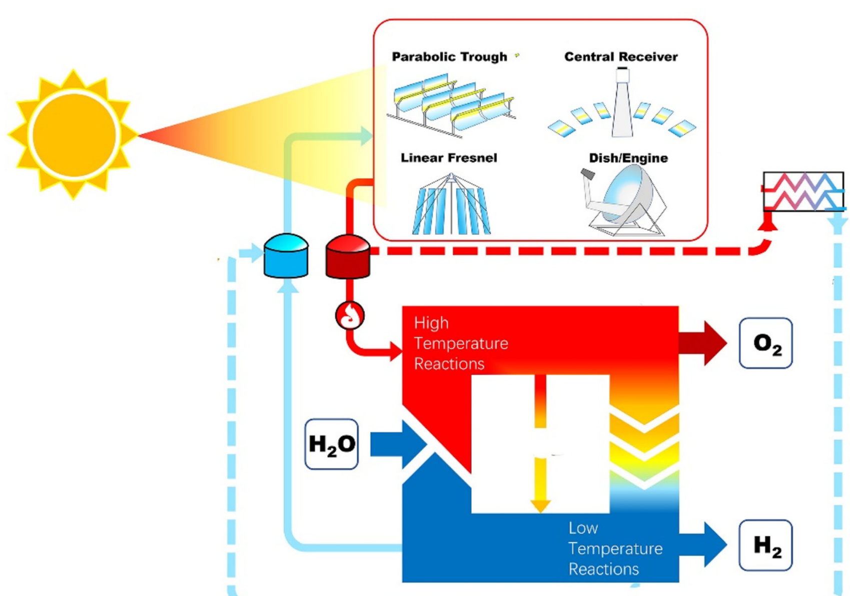

Figure 5: The schematic diagram of solar thermo-chemical water-splitting process for hydrogen production.

Table 2: A summary of solar-thermo-chemical process.

Used solar system	System producing hydrogen and energy storage system	performance assessment	Ref.
Present a collector model.	The primary cycle division of carbon dioxide and water into thermochemical components and use of renewable resources as a process heat source.	High temperature carbon dioxide and hydrogen production and decreased emissions of carbon dioxide.	Zhu et al. (2012)
Present a collector model.	The thermochemical cycle, including zinc, sulphur, and iodine, was constructed using a complete flowsheet. Several thermochemical cycles have been compared to one another.	There have been studies and comparisons of different thermochemical cycles to find out how operating conditions affect the system.	Zhang et al. (2015)
Examining the essential elements of various-sized parabolic solar collectors.	A comprehensive flowsheet was used to design the thermochemical cycle, and many thermochemical cycles have been contrasted between each other.	Using the Monte Carlo approach, the geometric optimisation of a parabolic trough collectors is determined by the local concentration. Various diameters of the parabolic dish collector's primary parts were investigated.	Hoseinzadeh et al. (2018)
Present a collector model.	Coal power facilities use thermal energy storage systems to store electrical energy.	The open network, the five-step cycle, and the electrochemical cycle are three types of thermochemical cycles that are created.	Zhang et al. (2016)
Present a collector model.	Hydrogen synthesis from perovskites and other sulfur-based processes are the foundation of thermochemical energy storage.	Overview and evaluation of thermochemical storage facilities depending on variety.	Prieto et al. (2016)
Present a collector model.	Electrical output that is consistent and sustainable may be produced via storage of thermal energy.	16% less oil mass flow and a 3.3% lower melt salt output temperature.	Yu et al. (2020)

The results showed that its energy efficiency is 44.5% and that the produced hydrogen costs about $1.88/kg. Sadeghi and Ghandehariun (2022) created a solar thermo-chemical cycle using molten salt at high temperatures to produce hydrogen. The thermodynamic and economic evaluations were conducted using the total revenue requirement approach and multi-objective optimization. The outcomes indicated that the best thermal efficiency and hydrogen cost about $7.4/kg. In addition to the literature review in this section, Table 2 shows a summary of solar-thermo-chemical process.

The solar thermochemical hydrogen generation system is the subject of numerous research projects. In similar systems, the solar thermochemical process and Rankine-heated steam are employed to generate the required electrical energy. The authors of (El-Emam and Özcan 2019; Farsi et al. 2020) investigated hydrogen production via solar thermo-chemical water splitting. The presented studies have shown the electrolysis process is not thermodynamically predicted and that the electrolyser reaction conditions have a high effect on the hydrogen production rate and cost.

When it comes to producing sustainable power and hydrogen, concentrated thermo-chemical water-splitting technologies have the ability to close the gap between supply and demand. The most widely used and most commercially successful concentrated solar power technology is the parabolic trough thermal system. Designers hoped that this would motivate the cross-fertilization of ideas and the development of new initiatives combining academic and industry collaboration in this hard inter-disciplinary subject. Researchers think that photo-thermo catalysis will be a key part of "greening" and making industrial operations more sustainable for a long time to come.

There are several challenges of solar thermochemical process for green hydrogen production based on solar energy than summrised as:

(1) High capital and operational costs: Solar thermochemical processes require significant investment in technological development and infrastructure. Furthermore, the cost of operating the system can be high due to the need for highly skilled personnel and specialized materials.
(2) Limited efficiency: Solar thermochemical processes are not as efficient as other hydrogen production methods. The overall efficiency of these systems is typically less than 50%, and some processes may not be able to reach even this efficiency rate.
(3) High temperature and pressure: Solar thermochemical processes operate at temperatures and pressures that are typically much higher than other hydrogen production methods. This can lead to increased safety risks and require more expensive materials and processes.
(4) Corrosion of materials: Solar thermochemical processes can cause corrosion of the materials used, which can lead to increased maintenance costs and reduced efficiency over time.

(5) Limited scalability: Solar thermochemical processes are not easily scalable and the infrastructure required for large-scale production is expensive and complex.
(6) Complexity: Solar thermochemical processes are often more complex than other hydrogen production methods. This can lead to increased costs for training personnel and for developing the process.

2.1.3 Solar methane cracking process

Methane cracking provides a variety of advantages:
– There are no carbon emissions, as may be shown from equation (4).
– Crystalline carbon is created, which makes carbon collection simple and relatively inexpensive.
– A high-quality nanoparticle with a dimension of 20–100 nm, carbon is created (Keipi et al. 2016).
– Low-cost hydrogen production is largely a result of the significance of carbon nanoparticles high energy usage efficiency.

When compared to the energy-intensive carbon capture and storage processes, which have an energy efficiency of 54% and 43%, respectively, methane cracking has an energy efficiency of about 55% (Geißler et al. 2016).

$$CH_4 \rightarrow C + 2H_2 = 74.85 \text{ kJ/mol} \quad (4)$$

Today, the main issue for methane cracking is removing carbon particle influences on operation (Abánades et al. 2012). This is due to the fact that with a typical reactor, such as a tube reactor, carbon nanoparticles may readily be absorbed into the catalyst surfaces and the reactor wall, which can result in the catalyst being inactive and the reactor becoming blocked. An inventive approach to addressing the issues brought on by carbon particles is liquid-metal nanotechnology (Gulevich et al. 2008; Steinberg 1996). This method involves first heating the liquid metal to an extreme temperature, such as 1200 K, and then rapidly exchanging heat with the methane in a bubble reactor. Without a catalyst, the methane cracking process is possible at this high temperature range. Additionally, as the majority of carbon particles congregate on the surface of liquid metal, its high density may aid in the collection of these particles. Tyrer (1931) was the first to suggest using liquid metal techniques for methane cracking, and it has received a lot of attention lately with the advancement of fourth-generation nuclear technology and concentrating solar energy technologies (Serban et al. 2003). The study of this liquid-metal technique is still in its early stages, however. Some of the studies looked specifically at the bubble reactor capabilities. A similar model was developed by Paxman et al. (2014) to explain the heat and mass transport of a single methane bubble in the bubble reactor. The effects of reactivity and pressure changes on the bubble form were disregarded in favour of treating the methane bubble as a hard sphere. Experimental testing of the bubble reactor performance using a single-hole entry was done by Geißler et al. (2015). The working temperature was up to 1000 °C, and the entrance size was 0.5 mm. The greatest methane production rate was discovered to be about 30%. A more precise model was created by Plevan et al. (2015) to analyse the functioning of the bubble reactor. The preheater, orifice, liquid metal section, and gas segment above the liquid metal were the four parts that made up the reactors. More studies concentrated on using experimental techniques to look at the reactor core methane exchange rate. Porous medium was injected into the liquid metal by Parfenov et al. (2020). The experimental findings show that the rate of exchange of methane for this bubbling reactor with a porous medium may reach 78% when the diameter of the single-hole entry is 0.5 mm, and the range of operating temperatures is 930–1175 °C.

Some redesigned bubble reactors were suggested to increase the exchange rate of methane, and their capabilities were tested experimentally. Porous entry was used by Wu et al. (2008) to replace single-hole entry. The research findings demonstrated that porous entrances, which may create smaller bubbles, can provide better outcomes than single-hole entrances. Methane conversion rates for single-hole and porous entrances are 51% and 57%, respectively. A capillary-type bubble reactor was suggested by Schultz and Agar (2015) to prolong the methane bubble period of residence in the liquid metal. The reactor had a 2 mm diameter and could withstand operating temperatures of up to 1100 °C. According to the findings, methane converts at a rate of roughly 32%.

According to the aforementioned experimental findings, it is exceedingly difficult for methane to entirely change into hydrogen using a bubble reactor. A separation technique such as membrane technology is required in order to separate the generated hydrogen from the unreacted methane. It is foreseeable that both the procedures of reactivity and separation need a significant quantity of energy. Since one of the major benefits of this hydrogen generating technology is its zero-carbon emissions, some study should be done to identify the sort of energy source that can be used in this system without increasing carbon emissions. This study presents the creation of a unique, carbon-free method for the manufacture of carbon and hydrogen nanoparticles. The only source of energy used was solar thermal energy. The performance of the whole system and its main facilities were then calculated using a system based upon the first law of thermodynamics. This unique system energy efficiency was assessed, and the impacts of various key factors on the efficiency were investigated to identify the significant parameters.

2.1.4 Solar thermal high temperature electrolysis process

The combination of solid oxide electrolysis cells and a concentrated solar power system is highlighted as one of the hydrogen production technologies. The ability to supply both electricity and heat at high temperatures at the same location provided by concentrated solar panels allows it to meet the energy needs of solid oxide electrolysis devices in terms of including both thermal and electric duty. As a consequence, the combining of concentrating solar energy with high-temperature electrolysis to produce hydrogen is particularly appealing since it may result in synergies that benefit both technologies.

Various operational environments and uses have led to the development of many solar hydrogen technologies. In their system proposal, Seitz et al. (2017) propose an MW-scale combination of a parabolic trough system with solid oxide electrolysis cells. They investigated the impact of storing phase-change materials to extend hydrogen generation during the hours when there is no sunlight. They came to the conclusion that a thermal energy storage capacity of 25.6 MWh would allow for a 50% increase in production time and a 34% decrease in hydrogen cost. Additionally, Derbal-Mokrane et al. (2011) combine high-temperature electroplating with a parabolic trough section used to generate thermal energy. A photovoltaic power plant provides the electricity input independently. According to the outcomes, 400 kg/h of hydrogen requires 5 MW of thermal power and 14 MW of electrical power. Additionally, 140,000 m^2 of space is needed, more than 90% of which is needed for the photovoltaic sector.

Although intended to produce both thermal and electrical energy necessary for the electrochemical reaction, Sanz-Bermejo et al. (2014a) investigated into the integration of lid oxide electrolysis cells with a 10 MW solar tower facility for direct steam generation. The solar system is constructed to meet the heat requirement of the electrolyser as well as the electric consumption of the stack of lid oxide hydrolysis cells and the increased plant balance. The outcomes indicate that if process steam is collected from the high-pressure turbine section and the solar power plant feed water is heated with rejected hot fluid from the electrolyser, the performance losses of the solar power plant while the stack is run at atmospheric pressure may be decreased by 60%. The productivity of the reference hybridization plant increases in pressured mode by 5.8%, and oxygen is produced as a byproduct of pressure swing adsorption is used. Mohammadi and Mehrpooya (2019) employ the same concentrated solar power technology with the aim of improving the system performance and lowering the overall land occupancy. In order to produce electricity, a portion of the thermal energy generated by solar trough collection is sent to an organic rankine cycle; thermal energy storage is also added to ensure continued operation.

A power-to-gas plant is shown in another article by Sanz-Bermejo et al. (2014b), which combines grid-connected solid oxide electrolytic cells using Linear Fresnel techniques with ceramic thermal energy storage. While electrical heaters provide the thermal energy to reach the electrolyser operational temperature (750 °C), collectors keep an eye on the condensation of the reacting feed water. The achieved nominal aim of 400 kg d1 of hydrogen can reach values of over 550 kg/day, depending on the quantity of thermal energy storage modules. There is also a chance that the Solid Oxide Electrolysis Cells will only work sometimes to keep the grid in balance.

To the best of the authors understanding, only one study has looked at the techno-economics of connecting solid oxide electrolysis cells with a parabolic dish solar system to generate around 41 kg/d of hydrogen. According to (Mohammadi and Mehrpooya 2018) proposal, a 0-dimensional prototype of an air compressor storage system combined with a solar dish hoarder to provide superheated steam to the cathodic sites of the solid oxide electrolysis cells stack and electric power to a high-temperature electrolyser is also possible. The high thermal electrolysis system and the compound parabolic collector are both dispersed and modular devices that enable a synergistic system implementation practically without the requirement for an electrical grid connection and with the potential for installation in off-the-grid locations. The primary issues with high-temperature electrolysis systems are the thermal management of the electrolyser stack and thermal integration with both the heating element and the target. These issues are explicitly addressed in this study.

Off-design analysis, which will be the focus of future studies, may improve the feasibility evaluation of completely renewable solar hydrogen generation by studying the linkage of solar energy distributions with representative hydrogen demand profiles. In addition, the inclusion of a thermal energy storage system and the potential consequences of a carbon price must be explored. A future study would also include a well-to-wheel cost comparison that included the proposed configuration settings as a hydrogen production phase in the total hydrogen distribution chain.

2.2 Indirect approaches for solar-based water splitting

There are a number of limitations to direct thermal, including poor conversion efficiency, excessive heat loss, and safety concerns. As a result, indirect approaches are the scientists primary emphasis. The indirect approach is the use of solar energy to produce water-based hydrogen via a series of intermediary stages. As shown in Figure 6, the indirect method schematic design has two phases. The electrical energy is produced in the first stage by solar radiation. The produced power is then used to split water in an electrolyser to make hydrogen in the subsequent step (Frowijn and van Sark 2021).

2.2.1 Electrolysis process

Water electrolysis is a tried-and-true method that has been used in many industries for more than 100 years. The technique of splitting oxygen and hydrogen by using electrical energy is known as water electrolysis, as shown in equation (5) (Balta et al. 2010). While the necessary electrical energy reduces with temperature, the overall energy needed for hydrogen production somewhat increases. This is particularly crucial since the majority of the power generated worldwide is derived from fossil fuels with very poor efficiency, this is particularly crucial. It is now regarded as a crucial procedure that may be used to produce high-purity hydrogen from both water and sources of renewable energy. In the near future, water electrolysers will likely play a bigger role in the decentralised production of hydrogen, such as in hydrogen refuelling stations.

$$H_2O + \text{Electricity} \rightarrow H_2 + 0.5\,O_2 \quad (5)$$

Electrolysis is the technique of using electricity to separate water molecules to produce hydrogen and oxygen. Figure 7 depicts the electrolysis schematic diagram. Water may be divided by using a DC supply.

The optimum way for splitting water is established by electrolysis, a developed and significant strategy (Zhang et al. 2010). It includes producing hydrogen via a reaction between any of the aforementioned substances and water. Electrolysis is carried out using proton exchange membrane, alkaline, and solid oxide electrolysis cells (Marshall et al. 2007).

In solid oxide electrolysis cells and alkaline conditions, water could well be divided into hydroxide particles and

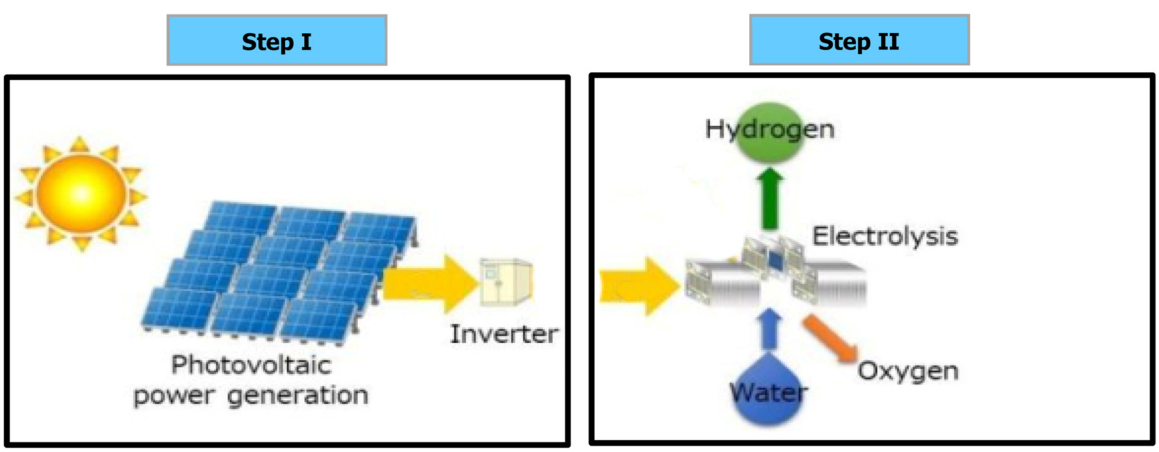

Figure 6: The schematic of the indirect-solar hydrogen production approach.

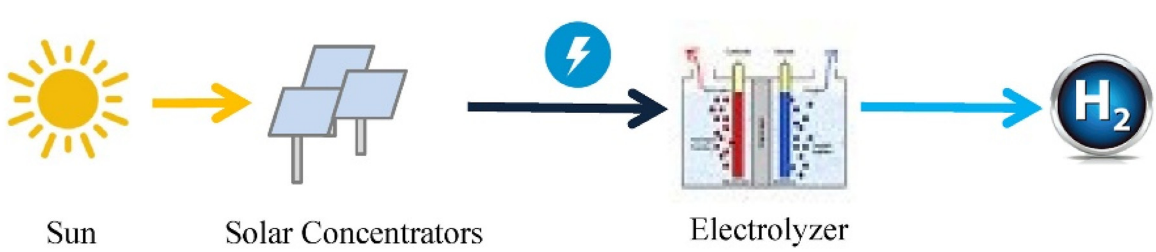

Figure 7: The schematic of the water electrolysis diagram.

Table 3: The characteristics of the main electrolysis technologies (Chi and Yu 2018; Kumar and Himabindu 2019).

Proton exchange (H^{+})	Solid oxide (O^{2-})	Alkaline (OH^{-})
The PEM working concept water electrolysis with electrolytes causes protons to move to the cathode and discharge water movement, culminating in the contraction of hydrogen by applying an electric field to a membrane for proton exchange.	Electrochemical systems that can transition between electrolytic and combustion modes are fueled by solid oxide cells. The solid oxide electrolyser converts water vapour to hydrogen gas. Production of hydrogen at elevated temperatures enables lower electricity consumption because the temperature increase provides a steadily increasing portion of global power generation. Additionally, it permits solid oxide electrolyser operating efficiency of the highest order.	Alkaline electrolysis operates on a fundamental principle when a current flow is sent through water. Hydrogen and oxygen breakdown into separate ions. The electrolyte solution moves faster when potassium and sodium ions, which are positively charged, and hydroxide and chloride ions, which are negatively charged, are added.
Charge carrier for proton exchange is H^{+}	Charge carrier for solid oxide is O^{2-}	Charge carrier for alkaline is OH^{-}
Temperature ranges from 20 and 200 °C	Temperature ranges from 500 and 1000 °C	Temperature ranges from 20 to 80 °C
65–82% of efficacy	Up to 100% of efficacy	59–70% of efficacy
The advantages of proton exchange include high-quality hydrogen production, a concise design, rapid reaction, and rapid startup.	The advantages of solid oxide electrolysis cells electrolysis include reduced energy usage, low monetary value, and enhanced kinetics.	The advantages of alkaline electrolysis include its evolved technology, cheap monetary cost, and relative firmness.
The disadvantages include costly high polymeric membranes and precious metals.	The disadvantages include incorrect sealing, safety issues, and mechanical instability.	The disadvantages include gas permeation and accelerating dynamics.

hydrogen at the cathode side. The hydroxide particles are converted to O_2 on the anode side (Teng et al. 2020). The solid oxide electrolysis cells elecrolyser uses less electricity since there is an increase in temperature during intermediate phases. In terms of total electricity generated and spent, this warming trend induces better electrolysis (Karimi et al. 2022; Mehrpooya et al. 2019). The chemical process behind solid oxide electrolysis cells, alkaline, and proton exchange membrane is shown below (see Table 3).

2.2.2 Photolysis process

Photolysis is the process by which sunlight is used to separate water molecules into oxygen and hydrogen (Fujishima et al. 2007). The photolysis process is started when sunlight is absorbed over a semiconducting surface of a material (Luo et al. 2014; Nada et al. 2005). As an electron-hole pair is created when a photon contacts the semiconductor material surface of the anode with an energy band gap equivalent to or larger than that of a semiconductor, the energy band gap of this material plays a significant role in boosting photolysis conversion efficiency (Singh et al. 2015). The anode in the holes converts the water into O_2 and H+. The H+ is produced from hydrogen by the flow of electrons across an electrical system at the cathode (Bak et al. 2002a). The hydrogen production is summarised by the fundamental equations as below:

$$\text{Anode } 2p^{+} + H_2O \rightarrow 2H^{+} + 0.5\,O_2 \quad (6)$$

$$\text{Cathode } 2e^{-} + 2H^{+} \rightarrow H_2 \quad (7)$$

$$\text{Total } H_2O \rightarrow H_2 + 0.5\,O_2 \quad (8)$$

Figure 8 shows a demonstration of photolysis in action.

For the purpose of using photolysis to produce hydrogen. The potential of photo-electro-chemical cells has been very promising (Chiu et al. 2019; Voloshin et al. 2015). Photocathode and photoanode are the two photoelectrodes that make up photo-electro-chemical devices in general. These conductors are submerged in water or an aquatic solution, and solar radiation is used to split the oxygen and hydrogen (Baykara 2004). As a result, it is a superb and useful entire hydrogen production system that is driven by the sun. Photo-electro-chemical cells are also useful tools for the chemical method of producing hydrogen by water electrolysis under solar radiation (Jacobsson et al. 2014).

The efficiency of photo-electro-chemical cells, a possible solar-only hydrogen production method, has been limited by material limitations. The goal of this work is to improve the efficiency of photo-electro-chemical cells by finding and making semiconductors that are resistant to corrosion and have the right conductivity and valence band edge alignments for photo-electro-chemical applications (Wu et al. 2002).

The relevant stimulus causes the intermediary cations and anions to develop depending on the kind of catalyst. For example, when catalysts get enough light to stimulate electrons to migrate from the covalent energy area to the conductive energy region, they become active to produce

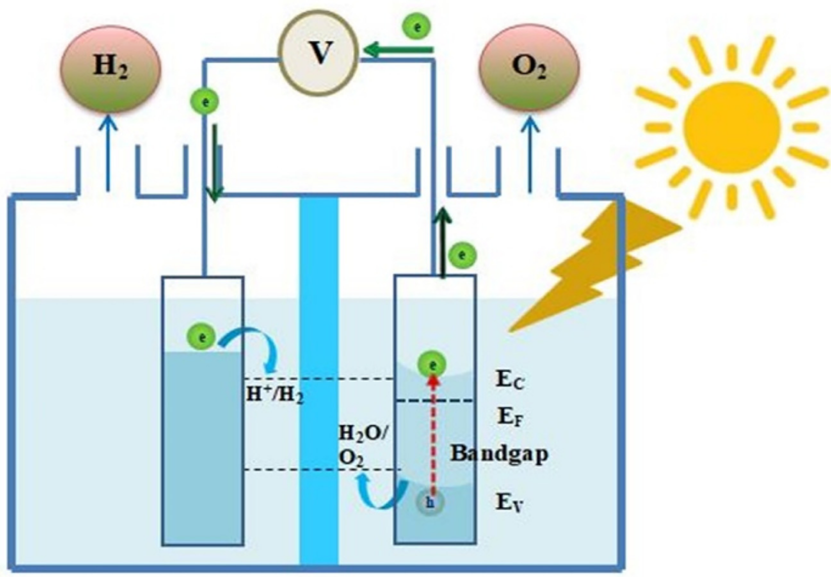

Figure 8: Schematic illustration of the photolysis process (Bajorowicz et al. 2018).

both positive and negative ions. The photocatalyst separates into an electronic configuration if it belongs to the semiconductor family. Anions or e travel towards the cathode in an electrolytic method, whereas cations or hydrogen ions migrate towards the anode (Yuan et al. 2021).

The photo-electro-chemical cells have indeed been continuously improved for single photoelectrode (Fujishima and Hond 1972a), hybrid photoelectrode (Morisaki et al. 1976; O'regan and Grätzel 1991), bi-photo-electrode (Nozik 1976), and systems with sensitised photoelectrodes (El Zayat et al. 1998). The efficiency of energy conversion of water photoelectrolysis is essentially governed by the characteristics of the photoelectrochemical materials (Bak et al. 2002b). In order to be effective, electronic implementation must have the following characteristics:

- Higher stability.
- Cheap material.
- A comparatively lower amount of bandgap than that of H^+/H_2.
- A more favourable level of conductive band compared to that of H_2O/O_2.
- The ability to absorb the majority of photons in the solar spectrum before they are absorbed.

In addition to these benefits of the photo-electro-chemical cell, researchers are looking into the basic ways to make a competitive cell for producing hydrogen as below:

Advantages

- Availability of raw materials in plenty.
- It produces hardly any trash or emissions.
- Easier to transport and store.
- The sole by-product is O_2.

Disadvantages

- Relative need for high solar energy.
- Ineffective transformation.

2.2.3 Solar furnace process

There are numerous significant benefits to using concentrated solar radiation in solar furnaces as the source of energy for high-temperature process heat. Since contaminants are released throughout the solar processing, and if the carbon created is ultimately stored, there is not have any emissions of CO_2 from the whole production process for the production of power or hydrogen. Since no combustion takes place within the reaction chamber, the hydrogen that can be produced is free of carbon dioxide and is thus suitable for use as fuel in fuel cells and other hydrogen-consuming devices.

The pioneers of high heat solar energy that is used in solar furnace development were Trombe and Fox (1957). When they started looking into high-temperature metalworking, the inorganic biochemistry of the rare earth elements, and the characterisation of ceramic materials in the middle of the 20th century, they developed an interest in this field.

Modern high-flux solar research facilities are offered by several organisations worldwide. The feasible solar flux values for each university are shown in Table 4. The maximum solar flux recorded to date is 16,000 kW/m^2, or 16,000 Suns worth of concentration.

A solar furnace is a heat-dispersing apparatus that generates energy using a diffraction pattern or a parabolic mirror (Bilgen 2001). Although this approach relies on renewable energy, it is no longer in use because of its cost

Table 4: The global most advanced solar flux used in solar furnaces.

Country	Obtained solar flux (kW/m^2)	Collector area (m^2)	Year	Reference
Switzerland	5000	58	1999	Haueter et al. (1999)
France	9700	58	2008	Reinalter et al. (2008)
Spain	15,000	58	2009	Garcia et al. (2019)
Spain	10,000	45	2009	Lovegrove et al. (2011)
Australia	13,000	510	2011	Rojas-Morín and Fernández-Reche (2011)
France	15,000	3.15	2018	Guillot et al. (2018)
France	11,000	2845	2019	Laubscher et al. (2020)
USA	6000	36	2019	Djafour et al. (2011)

and space requirements. A Fresnel lens or a parabolic mirror are used in a solar furnace, a heat diffraction device, to create energy.

2.2.4 Photovoltaic conversion process

Photovoltaic is one of the most widely used processes for generating hydrogen from solar energy. Beginning in 1970 (Abdin et al. 2015; Lehman et al. 1997), hydrogen was created by electrolyzing water using power generated by photovoltaic cells. Photovoltaic cells use solar energy to create electricity.

During electrolysis, hydrogen and water molecules are separated using electrical energy. One of the most popular methods for producing hydrogen using energy from photovoltaic cells is photovoltaic-hydrogen (Dreher et al. 2022). This approach uses a photovoltaic electrical power to provide energy for the electrolysis of water. A better performing photovoltaic power plant process improves the electrolysers capacity to create hydrogen (Olateju et al. 2014; Siddaiah and Saini 2016). Hydrogen may be produced cleanly and sustainably by using PV power plants. As a result, there has been a lot of study done on solar-powered hydrogen manufacturing devices (Habibollahzade et al. 2018). The schematic for the solar-hydrogen plant is shown in Figure 9.

To improve the performance of such system, lower its cost, and make the production of hydrogen more feasible, solar-powered electrolysis has to undergo significant changes. The electrical efficiency of the photovoltaic system must be amplified by the electrolysis system efficiency for attempting to convert electricity to hydrogen fuel energy in order to determine the overall efficiency of solar hydrogen production (see equation (9)).

$$\text{Solar hydrogen efficicny} = \text{photovoltaic efficicny} \times \text{electrolysis efficicny} \quad (9)$$

This is needed because photovoltaic electricity production and electrolysis are both needed to make solar hydrogen.

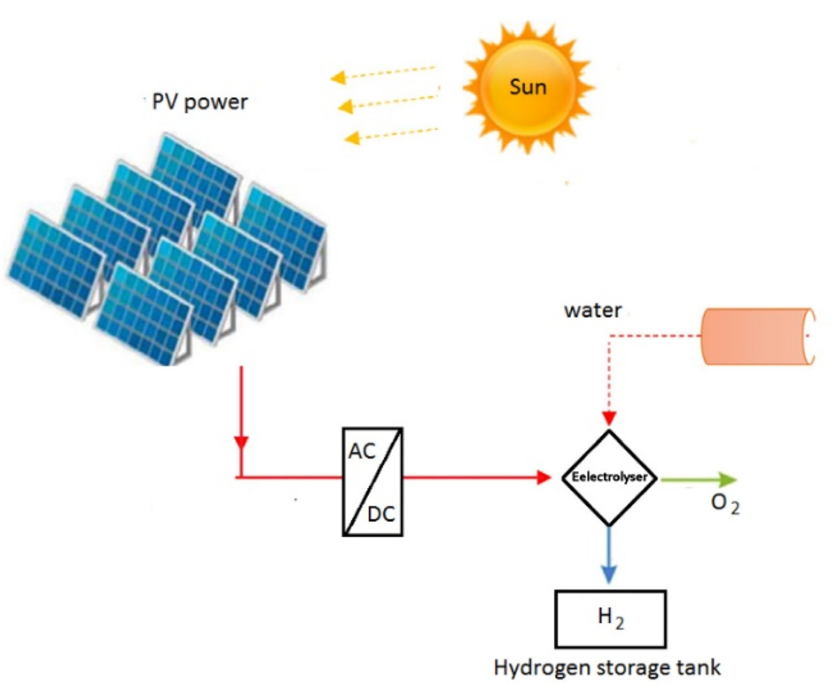

Figure 9: Schematic of photovoltaic-hydrogen production.

2.2.5 Solar thermoelectric conversions process

Due to the unique benefits, they provide, thermoelectric generators have lately become a potential alternative to other renewable energy sources. There is significant interest in using thermoelectric technologies for power and hydrogen production because to its solid-state construction, quiet operation, lack of moving components, and minimal maintenance needs (Khanmohammadi et al. 2022; Malik et al. 2021). The thermoelectric generators relatively low conversion efficiency, however, has long restricted their use to situations where dependability and durability are crucial factors. Thermoelectric generators are a great choice for hydrogen production because, thermal energy is obtained from the sun (Chen et al. 2016). In this regard, the recent years have seen a lot of interest in the use of thermoelectric generators in solar energy conversion systems. In most instances, thermal or optical concentration is required to achieve appropriate power output levels since the incoming ambient solar flux would be too low to produce significant temperature gradients and guarantee the efficient functioning of thermoelectric generators (Mohamed et al. 2022). The schematic of solar thermoelectric hydrogen-conversion is shown in Figure 10.

Whenever a difference in temperature reaches its stable condition, the thermoelectric effect in semiconductors manifests itself. The transition of heat irradiance from solar panels is another indirect way to observe this process. The equipment that carries out the aforementioned conversion due to the panels heat irradiation is a thermoelectric generator (Musharavati et al. 2022). A solar collector and an electrolyser for producing hydrogen are incorporated within the thermoelectric generator. The thermoelectric generator replaces this condenser-integrated cooling system and power generation system. Thermoelectric generator diverts this surplus energy production to an electrolyser to produce hydrogen. The system total cost per G.J. is $65.97 and its greatest energy efficiency is 13.3%. Hydrogen is produced at a rate of 2.3 kg/h in a balanced working system. As a result, thermoelectric generator is employed in a system rather than a condenser since it performs better and is more practical (Ge et al. 2022; Hallenbeck et al. 2012).

2.2.6 Biophotolysis process

Biological production of biohydrogen from biowaste, freshwater, and biomass (Bechara et al. 2021; Javed et al. 2021). Essentially, the photo-bioreactor creates hydrogen or splits water into hydrogen and oxygen using sunlight (Javed et al. 2022). This ecologically beneficial method employs microorganisms or bioreactor agents to absorb harmful gases like carbon monoxide and carbon dioxide. Through biophotolysis, the plant creates biological hydrogen (Ghiasian 2019). The following reactions constitute the conversion of solar energy into chemical energy that may be used. The conversion of water into hydrogen by microalgae is as follows.

$$2H_2O \xrightarrow{\text{Light energy}} 2H_2 + O_2 \qquad (10)$$

In a single step of bio-photolysis (Ferraren-De Cagalitan and Abundo 2021), dinoflagellates convert hydrogen atoms into oxygen through photosynthesis, as seen in Figure 11.

Hydrogen ions are converted to hydrogen by the enzyme hydrogenase (Kumar et al. 2019). As this hydrogenase enzyme is vulnerable to oxygen (Melitos et al. 2021), oxygen must be preserved urgently at a level below 0.1%. At high and total solar intensities, a considerable proportion of photons (90%) collected by the photosynthetic machinery are not employed in the photosynthesis process but rather in the process of fluorescent (Mahidhara et al. 2019). In indirect bio-photolysis (Elmorsy et al. 2022; Fujishima et al. 2000; Fujishima and Honda 1971; Fujishima and Honda, 1972b;

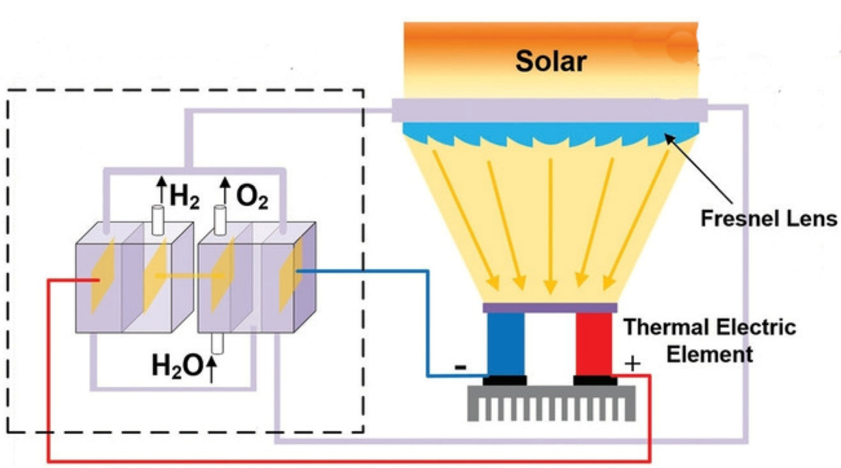

Figure 10: Schematic of solar thermoelectric hydrogen production.

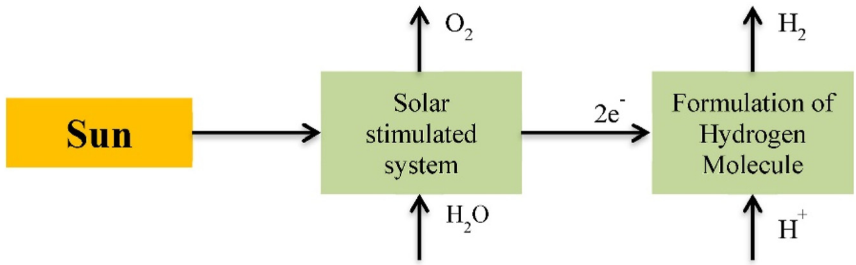

Figure 11: Schematic of biophotolysis for hydrogen production.

Ghirardi et al. 2014), solar energy excites electrons from a proton donor, and a portion of these radicals create hydrogen. Since real hydrogen synthesis is mediated by a biological catalyst, the process may take place at room temperature.

3 Photocatalysis and powder photocatalysis for water splitting

Photocatalysis is divided into two classes. One is the use of anti-stain, self-cleaning, and superhydrophilicity qualities to enhance the living environment (Hassan et al. 2022f). Numerous industrial goods use titanium dioxide (TiO2) photocatalysts. Another path of photocatalytic activity is the transfer of light energy, as shown by water splitting. Since the Honda-Fukushima phenomenon was revealed (Ge et al. 2019; Hassan et al. 2022g), researchers have researched the splitting of water with light energy using powder and electrode systems. Even though it falls under fundamental research, it remains a difficult problem. Significant advances in this area of study have been extraordinary. Photoelectrochemical water splitting can undoubtedly help with green, sustainable hydrogen production. The ultimate objective of this domain is to develop artificial photosynthesis and solar hydrogen production from water.

3.1 Basis of photocatalytic reaction

Photocatalytic reactions are an important part of green hydrogen production based on solar energy. This process takes place when a photocatalyst, usually a semiconductor material, absorbs light energy from the sun and uses it to split water molecules into hydrogen and oxygen. This is known as the water-splitting reaction, and it is the primary way for hydrogen to be produced from renewable sources. The photocatalyst is usually composed of titanium dioxide or zinc oxide, and when the photocatalyst is placed in direct sunlight, it absorbs the light energy and creates electron-hole pairs. The electrons and holes then react with the water molecules, breaking them into hydrogen and oxygen. This process is highly efficient and allows for the production of large amounts of hydrogen with minimal energy inputs. Semiconductors have a binding energy in which an appropriate band gap separates the conduction band from the depletion region. When light is irradiated, the band structure and valence band create electrons and holes, respectively. Similar to electrolysis, photo-generated electrons and holes induce redox reactions. For water splitting, hydrogen bonds are reduced by electrons to generate hydrogen and oxidised by holes to form oxygen. Important characteristics of semiconductor photocatalytic activity substances are the band gap width and energy levels of the conduction and valence bands. As seen in Figure 12, water splitting occurs on heterogeneous photocatalysts with semiconducting characteristics.

3.2 Photocatalytic reaction process in a powdered system

Powdered photocatalytic systems have the potential to play a key role in green hydrogen production based on solar energy. In such systems, a photocatalyst is used to absorb solar energy and then splits water molecules into oxygen and hydrogen, thus enabling the production of hydrogen. This process is usually carried out in a reactor containing the photocatalyst in powder form. The powder photocatalyst system is advantageous due to its large surface area, which allows for efficient absorption of light and increases the reaction rate. Additionally, the powder form is less expensive and easier to handle than conventional photocatalysts, such as nanostructured particles or films. It is also more stable and can be used for long-term applications, making it an attractive option for green hydrogen production. As seen in Figure 11, the electrolysis of water by photocatalysts seems simple and straightforward. However, due to an uphill response that facilitates back reactions, it is a very difficult reaction. The conduction band is a thermodynamic need, but not a sufficient cause. As demonstrated in Figure 13, the photocatalyst properties are influenced by a number of

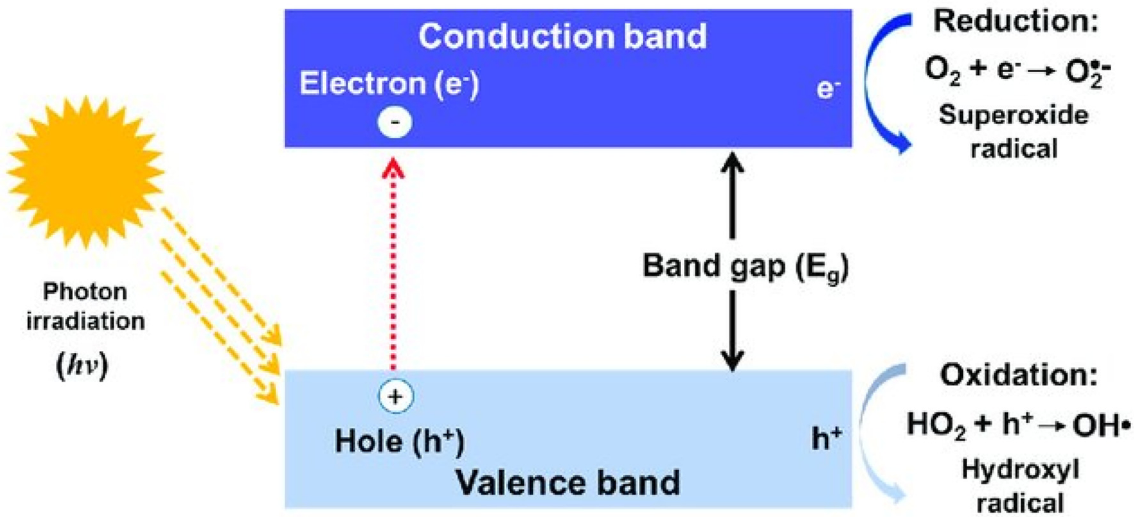

Figure 12: Water splitting principle on semiconductor photocatalysts (Abbas et al. 2022a).

significant parameters. Electrons and holes that are photogenerated must be separated and move to the surface. Bulk parameters, including crystallinity, have a significant impact on this procedure. The greater the crystallinity, the fewer the imperfections that serve as recombination sites for photogenerated electrons and holes, hence increasing the lifetime and mobility (Abbas et al. 2022b; Hassan et al. 2022h; Jaszczur et al. 2016; Jaszczur et al. 2020). Surface features, on the other hand, affect the kinetics of the amount and quality of binding sites for redox processes involving photogenerated electron and hole pairs. Typically, the number of active spots is proportional to the surface area. Even if photogenerated holes and electrons possess thermodynamically adequate potentials for hydrogen production, they must recombine if there are no active sites for electrochemical reactions on the surface. Consequently, a catalyst is often placed on the surface to introduce the active site. Photocatalysts need acceptable bulk and surface qualities as well as an energy structure. Therefore, it makes sense that photocatalysts should consist of highly functional elements (Guo et al. 2022; Gao et al. 2023; Hassan et al. 2023a; Hassan et al. 2023b; Jin et al. 2022; Wang et al. 2022c; Xia et al. 2023; Zhao et al. 2022). The process in a powdered system photocatalytic reaction in green hydrogen production based on solar energy can summarised as:

(1) Harvest solar energy to generate electricity.
(2) Use electrolysis to split water molecules into hydrogen and oxygen.
(3) Use a photocatalyst to accelerate the reaction rate of water splitting.
(4) Collect and store the produced hydrogen.
(5) Use the collected hydrogen for various applications such as energy generation, fuel cells, and fuel for transportation.

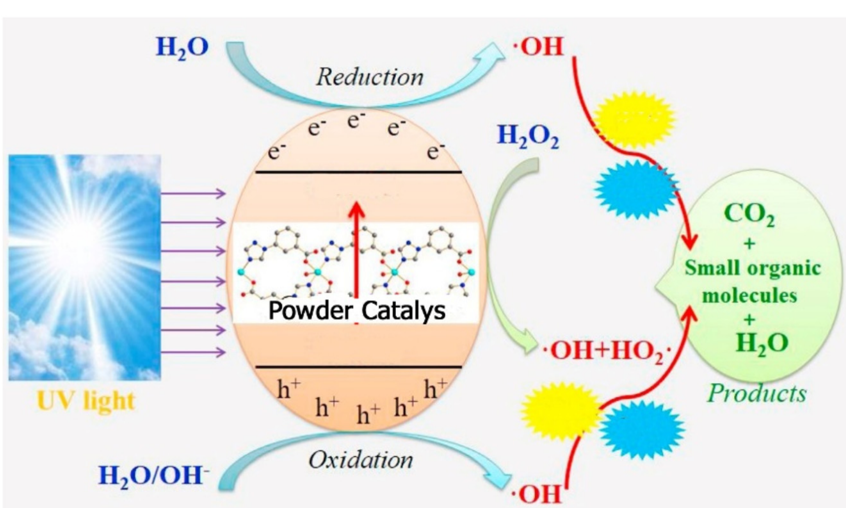

Figure 13: Approaches for the photocatalytic reaction of a powdered system.

There are several challenges of powdered system photocatalytic reaction in green hydrogen production based on solar energy, that can summarised as:
(1) Low efficiency: The efficiency of a photocatalytic reaction is typically lower than that of a traditional chemical reaction, and the efficiency of the powder system is even lower due to the difficulty of dispersing the powder evenly throughout the reaction chamber.
(2) Difficulties in scaling up: In order to increase the amount of hydrogen produced, the reaction chamber must be scaled up. This is difficult to do with a powder system, since it is difficult to ensure that the powder is evenly dispersed throughout the chamber.
(3) Sensitivity to environmental conditions: The photocatalytic reaction is sensitive to environmental conditions such as pH, temperature, and light intensity. Thus, any changes in these parameters can affect the efficiency of the reaction, leading to lower yields.
(4) Contamination: The powder system has a higher potential for contamination, since it is more difficult to keep the powder particles from escaping the reaction chamber and entering the environment. This can lead to a decrease in the efficiency of the reaction.

4 Appealing directions in green hydrogen production based on solar energy

The appealing directions in green hydrogen production based on solar energy can summarised as:
(1) Increase Investment in R&D: Investing in research and development is key to unlocking the potential of solar-powered green hydrogen production. This includes investing in the development of new materials and technologies that can improve the efficiency of solar-powered hydrogen production.
(2) Utilize Low-Cost Solar Technologies: To maximize the economic benefits of solar-powered hydrogen production, governments and businesses should leverage low-cost solar technologies, such as concentrating solar power (CSP) and photovoltaics.
(3) Pursue International Collaborations: Countries and organizations should explore international collaborations to accelerate the development and adoption of solar-powered hydrogen production. This could include sharing best practices, exchanging research and development results, and exploring financing models.
(4) Advance Infrastructure Development: Governments and organizations should prioritize the development of infrastructure to support the production and distribution of green hydrogen. This includes investing in pipelines, ports, and refuelling stations.
(5) Foster Public-Private Partnerships: Governments, businesses, and organizations should explore public-private partnerships to develop, finance, and scale up solar-powered hydrogen production. This could include joint ventures, subsidies, and other incentives.
(6) Leverage Existing Resources: Governments and organizations should leverage existing resources to further the development of green hydrogen production. This includes utilizing existing renewable energy sources, such as wind and solar, to produce hydrogen.

5 Science challenges in green hydrogen production based on solar energy

The science challenges in green hydrogen production based on solar energy can summarised as:
(1) Developing efficient and cost-effective methods for solar energy to split water molecules into hydrogen and oxygen.
(2) Developing efficient and cost-effective ways to store and transport hydrogen.
(3) Developing renewable catalysts for efficient hydrogen production.
(4) Finding ways to reduce the cost of utilizing solar energy for hydrogen production.
(5) Improving the durability of electrolyzers and other equipment used to produce hydrogen.
(6) Generating hydrogen from solar energy with minimal by-products.
(7) Developing technologies to effectively convert solar energy into hydrogen.
(8) Finding ways to maximize the efficiency of solar hydrogen production systems.
(9) Developing ways to scale up solar hydrogen production systems.
(10) Reducing the environmental impact of hydrogen production from solar energy.

6 Conclusions

Green hydrogen production based on solar energy is a promising renewable energy technology with a wide range of potential applications. However, there are still some significant challenges that must be overcome in order to make the technology viable. These include cost reductions, efficiency improvements, and the development of better storage and transport systems.

The most promising approach to producing green hydrogen is through the use of water electrolysis. This process requires energy input to separate the oxygen and hydrogen molecules, so an efficient and cost-effective energy source is needed. Solar energy is the most suitable choice, as it is clean and renewable. PV cells are the most commonly used technology for this purpose, but novel concepts such as solar-driven water splitting and direct solar-thermal processes have also been explored.

To maximize efficiency and reduce costs, further research is needed to optimize the process and develop better materials for solar cells, catalysts for water splitting, and more efficient storage and transport systems. In addition, it is essential to develop policies and regulations to support the production and use of green hydrogen. Overall, green hydrogen production based on solar energy is a promising technology with great potential. With the right investments in research and development, it could become an important part of the global energy mix in the near future.

Recent projections indicate that the worldwide ultimate energy demand for hydrogen might range from 3% to 8% until 2050, depending on how hopeful the technology and economic projections were. This would equate to several million additional fuel cell cars being used globally. Fuel cell cars are the most potential hydrogen technologies and are thought to be the primary force behind the adoption of hydrogen as an energy resource, but permanent fuel cell hydrogen production is anticipated to remain a niche business at least until the year 2050. The establishment of widespread use of hydrogen as an energy resource, meanwhile, remains questionable and is dependent on the advancement of end-use technologies, considerable cost reductions, the creation of a sufficient hydrogen network, and competitiveness with alternative technologies. Options with much greater total energy efficiency include battery electric cars and series connected hybrids. These vehicles will be made accessible in a few years at relatively minimal extra investment costs. Nevertheless, in conjunction with the limited biofuel possibilities and renewable power, hydrogen could be a practical supplemental fuel for future hybrid cars. Hydrogen has the potential to reduce greenhouse gas emissions in automotive size classes and consumer groups in ways that battery-electric cars cannot. Upcoming hydrogen-electric hybrid vehicle designs still need to be examined and evaluated in more depth. The primary condition for the major environmental advantage of such a situation is the large-scale generation of competitive hydrogen from renewable sources of energy. In this case, using solar thermal energy to make hydrogen could be a long-term way to get it.

Regarding solar thermal technologies to be reliable and marketed, a number of obstacles relating to materials, components, technological, and operational ideas still need to be resolved. All processes need to have their technical principles for heat and mass fluxes, material transformation, and separation better developed. The temporal variation in load and temperature variations in space are additional issues. Major research goals include the selection, qualification, and accreditation of suitably resistant materials for essential components. Long-term plans call for commercial facilities with a capacity of at least 100 MW. However, carbon-free solar thermal methods like the hydrosolar process, which produce pure hydrogen, are still in the early stages of research. After 2020, the first industrial units for mass manufacturing are anticipated. In contrast, the method of solar methane reforming has been under development longer, and a first prototype plant has already been realised. The technology can be produced at a practically competitive cost and may be added to or integrated into conventional operations.

Even with carbon capture and storage technology, it is anticipated that fossil fuel-based hydrogen generation will continue to be the most affordable hydrogen supplier at least until 2030. Up to that point, hydrogen generated by electrolysis and wind energy may be a competitive and sustainable choice in the major markets for hydrogen fuel cells. Additionally, depending on natural gas pricing and the continued improvement of the process, solar steam methane reformation could, in certain years, be cost-competitive with traditional methods of producing hydrogen and syngas. Based on existing process designs, estimated hydrogen costs for long-term carbon-free concentrated solar processes indicate that these technologies could have very significant potential. However, in-depth research still yields greater values, so in addition to research and development efforts, it is important to take into account the potential for additional cost savings, market penetration, and mass manufacturing of materials and components. Intercontinental transportation of hydrogen generated by solar thermal methods seems to be feasible only in the long run and if fuel prices dramatically increase relative to the existing level in Europe. However, there are other reasons to develop concentrated solar processes in addition to a potential need for hydrogen for mobility. Within the next twenty years, the most significant stimulus for the advancement of solar thermal processes and the realisation of pilot plants will be the rising industrial hydrogen consumption in nations with high direct solar radiation. In the long run, many hundreds or thousands of industrial concentrated solar plants might possibly provide the estimated hydrogen demand of roughly 2 EJ. Sites for industrial applications on a commercial level need to have large-scale access to water, energy, and methane, as well as high direct solar radiation levels of over 2000 kWh/m^2/year (preferably above 3000 kWh/m^2/year). To get the water needed to make hydrogen, solar heat could also be used to clean and remove salt from saltwater (Ferraren-De Cagalitan and Abundo 2021; Ghirardi et al. 2014; Kumar et al. 2019; Melitos et al. 2021; Mahidhara et al. 2019).

Solar thermal technologies, which use solar energy and water as pure, almost infinite sources of hydrogen, show a significant possibility for carbon-free and sustainable hydrogen production on a massive scale, despite the previous difficulties and present limitations. In contrast to new solar methods, where significant cost reductions are anticipated owing to the continued advancement of process and component design and manufacturing techniques, the costs of traditional hydrogen generation are largely influenced by increasing fossil fuel prices. By the time a market for hydrogen fuel and a sizable demand have emerged, marketplaces for solar hydrogen could emerge as a consequence of ambitious climate policies and the political desire for renewable hydrogen. Because of this, government and business support for hydrogen technology should come with a detailed plan for the long-term use of renewable and environmentally friendly ways to make hydrogen.

7 Future outlook

(1) In the future, biophotolysis will develop in terms of hydrogen production. The result of the whole process, including bioagent-triggered or -involved reactors, must be adjusted in a favourable way, and environmental suitability should be altered while taking the economic impact into consideration.
(2) The development of a hydrogen generation technology that is efficient, dependable, cost-effective, and environmentally benign necessitates a harmonious interplay between several scientific fields and strong theoretical knowledge.
(3) In thermochemistry, there are several obstacles to overcome, such as the price of the concentrated mirror mechanism, the efficiency of reactant concentration, and the need for reactors that can resist high temperatures.
(4) Electrolysis: It is currently unknown which of the processes is the most productive given the current state of technology. They vary in terms of effectiveness, adjusting complications, and cost. Various system states, such as incorporating solar array output via a DC-DC converter to get a better voltage and current profile at the end, are among the viable alternatives that have not been exhaustively examined. In the same suggested system, a charge controller for a battery bank is intended to be placed to reduce fluctuations in net power production, which are mostly caused by erratic solar irradiance. Integration of fuel cells, photovoltaics, and an electrolyser might provide a further set of devices for the same function as those described above. In addition, considerable improvement in the commercial dependability of photocatalytic degradation, biophotolysis, and thermo - chemical hydrogen generating systems is also required.

The distinctive and new points of view in green hydrogen production based on solar energy can be expressed as:
(1) Utilizing Concentrated Solar Power technologies to generate high temperatures to drive high-efficiency electrolysis.
(2) Exploring the use of hybrid systems combining solar and wind energy to enable round-the-clock hydrogen production.
(3) Investigating the potential of combining solar energy and biomass resources to produce hydrogen.
(4) Developing efficient and cost-effective ways to store and transport hydrogen.
(5) Exploring the potential of utilizing solar thermal energy storage systems to produce hydrogen.
(6) Investigating the potential of using renewable energy sources such as solar, wind, and wave power to produce hydrogen at a large scale.
(7) Developing novel catalysts for efficient solar-driven hydrogen production.
(8) Developing advanced membrane technologies for efficient hydrogen separation.
(9) Developing and deploying low-cost, efficient solar-driven hydrogen production systems.
(10) Exploring the potential of using solar-powered, mobile hydrogen production plants.

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