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Review

Present and Projected Developments in Hydrogen Production: A Technological Review*

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ABSTRACT

Energy supplies that are safe, environmentally friendly, dependable, and cost-effective are important for society's long-term growth and improved living standards, though political, social, and economic barriers may inhibit their availability. Constantly increasing energy demand is induced by substantial population growth and economic development, putting an increasing strain on fossil fuel management and sustainability, which account for a major portion of this rising energy demand and, moreover, creates difficulties because of greenhouse gas emissions growth and the depletion of resources. Such impediments necessitate a global shift away from traditional energy sources and toward renewables. Aside from its traditional role, H_2 is viewed as a promising energy vector and is gaining international attention as a promising fuel path, as it provides numerous benefits in use case scenarios and, unlike other synthesized carbon-based fuels, could be carbon-free or perhaps even negative on a life-cycle criterion. Hydrogen (H_2) is one of the most significant chemical substances on earth and can be obtained as molecular dihydrogen through various techniques from both non-renewable and renewable sources. The drive of this paper is to deliver a technological overview of hydrogen production methods. The major challenges, development and research priorities, and potential prospects for H_2 production was discussed.

1. Introduction

Significant increases in energy demand are being driven by massive population growth and economic development around the world. Power generation is a vital component of any country's industrial revolution. Fossil fuels meet a sizable portion of the world's growing energy demand, but they face severe challenges due to rapid depletion. The main disadvantages of using these conventional methods (fossil fuels) are increased carbon dioxide (CO_2) emissions and global warming (Abouelfadl, 2012, Ugbeh Johnson et al., 2022). Because of obvious rise in environmental issues, renewable energy resources appear to be the most favourable source to replace these traditional resources. The global transition from traditional to renewable energy resources is a requirement for the global transition from fossil fuels to renewable energy resources (Ishaq, Dincer & Crawford, 2021). Renewable energy resources, such as geothermal, wind, solar, ocean thermal energy conversion (OTEC), hydro, and biomass, are the processes to replace fossil fuels (Uyar & Beşikci, 2017). The variable and uncertain nature of some desirable energy resources (renewable), such as wind and solar, means H_2 can fully utilise renewable energy resources and can be used not only as a fuel but as an energy carrier and storage medium. It can play a critical role in decarbonizing the dominant areas to achieve net-zero carbon dioxide emissions by 2050 (Ishaq, Dincer & Crawford, 2021).

Hydrogen H_2 is gaining popularity around the world as a unique energy source and possible future fuel as it professes carbon-free remedies (Ishaq, Dincer & Crawford, 2021, Tashie-Lewis & Nnabuife, 2021). By 2070, the global demand for H_2 is expected to reach more than 500 million metric tonnes. The transportation area is projected to become the largest consumer of H_2 as automobile companies are moving out from traditional combustion engines and, as a result, petroleum-based motor fuels (Madhumitha, 2021). By 2070, it is expected that the sector will require 158.2 million metric tonnes of H_2 as shown in Figure 1.

Furthermore, it is worth noting that current fuel transportation and storage facility that is employed for other fuels (chemical) can be used for H_2 transportation and storage (Ishaq, Dincer & Crawford, 2021). Various local resources can be employed to generate clean H_2, like natural gas (Schneider et al., 2020), coal gasification (Kopacz et al., 2016), nuclear power (El-Emam, Ozcan & Zamfirescu, 2020), and renewable energy resources like wind (Dinh et al., 2021), OTEC (Kazim, 2005, Ahmadi, Dincer & Rosen, 2015, Cai, 2016), solar (Sattler et al., 2017),

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Nomenclatures

ATR	Auto Thermal Reforming
ANL	Argonne National Laboratory
AGRs	Advanced Gas-cooled Reactors
EVA	Ethylvinyl Acetate.
EJ	ExaJoule, or 1018 joules
HTGRs	Helium-cooled high-Temperature Gas-cooled Reactors
HTGR	High Temperature Gas Reactor
GWP	Global Warming Potential
IEA	International Energy Agency
SMR	Steam Methane Reforming
HTES	High-Temperature Electrolysis of Steam
NG	Natural Gas
LWR	Light Water Reactor
S-AGR	Supercritical carbon dioxide Advanced Gas Reactor
SI	Sulfur Iodine
SOEC	Solid Oxide Electrolysis Cell
CuCl	Copper Chlorine
CCS	Carbon Capture and Storage
HHV	Higher Heating Value
OTEC	Ocean Thermal Energy Conversion
PSA	Pressure Swing Absorption
PEC	Photo-Electrochemical
POX	Partial Oxidation
WACC	Weighted Average Cost of Capital
WGS	Water Gas Shift

biomass (Shayan, Zare & Mirzaee, 2018), geothermal (Mahmoud et al., 2021), and hydro (Bødal & Korpås, 2020). The governments in most countries have enacted laws or policies to increase the number of renewable energy capacity installed by 2030. According to BloombergNEF's projections, 721 gigawatts of wind, biomass, solar, geothermal, and marine power plants will be needed to meet the targets over the next decade (Acar and Dincer, 2014). According to Ren21 United Nations Sustainable Development Goals (2020), fossil fuels account for 81.2 percent of global energy supply, with renewable energy sources (2.0 percent wind/solar, 9.3 percent biofuels, and 2.5 percent hydro) accounting for 13.8 percent and nuclear energy accounting for 4.9 percent. Several hydrogen-based projects have already received funding from all over the world. The Oyster consortium, for example, was awarded 5 million euros to research subsea hydrogen production (OYSTER, 2021).

Several reviews have been published that cover various aspects of hydrogen production (Mahmoud et al., 2021, Dahiya et al., 2021, Pal, Singh & Bhatnagar, 2021, Bhandari, Trudewind & Zapp, 2014, Boshagh, 2021, Habib et al., 2021, Siavash Moakhar et al., 2021, Naikoo et al., 2021, Li et al., 2021, Aziz, Darmawan & Juangsa, 2021, Shiva Kumar & Himabindu, 2019, Wang et al., 2014, Ji & Wang, 2021, Ahmad Kamaroddin et al., 2021, Vincent & Bessarabov, 2018, Agrafiotis et al., 2014, Acar & Dincer, 2019, Williams, 2021); see Table 1. However, several aspects have yet to be covered or thoroughly examined. Despite the fact that H_2 production is a technically proven technology, its further deployment is being hindered by some uncertainties and complexities. Furthermore, because H_2 production is a rapidly evolving field, recent progress, development needs, and future projections must be reviewed and discussed. A recent study (Ishaq & Dincer, 2021) compared various renewable-energy-based H_2 production approaches. A review by (Safari & Dincer, 2020) focused on thermochemical water-splitting cycles for H_2 production. Review work on the steam reforming process (SMR) for H_2 production was published, as well as a detailed economic analysis, to provide an economic and environmental assessment for H_2 production using various feedstocks, such as biogas, natural gas, biomass, and ethanol (Kaiwen, Bin & Tao, 2018). A review on solar thermal methane reforming for H_2 and syngas production was published (Agrafiotis et al., 2014). Solar-based steam methane reforming has been proposed as a viable and feasible way to create a transition to a solar H_2 economy and fossil fuel decarbonization. A review of solar reactors at each scale was presented, along with recommendations for future research. Based on H_2 production approaches, current research work carried out an environmental impact valuation and comparative study of non-renewable and renewable sources (Acar & Dincer, 2014). They investigated and compared the performance of various hydrogen production methods, as well as assessed the social, economic, and environmental implications. Coal gasification, natural gas reforming, biomass gasification, wind and solar, S–I cycles, thermochemical CuCl cycles, and electrolysis (high-temperature) were among

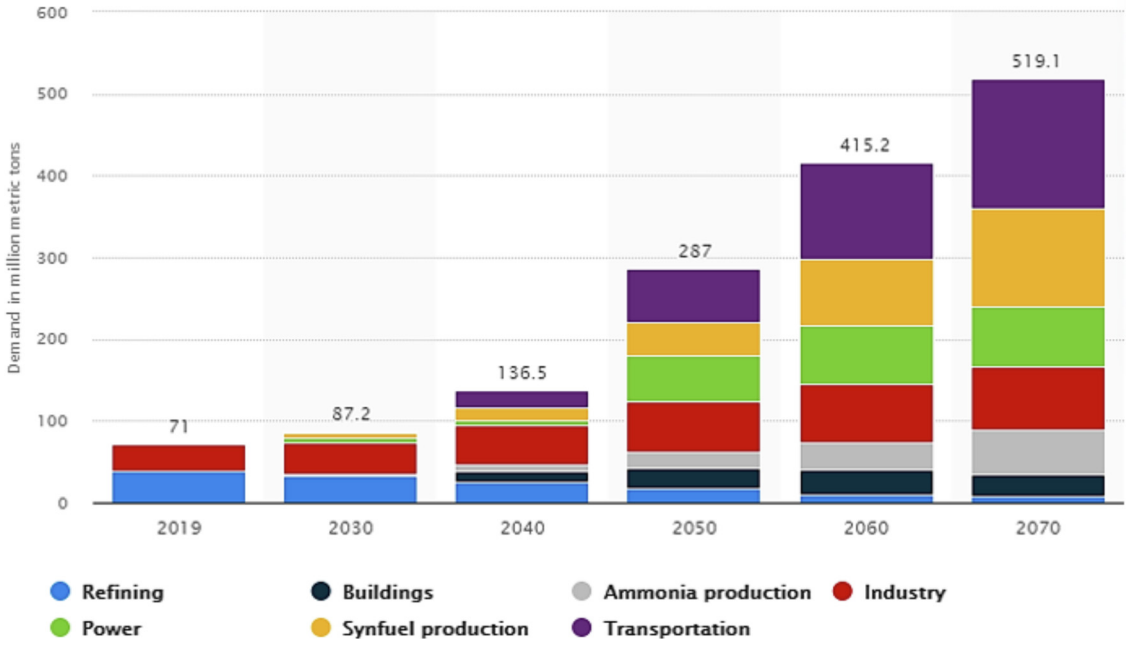


Figure 1. From 2019 to 2070, forecast global H_2 demand by sector in a sustainable growth scenario (in million metric tons)[6].

Table 1
Summary of review studies on hydrogen production.

Ref.	Review scopes	Comments/Results
(Zhang et al., 2019)	This study examines the major exergy factors, which include feedstock characteristics, gasification temperature, biomass concentration, reactor pressure, residence time, and reaction catalyst.	The energy efficiency gains of hydrogen production, according to the findings, are primarily in the 0.04–42.05 percent range. Biomass feedstock may have an impact on H_2 production by altering the H_2 yield and heating value of biomass. Increments in biomass concentrations reduce energy efficiency, while increases in gasification temperatures usually increase energy efficiency. Finally, increases in residence times may increase substantially, which would then decrease energy efficiencies.
(Cao et al., 2020)	This article examines the two most widely used biomass-to-H_2 techniques and emphasises the importance of operating conditions and factors in the catalytic structure design.	The critical problems for biomass H_2 production is to realise the scalability and controllability of the production process, enhance the efficiency and the reaction rate, reduce production costs, and speed up the industrial development process.
(Rashid et al., 2015)	The impacts of energy requirement, temperature, process efficiency, practical cell voltage, and pressure on the potential kinetics of H_2 production, as well as the impact of electrode materials on conventional H_2O electrolysis for high temperature electrolysis, alkaline electrolysis, and PEM electrolysis, are investigated in this review paper.	Water electrolysis has a low share of the H_2 production market due to its maintenance demand, stability, low efficiency, and low durability when compared to other existing technologies.
(Safari & Dincer, 2020)	Various hydrogen production methods via hybrid and thermochemical cycles are discussed and compared in this study, comprising two-step Zn0 (Zinc oxide), three-step S-I (Sulfur-Iodine), four-step $MgCl_2$ (Magnesium-Chlorine), $FeCl_3$ (Iron-Chlorine), and $Cucl_2$ (Copper-Chlorine.	According to a comparison analysis, vanadium-chloride has the utmost energy efficiency of 77 percent, while the sulfur-iodine and hybrid sulphur cycles are the most favourable in terms of GWP, with GWPs of 0.50 and 0.48 kg CO_2/kg hydrogen, respectively.
(Chen et al., 2020)	In this review, the authors summarised the major characteristics of the SMR process's catalyst and reaction engineering and evaluated them by comparing them to its derivative techniques, such as partial oxidation with O_2, dry reforming with CO_2 (DRM), and autothermal reforming with O_2 and H_2O.	SMR is still a complex reaction process that could be improved in terms of operational engineering and catalyst design.
(Bundhoo, 2019)	On a global scale, this study estimated the potential for bio-H_2 production from dark fermentation of crop residues.	According to published bio-hydrogen yields, untreated rice straw has the highest estimated global bio-hydrogen potential at 58,002 Mm^3/year, followed by untreated wheat straw at 34680 Mm^3/year. This equates to a raw rice straw bio-energy potential of 623 PJ/year and a wheat straw bio-energy potential of 373 PJ/year, whereas pre-treatment of crop residues greatly increases the bio-energy and bio-hydrogen potential. However dark fermentation of crop residues has a large bio-energy potential, it is limited by a number of constraints. As a result, combining the dark fermentation and anaerobic digestion processes into a two-stage process appears to be the most cost-effective choice for large applications.
(Yukesh Kannah et al., 2021)	The sensitivity overview of various hydrogen production processes, including gasification, pyrolysis, water electrolysis, dark fermentation, natural gas steam reforming, photobiolysis, and renewable liquid reforming, was examined in order to assess their benefits, drawbacks, and cost-effectiveness.	In terms of economics, natural gas steam reforming is the most efficient, low-cost method of producing H_2.

the methods considered. The environmental impacts of the methods are determined and compared with regards to acidification potential, global warming potential, as well as exergetic and energetic efficiencies and production costs. In a recent study, life cycle assessments were carried out for a variety of H_2 production methods (Ji & Wang, 2021).

This research presents a technological review of H_2 production approaches such as nuclear energy, electrolysis, coal conversion, natural gas reforming, biomass, wind energy, solar energy, and biological processes, as well as the major challenges and R&D priorities. The ever-increasing interest in H_2 applications necessitates a thorough examination of H_2 production and future prospects Table 2. shows some studies on H_2 production processes.

In writing this review paper, we started with existing resources and specific methods like natural gas reforming, thermochemical cycles, coal, and H_2O electrolysis for hydrogen production, as well as technological developments in hydrogen systems. This paper also offers a vital and relevant source for technological advancement, and research in the fields of H_2 production and utilisation. The literature that was reviewed was chosen based on specific keywords.

2. Methods of producing hydrogen

Hydrogen (H_2) can be produced through a various of means, including solar energy, nuclear energy, electrolysis, coal conversion, natural gas reforming, wind energy, biomass, and biological processes (Dahiya et al., 2021, Zhang et al., 2018, Wang et al., 2019, Wismann et al., 2019, Castelló et al., 2020, Wu & Williams, 2009, Wu et al., 2013, Wu & Williams, 2011, Masoudi Soltani et al., 2021). Currently, almost all H_2 is produced through the water electrolysis or steam reformation of methane. The biological production of bio-hydrogen using microorganisms is a technological advancement that has the potential to produce renewable H_2 from biomass. Steam reforming, partial oxidation, and gasification are all thermocatalytic processes used to produce H_2. A description of the diverse processing techniques and feedstocks is provided in Figure 2. A short description of each current technology; key technological issues; potential advancements for future technology, where possible; and the feasible benefits and drawbacks of employing the techniques for H_2 production, along with recommendations, will be highlighted.

2.1. Nuclear Energy

Without emitting any CO_2, H_2 can be produced by employing reactors for H_2O splitting via thermochemical or electrolysis methods. Hydrogen production could be made more efficient by significantly increasing the temperature of the H_2O before splitting its molecules via electrolysis or thermochemistry. Such methods necessitate temperatures ranging from 700–1000°C. Existing near-term, H_2O-cooled

Table 2
Selected studies on hydrogen production methods.

References	Research focus	Approach used	Results
(Chen et al., 2019)	Environmental and thermodynamic analysis of embedded coal supercritical water gasification for H_2 production	Life cycle analysis and thermodynamic analysis.	The waste heat of the effluent from the heat exchanger causes the greatest energy loss, according to the findings. The organic Rankine cycle can achieve 53.3 percent energy efficiency when the coal and temperature concentrations are 700°C and 15 wt%, respectively.
(Ishaq & Dincer, 2019)	solar energy-based autothermal and steam combined reforming systems with natural gas.	Carbon emission and cost analyses, as well as study of multi-objective optimization.	Energy and energy efficiency were found to be 59.1% and 31.1 percent, respectively.
(Wang, Lu & Zhong, 2021)	Catalysts' role in hydrogen production from water electrolysis	Systematic details in terms of catalysts' morphology, composition, structure, active sites, and their correlation	The activity of the catalysts was found to be composition-dependent, with a maximum oxygen evolution reaction activity for an Au:Co ratio of 2:3
(Zhang & Wan, 2014)	Modeling a wind-H_2 energy storage system for wind energy curtailment	It is based on real-time data in terms of a 10-minute average over a year in a wind farm.	The SRP integration modelling process was observed to be flexible than using separate CFD models, and it can be applied to industrial furnace reformer tubes.
(Acar & Dincer, 2019)	Options for hydrogen production review	Environmental and reliability, as well as economic, social, and technical performance.	Among the selected hydrogen production sources, solar technique has the best environmental efficiency (8/10) and the highest overall average ranking 7.40/10 nuclear power has the worst environmental efficiency 3/10, and geothermal has the lowest overall average ranking (4/10/10) .
(Iribarren et al., 2014)	Hydrogen production from lignocellulosic biomass gasification	A base-case system for H_2 production via biomass gasification was defined based on a review of technological options, and its environmental and thermodynamic performance was assessed using a life cycle assessment and an exergetic analysis.	The total energy loss of the plant (primarily due to flue gas streams) was found to be 4.6% of the overall energy, while 47 percent of the total energy vanishes due to energy destruction within the plant's specific components.

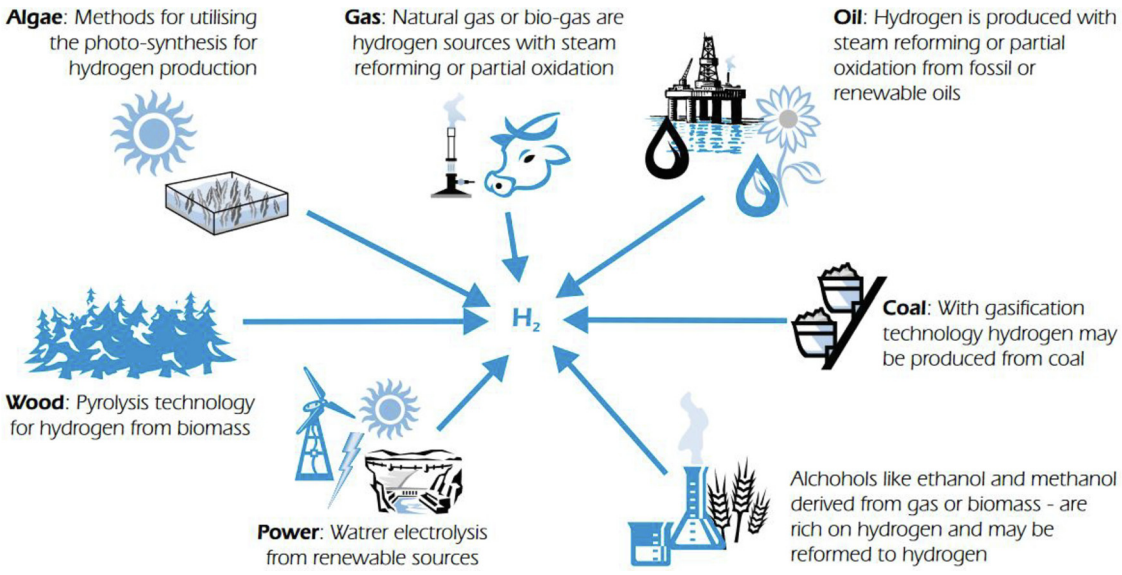


Figure 2. Selected technology options and feedstocks.

ALWRs and LWRs produce temperatures below 350°C and thus cannot be employed for such applications. Though, other coolants for different Generation IV reactor purposes have been developed to achieve high-temperatures (>700°C) and may be coupled to thermochemical plants (Forsberg, 2003). According to a new article by the Electric Power Research Institute, using nuclear reactors to supply the heat required in the SMR process could be more cost-effective than using them for H_2O splitting (Chen et al., 2020). Nuclear-based SMR would minimise the application of natural gas in the process as well as carbon dioxide emissions Table 3. compares the different possibilities for nuclear H_2 production.

2.1.1. Steam Electrolysis at High Temperatures

The rate of energy (thermal) demand is adjusted via a reduction in electrical energy demand, which optimizes thermal-to-H_2O heat performance. Increased temperatures aid in the reduction of anodic and cathodic over-voltages. As a result, higher temperature electrolysis of steam (HTES) is beneficial from both a thermodynamic and a kinetic perspective (Yildiz & Kazimi, 2006). The system efficiency of HTES appears to be less temperature-sensitive than thermochemical approach. However, much more research into the technology is required. The reliability of the electrolyte and electrode materials is unknown and should be investigated. Furthermore, high pressure increases the required overvoltage while decreasing the size of the transmission lines and chemical units. The size of the electrolysis cell scale-up should be sought (Kalyva et al., 2015).

2.1.2. Thermochemical reactions

A current test of hundreds of potential reactions identified two specific thermochemical cycles for producing H_2 from H_2O (processes that allow chemical reactions to occur at high temperatures) with highly efficient and potential usefulness to nuclear heat sources. The calcium-bromine-iron (Ca-Br) and sulfur-iodine (S-I) cycles are examples of these. The CuCl thermochemical cycle has also been identified for this purpose by Argonne National Laboratory (ANL)

Table 3
A Synopsis of Nuclear Hydrogen Production Alternatives (Yildiz & Kazimi, 2006).

Features	Methods			
	Electrolysis		Thermochemistry	
	H_2O	High-Temperature Steam	CH_4 Reforming	H_2O Splitting
Temperature required (°C)	>0	>300 for LWR >600 for Cu-Cl cycle	>700	>850 for S-I cycle >600 for S-AGR
Chemical process efficiency (%)	75–80	85-80	70–80	>45, depending on the temperature
Coupled to LWR efficiency (%)	27	30	Not viable	Not viable
Coupled to AHTR, HTGR, or S-AGR efficiency (%)	Less than 40	40–60, depending on the temperature	>70	40–60, depending on the temperature and cycle.
Benefits	Proven and tested process with LWRs	It can be linked to reactors that operate at intermediate temperatures.	Proven	CO_2 emissions are eliminated.
			CO_2emissions are reduced by 40%.	
	Removes CO_2 emissions,	Eradicates CO_2 emissions		
Draw-backs	Low efficiency	High-temperature reactors are required.	CO_2 emissions are not eliminated	Complex chemistry
		Requires durable HTES unit development.	Based on methane prices	Needs development

(El-Emam, Ozcan & Zamfirescu, 2020). A sulfur-based hybrid method that does not need iodine and has a single electrochemical step (Juárez-Martínez et al., 2021). Researchers at Westinghouse have proposed a sulfur-based hybrid technique that does not need iodine and uses a single electrochemical low-temperature step for H_2 production and reforming sulfuric acid. The low-voltage electrolysis process (low frequency compared to water electrolysis) could enable much more substantial electrochemical cell levels. These reactions require temperatures that are typically larger than those provided by ALWRs and LWRs. Various GEN IV reactors, however, can deliver the required high temperatures and heat. The temperature (> 700°C) would allow nuclear heat to be used in conjunction with the SMR techniques (Juárez-Martínez et al., 2021). Higher temperatures would improve reaction efficiencies.

2.1.3. Advanced Nuclear Reactor Technologies

Numerous elements of nuclear energy technological advances for the generation of electricity are beneficial for producing H_2 but not covered in this paper. Amongst these is the design of high-temperature reactors capable of providing coolants at temperatures exceeding 800°C. This appears to be most easily accomplished with the helium-cooled gas reactor technique of high temperature gas-cooled reactors (HTGRs). The effects of irradiation at higher temperatures must be investigated. The helium power cycle's operation and control at extremely increased temperatures have yet to be proved. The advancement of a supercritical carbon dioxide power cycle should be prioritised. It may be possible to achieve high-power cycle efficiencies at reduced temperatures than helium gas turbines (Kersten et al., 2021). This will benefit the high-temperature electrolysis method.

- Preferences for development and research in nuclear H_2 production include the following:
  Steam electrolysis (High-temperature) method should be further developed. The following concerns should be looked into: overvoltage reduction, safe and efficient separation of gas products, the durability of electrolytes and electrodes, as well as the effects of operating pressure.
- The improvement of thermochemical techniques for accomplishing H_2O splitting without carbon dioxide emissions ought to be investigated at the laboratory scale for viable cycles such as the S-I cycles. Materials discrepancies at high temperatures, determining the efficiency of the integrated processes, catalysts to improve the reaction at low temperatures, and the way to optimise it via cautious thermal management of mass flows and heat should be included in the R&D programme.
- The advancement of a supercritical carbon dioxide cycle should be prioritised. It can be used directly with a CO_2–cooled reactor like the AGR or indirectly with other reactors like the HTGR. It could be the bottoming cycle for a high-temperature reactor, whose coolant would supply heat to a thermochemical plant at higher temperatures. To validate the cycle thermodynamics, thermal conversion performance for a moderate-size compressor and turbine (in the MWe range) must be demonstrated.

2.1.4. Nuclear hydrogen production plants cost

The cost of producing hydrogen using electricity produced from established nuclear power via water electrolysis is similar to using grid electricity to produce hydrogen. With natural gas prices at $4.5/million Btu today, even when the cost of hydrogen delivery is factored in, this cost is about a factor of three higher than what traditional SMR can achieve. In the future, the advanced power efficiencies of highly developed nuclear power plants may reduce this cost differential to a factor of 1.5 (Yildiz & Kazimi, 2006). The value of hydrogen production via MHR-SMR is determined by the price of natural gas raw materials for the reforming process. On the other hand, MHR-SMR is less sensitive to natural gas prices than standard SMR. The work of (Yildiz & Kazimi, 2006) estimates that if natural gas prices rise above $6/million Btu, this approach may be cost competitive with traditional SMR. However, no taxes or fees for CO_2 production were included in their analyses.

The cost of producing hydrogen by the nth-of-a-kind of MHR utilising the SI process was studied by (J Brown et al., 2003). The authors determined the cost of producing 800 t of hydrogen per day by utilising heat from four 600 MWth units, each producing a coolant at 850°C and having a 42% efficiency level. Beginning with an overnight cost of $470/MWth for the nuclear electric plant, adding a heat exchanger, and replacing the electrical generating capacity with a thermochemical plant resulted in a total plant capital cost of around $750/MWth. According to a comprehensive article on the costs of nuclear power at notable plants built in the last ten years in Finland, Korea, and Japan, the overnight costs of plants range from $530 to $800/MWh (Sadekin et al., 2019). The annual operating costs of the MHR nuclear plant are projected to be $93.9 million, while the annual operating costs of the hydrogen plant are $50.7 million. As a result, the cost of producing hydrogen is around $1.50/kg. Hence, one could claim that future changes will make it easier to achieve optimum results in the conversion of nuclear thermal energy to hydrogen production. Moreover, having more units in one location could lead to reduced costs. Therefore, larger plants may well be linked to lower plant and operational costs. Utilising idealistic assumptions about recent advancements in nuclear plant development and thermo-

chemical plant performance, the cost of a 1200 t/day MHR-SI hydrogen plant could be postulated to attain $600/MWth as the technology evolves (Sadekin et al., 2019). Adding the normal contingency and permitting costs could add approximately one-third to this cost, leading to a more efficient plant projected cost of $800/MWth and, assuming a three-year construction time, a hydrogen cost of production of around $1.60/kg.

2.2. Coal conversion

Coal is a feasible alternative for producing H_2 in large, centralised plants when demand for H_2 is sufficient enough to cover a huge distribution facility. The States (USA) have loads of coal to produce all of the H_2 required by the economy for the next 200 years. Significant coal facilities have already emerged, commercial technology solutions for processing coal to H_2 are available from a variety of licensors, the price of H_2 derived from coal is one of the cheapest obtainable, and technology advancements are being established to meet future financial objectives. The main factor to consider would be that the emissions of CO_2 from producing H_2 from coal are relatively high when compared to other methods of producing H_2. This emphasises the importance of developing carbon sequestration strategies capable of handling huge number of carbon dioxide before the extensive application of coal to produce H_2 is achieved.

2.2.1. Coal Transportation

If coal is to become a significant source of potential hydrogen production, the system for supplying it to future hydrogen plants must be developed to satisfy these future demands. The existing production and delivery system capacity would have to be enhanced by 11% to meet 2030 hydrogen demand and by 57% to meet 2050 hydrogen demand (Ekmann & Le, 2014). When the demand for hydrogen grows strong enough to accommodate an associated transport, storage, and delivery system, coal becomes a feasible alternative for producing hydrogen in sizable central station plants.

The majority of bulk coal transportation is done by rail, with trucks used mostly for local transportation. For commercial gain, the majority of the world's coal consumption occurs in power plants situated close to coal mines, reducing the need for lengthy transportation. More than 60% of the coal being used for power generation in the world is consumed within 50 kilometres of the mine site (Ekmann & Le, 2014). The average distance travelled by rail in the United States is approximately 800 miles. This distance has grown in recent years as a result of the rising use of coal with lower sulphur content to meet sulphur oxide emissions standards in plants primarily located in the South and East (Ekmann & Le, 2014). Because coal is reportedly shipped over long distances in the United States, shipment to wide geographical areas should not be a constraint to the use of coal to produce hydrogen for at least the next three decades, as demand will not differ significantly from recent trends.

2.2.2. Coal Technologies in Use Today

In traditional coal fired power generation, a combustion boiler heats H_2O to generate steam and then uses it to power an expansion generator and a steam turbine. (Wang et al., 2017). There are different architectures of coal combustion boilers, the utmost reliable and advanced of which use pulverised coal to generate supercritical (high-temperature and high pressure) steam (Lockwood, 2017). Cumulative efficiencies are usually in the 36-40% range. Despite being a power generation staple for decades, this traditional combustion approach is unsuitable for producing H_2. Hydrogen-generation technologies use a conversion method rather than a combustion process. These conversion processes, like gasification, are suitable for producing power and/or H_2.

2.2.3. Technologies for Clean Coal

Clean coal technology solutions employ alternative means of converting coal to increase thermal efficiency and decrease emissions, resulting in a substantial cost of electricity that is cheaper than the cost of electricity from traditional plants. The integrated gasification combined cycle (IGCC), high-performance power systems (HIPPSs), and pressurised fluidized-bed combustion (PFBC) are among the systems currently under development (Lockwood, 2017). The target range is 55–60% HHV (higher heating value). All of the others, except the IGCC systems, depend on highly advanced emissions control facilities; the IGCC system employs a distinct conversion system that reduces emissions from the start. This gasification process is ideal for producing H_2 from coal (Lockwood, 2017).

2.2.4. Gasification Processes

Gasification processes usually require POX of coal with steam and oxygen in a high-pressure, high temperature reactor (Cormos et al., 2008). The short-duration reaction occurs in a significantly reducing atmosphere, producing a synthesis gas composed primarily of H_2 and CO with some steam and carbon dioxide (CO_2) (Kopacz et al., 2016). This syngas could be further shifted to increase H_2 production. The gas can be cleaned conventionally to recover elemental sulphur (or to produce sulfuric acid), and a high-concentration CO_2 stream can be easily separated and sent for disposal (Kaplan & Kopacz, 2020). The application of high temperatures, pressures, and O_2 reduces NO_x production. The ash and slag drawn from the reactor's bottom encompass heavy metals in a vitreous, inert material that is presently used as road fill. Increased temperature inhibits the formation of organic materials, and syngas processing removes more than 90% of the mercury. Syngas produced by existing gasification plants is being deployed in a wide range of processes, often from a single facility. Syngas is utilised as feedstock for fertilisers and chemicals. Syngas converted to H_2 is employed mostly for hydroprocessing in production and refineries. Among these applications are electricity generation via syngas combustion in a gas turbine and extra heat recovery steam generation via a combined cycle architecture. At least 111 gasification plants are currently in operation, using a wide range of feedstocks. The residual oils from crude oil refining, petroleum coke, and, to a limited extent, coal are examples of these. The syngas produced has commonly been used to manufacture successive chemicals; producing power from IGCC is a new invention, effectively established in the mid-1980s and operating commercially since the mid-1990s. As a result, gasification is a proven and established commercial processing technique (Nikolaidis & Poullikkas, 2017), with several companies offering licences to use it.

There are gasification plants that employs either an air-blown or an O_2-blown structure. Although the air-blown approach reduces the operating and capital costs of air separation facilities, the dilution of combustion products with N_2 makes CO_2 separation more complex and expensive process. Furthermore, the increased volume of inert nitrogen flowing across the plant expands vessel sizes and raises downstream equipment costs. Because O_2-blown options do not add extra N_2, once the sulphur compounds are eliminated from the syngas, what remains is a high-purity stream of carbon dioxide that could be separated quite quickly and effectively. Due to the requirement to investigate sequestration and CO_2 capture for future H_2 generation plants, only O_2-blown models are viable for evaluation. (Long & Wang, 2016).

2.2.5. Development and research preference for hydrogen production through coal conversion

Coal gasification is not an advanced commercial technique compared to the coal combustion approach and various H_2 generation mechanisms using other fossil fuels, mostly in terms of carbon dioxide capture and durability in electricity and hydrogen production. In this regard, the possibilities for development via technological advancement are important. The major concerns are capital costs and dependability (Normally, this is resolved by including backup devices). Both are significant rationale while IGCC techniques have not been broadly accepted for power generation in a highly competitive industry. The ability to switch between power and H_2 production will require additional capital, which must be recovered.

For commercial techniques available from a variety of licensors, researchers should focus on capital reduction techniques, gas cooler designs, standardization of plant design and execution concepts, oxygen plant enhancement, process integration, and acid gas elimination techniques. The significant improvements in performance and capital costs in these aspects can even merge to decrease the cost and maximise the efficiency of H_2 from coal by 10 to 15% from current levels. Because many components of the coal-to-H_2 method are similar to those used in coal-to-power systems, IGCC should be able to achieve similar reductions in power costs. These aspects are significant advancements to current technologies, so they should be achievable in the near future.

There is also the possibility that new technologies will improve the cost and efficiency of producing H_2 from coal. The best R & D opportunities for new gasification technologies seem to be for novel reactor designs (i.e entrained bed gasification), purification strategies, and enhanced gas separation. These technologies, as well as the principle of integrating them, are in their early stages of advancement and will need more time to validate their true potential and achieve commercial readiness. According to recent studies, the combined capacity of these novel techniques could reduce the cost of producing H_2 from coal by approximately 25%.

2.3. Natural gas reforming

Natural gas is a cost-efficient and effective feed for H_2 production when compared to other fossil fuels, in part since it is readily obtainable, simple to manage, and has a high H_2-to-carbon ratio, which reduces the formation of byproduct CO_2 (Fan et al., 2020). Natural gas is being imported into the States as LNG (liquefied natural gas), and imports are expected to increase. As a result, increasing the application of natural gas in a H_2 economy would only upsurge imports. As a consequence, natural gas is viewed as a transitional fuel for distributed generation units rather than a long-term fuel for central power plants in the H_2 economy. The basic methods for converting natural gas, primarily methane, to H_2 involve sequential reactions with either steam (steam reforming) (Faheem et al., 2021, Wang et al., 2019, Nguyen et al., 2019, El Hajj Chehade et al., 2020), O_2 (partial oxidation) (Lutz et al., 2004), or both (autothermal reforming) (Faheem et al., 2021). In practise, gas mixtures containing carbon dioxide, carbon monoxide (CO), and unprocessed CH_4 are produced and must be processed further. The reaction of CO with steam (H_2O-gas shift) over a catalyst produces extra H_2 and CO, and high-purity H_2 is recovered after purification. Carbon dioxide (CO_2) is currently vented to the atmosphere in most cases, but there are options for capturing it in centralised plants for subsequent sequestration (Antonini et al., 2020). The cost of sequestration seems to be prohibitive for distributed generation. Carbon dioxide (CO_2) emissions from distributed generation plants may be unavoidable during the transition to a H_2 economy except a substitute, such as hydrolysis with renewable electricity, becomes adequately appealing or researchers (R & D) considerably enhances distributed natural gas production processes.

During the transition, natural gas distributed generation appears to be the utmost cost-effective alternative for H_2 production. Although, it has never been done in a way that meets all of the unique necessities of this application. The primary issue is to create a H_2 appliance that can be mass-produced and operated in service stations safely with only periodic supervision by unskilled or semi-skilled personnel (El Hajj Chehade et al., 2020). The ability to mass-produce is required to meet demand during the transition when thousands of these units will be required, as well as to reduce manufacturing expenses. These units must be produced to maximise operating proficiency and include the controls, "turndown" capacity, and H_2 storage needed to achieve the variable demand for H_2 over 24 hours. In addition, they must be developed to accommodate the H_2 purity specifications of fuel cells. For this application, steam reforming process system is available, and companies have indeed produced distinct units in the desired size range. Whether auto-thermal reforming or POX can be used for distributed H_2 generation seems to be dependent on the development of new methods for recovering O_2 from air or splitting product H_2 from N_2 (Faheem et al., 2021). This is required since conventional cryogenic air separation becomes highly costly as unit size is reduced. Membrane separations, on the other hand, appear to be feasible for this application and could provide a way of generating small, cost-effective hydrogen units.

- There is currently limited demand for mass-produced H_2 devices, and the design of these devices should be encouraged. The top issues are the creation and establishment of the following:
  A mass-produced H_2 device designed for distributed generation in fueling stations, as well as
- a reliable H_2 scheme for fueling stations able of achieving varying H_2 demand seven days a week.

The main mechanisms for converting natural gas, primarily methane, to H_2 require reactions involving either partial oxidation, steam reforming, or both in cascading (auto-thermal) reforming. The following are the general reactions:

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

$$CH_4 + O_2 \rightarrow CO_2 + 2H_2$$

In practise, gas mixtures usually containing CO, CO_2, and unprocessed CH_4 are produced and must be processed further. The reaction of CO with steam (H_2O-gas shift) over a catalyst produces extra H_2 and CO_2, and high-purity H_2 is recovered after purification. Carbon dioxide CO is currently released into the atmosphere in most cases, but there are methods for capturing it for constant sequestration. The global production of H_2 is approximately 41 million tonnes per year. Because SMR accounts for more than 80% of this production.

2.3.1. Steam methane reforming

The steam methane reforming process consists of four primary phases (Figure 3). To remove sulphur compounds, natural gas is first catalytically treated with H_2. It is then reformed by passing it through a nickel-on-alumina catalyst while being mixed with steam (Faheem et al., 2021). This produces CO_2 and H_2. The CO is then converted to H_2 and CO_2 via a catalytic H_2O-gas shift. Finally, pressure swing adsorption (PSA) is utilised to purify the H_2. gas. The PSA reject stream is used to make a portion of the fuel that is burned in the reformer to provide the necessary heat energy. As a result, CO_2 from the PSA reject gas is currently vented along with the flue gas (Nguyen et al., 2019). A separation process would be added to capture the CO_2 if it were to be sequestered.

The following are the reforming reactions:

$$CH_4 + H_2O \rightarrow CO{+}3H_2$$

$$CO + H_2O \rightarrow CO_2 + H_2 \text{ (water-gas-shift reaction)}$$

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

The reaction of natural gas with steam to produce CO and H_2 necessitates a significant number of heat (206 kJ/mol CH_4). This heat is currently added in commercial practise by utilising fired furnaces with tubular reactors packed with catalysts.

2.3.2. Partial oxidation

Natural gas is partially oxidised with oxygen in a high-pressure, refractory-lined reactor. The O_2-to-carbon ratio is strictly managed to maximise H_2 and CO yield while keeping an adequate level of residual methane and CO_2 and minimising soot formation. A downstream facility is provided to eliminate the large number of heat produced by the oxidation reaction, convert CO to H_2, eliminate CO_2 that could be sequestered, and purify the H_2 product (Jahromi et al., 2022). Of course,

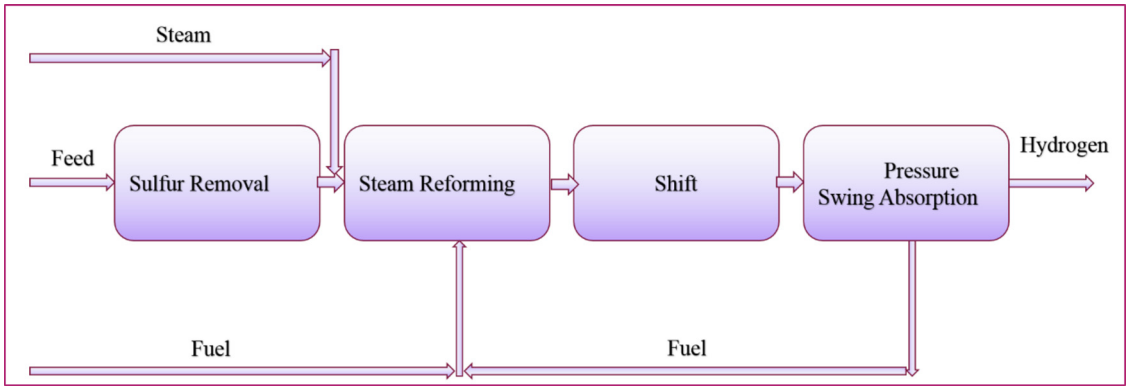


Figure 3. The steam methane reforming process schematic presentation.

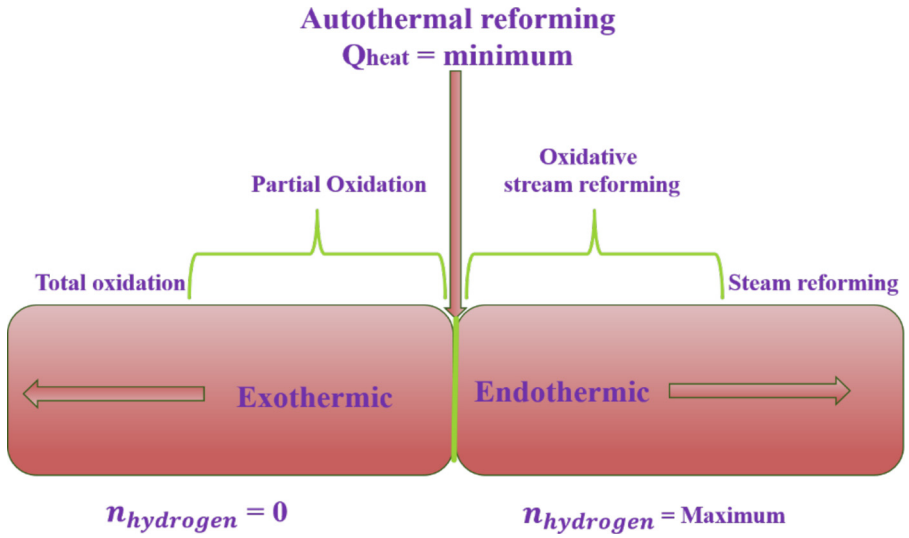


Figure 4. Operating conditions for Partial oxidation, steam reforming, and autothermal reforming (Lee, Lee and Hwang, 2019).

this process necessitates the presence of an O_2 source, which is normally provided by incorporating an air separation plant. Conversely, air can be used in place of O_2, and the product H_2 can be recovered from N_2 and other gases via palladium diffusion. Partially oxidation can also occur in the presence of an oxidation catalyst, which is known as catalytic partial oxidation (POX) (Wang et al., 2019).

2.3.3. Auto-thermal reforming

SMR is known to be endothermic, and are often employed industrially to meet the optimum heat input. When steam and O_2 are employed for the conversion and integrated with SMR in autothermal reforming (ATR), the necessary heat input can be met by partial methane combustion (Kim et al., 2021). The reformer is made up of a ceramic-lined reactor with a fixed-bed catalytic and combustion SMR zone after that. The heat produced in the combustion zone is transferred directly to the catalytic zone by the flowing reaction gas mixture, providing the heat required for the endothermic reforming reaction. Presently, ATR is primarily utilised for large conversion units. Secondary reforming is one of several patterns that integrate direct catalytic conversion and oxygen injection. It has been proposed that converting methane to elemental carbon and H_2 might be an appealing option, but this is unlikely. Such a process would result in a significant number of carbon by-product and <60% of the combined heat of combustion of the H_2 and carbon products is linked with the H_2 (Carapellucci & Giordano, 2020). Applications for a large amount of carbon must be found for this approach to become a feasible alternative Figure 4. depicts the operational range of a fuel processor for H_2 production.

2.3.4. The current natural gas conversion process

The SMR (steam methane reforming) is a popular technique for producing H_2 and synthesis gas around the world. The produced gas is employed to manufacture chemicals such as NH_3 and CH_3OH, as well as to enhance metals, electronic materials, petroleum, and to process food components. Natural gas SMR produces approximately 32 million tonnes of H_2 per year (t/yr) (80 million kg/day). Today, H_2 is also produced through ATR and partial oxidation. The extensive industrial experience gained from this productive capacity has resulted in numerous technological advancements, lowering costs and increasing efficiency. The tubular reactor in which the SMR reaction takes place is perhaps the most important component. Feedstock flexibility, higher tube wall temperatures, and better control of carbon formation have all resulted from progress. This progress resulted in lower steam-to-carbon ratios and higher efficiency. The H_2O-gas-shift unit has been optimised, and at different temperatures, a one-step shift can now be used instead of the previous two-step operation. Lastly, the H_2 product's purification has been streamlined by utilising PSA to remove CO_2, trace impurities, and methane in a single phase. While most present patterns do not include CO_2 capture, technology is now available to do so. An industrial selective absorption technique could be used to recover carbon dioxide for successive sequestration.

There has been advancement in the design and construction of bigger SMR systems. Single-train commercial plants with capacities of up to 480 000 kg H_2,per day200 million standard cubic feet per day (scf/d) are currently being developed, and even bigger plants can be built employing multiple trains. Smaller units, such as 300 kg/day, are being de-

veloped. In most cases, the units developed are incredible, with unique features designed to achieve the needs of a specific application, site, or user. At least one company is building commercial SMR H_2 plants as small as 300 kg/day with fixed-design units, which is one of the elements of mass production.

Natural gas-based partial oxidation is fully developed and commercially utilised. Because of economics, most commercial units today use lesser-value feeds than natural gas, like petroleum residues, coke, coal, or other byproducts. Moreover, from a technical standpoint, natural gas is a desired feed for POX, which can be employed to produce H_2 where competitive.

Today, larger units that produce a mixture of CO and H_2 for the Fischer-Tropsch process, or CO_3OH synthesis, use oxy-blown ATR with natural gas. This is appealing in part since the units can generate the required H_2-CO ratio during the synthesis step. Because the heat of reaction is added by combustion with O_2, the catalyst can be integrated as a fixed bed that can be scaled up to achieve significant advantages of plant size in both the ATR and the requisite plant. When CO_2 capture is included, ATR provides additional benefits. This is because the best separation process for this design recovers carbon dioxide at 3 atmospheres (atm), lowering the cost of compression to pipeline pressure (75 atm).

To summarize, all three methods ATR, SMR, and POX are advanced techniques for converting natural gas to H_2 today. Except for a large units, where ATR has an added benefit, SMR is less expensive than ATR. When the energy for air separation is factored in, SMR is relatively more stable and efficient. The POX has the benefit of being employed to lower-quality feeds such as petroleum coke, but this is unrelated to natural gas conversion.

2.3.5. Projected advancement of natural gas conversion plants

Considering the prevailing interest in H_2 economy promises and the present commercial demand for H_2, massive attention is being directed toward advancing natural gas conversion to H_2. Enhancements to catalysts and building materials, new separation processes, reactor concepts and process simplification which could enhance the integration of POX and steam reforming are all being researched. Catalytic POX is also being investigated. Because SMR and POX are mature techniques, the major possibilities for advancement involve developing cost-effective and efficient designs for specific applications. Numerous distributed generators will be required for the H_2 economy, and the cost of these generators should be drastically reduced via mass production of a generation "appliance." Such appliances can be improved more by customising the design to the fuel application. The H_2 compression costs would be reduced while efficiency would be improved if the conversion reactor pressure could be increased.

Appropriate, cost-effective H_2 purification techniques for distributed generators utilising ATR or POX must be established. Conversely, in such cases, there may be possibly appealing prospects to recover the required O_2 using membranes and thereby reduce the cost. Other principles are in the explorative research phase as well. These include novel or improved methods of supplying the endothermic heat of steam reforming or utilising the heat of reaction in POX. In the next 5 to 10 years, new, lower-cost designs for distributed generation are likely to progress to the commercial prototype stage. Several of these significant improvements may apply to large plants.

2.3.6. Research and development priorities for natural gas conversion

During the transition, distributed hydrogen generation from natural gas in fueling systems could be the most cost-effective possibility for H_2 production. Though, the potential cost of this alternative is indeterminate considering the engineering and technical uncertainties and specific considerations that require special attention.

The envisioned distributed generation of H_2 has never been realised because of these specific requirements:

- Mass production of large numbers of generating units is required to meet market pressure, lead to significant savings, and increase productivity; and
- unit operating and design processes that guarantee the safe and reliable operation of this equipment with only periodic monitoring by unskilled or semi-skilled operators.

Presently, such units have a market in the merchant industrial area, which accounts for approximately 12% of the overall H_2 market in the States.

Concurrently, centralised hydrogen generation in distinctive, large, and medium-sized plants is extensively utilized, and as a consequence, extensive commercial involvement exists in this sector. Considering the commercial market for H_2, it is expected that providers will continue to review and improve the techniques to make it competitive for large and medium-scale plants.

2.4. Electrolysis

There are two basic methods for generating H_2. The first method is to separate H_2 from hydrocarbons using techniques known as fuel processing or reforming. The second method is to produce H_2 from water by electrolysis, which separates H_2O into its O_2 and H_2 constituents. For decades, electrolysis methods have been used to dissociate H_2O and capture O_2 or H_2 specifically to achieve industrial chemical demands. Over the last several decades, electrolysis has indeed played an important part in the life support (O_2 replacement) in submarine and space applications (Sojoudi et al., 2021).

The benefits and applications of electrolysis are numerous. Electrolysis absorbs significantly large number of energy per unit of H_2 produced than hydrocarbon-based H_2 production. However, electrolysis is appealing as a potential source of H_2 energy for a variety of criterion. First and foremost, water (and the H_2 it consists of) is more widely available than hydrocarbons. Water geopolitical and depletion issues are less serious than hydrocarbon problems. Furthermore, there are some geographical areas in the States and around the world where hydrocarbons (particularly natural gas, the primary source of H_2 reformation) is simply unavailable; H_2 from H_2O could be the only feasible way of providing H_2 in such settings (Anwar et al., 2021).

Secondly, the net energy cost of producing H_2 via electrolysis must be considered in a monetary setting. If the goal is to substitute gasoline and/or other transportation fuels, electrolysis can be used to convert low-cost Btus into a high-value Btus (Rashid et al., 2015).

The electrolysis is viewed as a feasible, cost-efficient way of producing H_2 on a large scale and at a cost suitable for meeting the problems of supplying the H_2 demands of the initial generations of fuel cell automobiles. Electrolyzers are small and can be installed in existing fueling stations (Brauns & Turek, 2020).

Electrolysis provides a method for producing H_2 from renewable electrical power. Electrolysis is a method for converting electricity into fuel from an energy standpoint. As a result, electrolysis is a method of connecting renewable energy markets to transportation fuel markets. Renewable energy sources such as wind, solar, and hydropower generate only electricity at the moment (Yadav & Banerjee, 2018).

Finally, electrolyzers that work together with power-producing devices (such as fuel cells) reveal a novel architecture for markets involving distributed energy storage. Numerous electrolyzer manufacturers are working on products that can produce H_2 when primary electricity is available and then store and use that H_2 for successive regeneration into electricity as required. Numerous companies, for instance, are working on backup power devices that can function in the 1 to 20 kilowatt (KW) range for up to 24 hours, far exceeding the capacity of traditional batteries. This same principle is being directly employed to renewable sources, allowing for the production of power-on-demand from renewables that are essentially intermittent. Furthermore, electrolysis has the capacity to play a part in vehicle regenerative braking (Rashid et al., 2015). As the

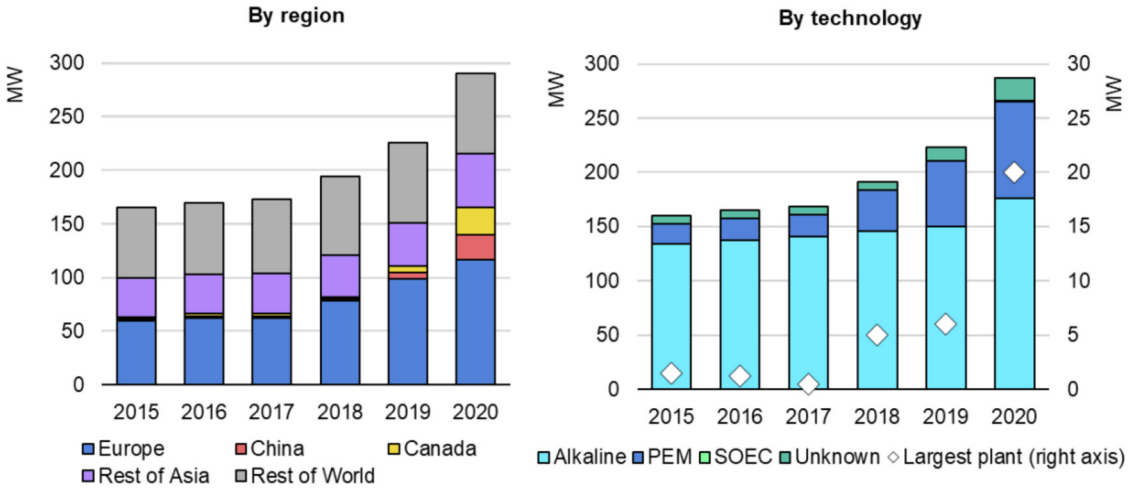


Figure 5. Global installed electrolysis capacity by technology and region (Hydrogen projects database 2021).

cost of electrolyzers decreases over time, electrolyzers and H_2 will have the suitable functionality and scale to enter the distributed generation marketplace.

2.4.1. Current electrolysis market

Niche Energy and Chemical Applications: Electrolyzers are currently only commercially feasible in a few industrial gas applications (excluding different non-commercial aerospace and military utilisations). Commercial applications comprise the remote fertiliser market, which does not have access to natural gas feedstock. The merchant or distributed, industrial hydrogen market is another key commercial market for electrolysis these days. This merchant market consists of H_2 supplied by trucks in a variety of containers. Large containers are known as "tube trailers." An industrial gas company will supply a full tube trailer to a customer and then return the empty trailer to be refilled. Customers with smaller-scale needs are served by cylinders that are supplied by trucks and installed by hand (Ahmad Kamaroddin et al., 2021).

Overall, the lower the quantity of H_2 demanded by a customer, the higher the all-inclusive delivered expenses. Customers who use tube trailers (such as glass, semiconductor, or specialty metal manufacturers) pay about $3.00 per 100 scf or about $12 per kg Cylinder customers (smaller manufacturing, research amenities, and laboratories issues) pay at least twice the price of a tube trailer. Today, the value of H_2 in distributed chemical markets is much higher than the value of H_2 if it were used as fuel. To compete with conventional transportation fuels, the price of H_2 must be in the $2.00/kg range. Electrolytic H_2 will need significant cost reductions and improved efficiency to compete in the vehicle fueling markets. Even so, several stationary energy-related electrolytic H_2 applications are starting to emerge. These smaller but high value energy uses deserve support and attention as a way to advance the pursuit of sustainable development of H_2 from electrolysis for prospective, larger-scale fueling markets (Sojoudi et al., 2021).

Applications of off-grid renewables: Another intriguing application for electrolysis is power-on-demand from intrinsically intermittent renewables. Offgrid, renewable-energy systems require power when the wind is not blowing or at night. The value difference between when electricity is available and when it is required is frequently large enough to justify the use of batteries to bridge this gap. When the duration and number of stored energy become large in comparison to battery functionality, an electrolyzer-H_2 regenerative structure may demonstrate a lower-cost solution, allowing for greater application of renewables for achieving off-grid energy requirements (Yadav & Banerjee, 2018).

The electrochemical approach of splitting water into H_2 and O_2 is known as the electrolysis of H_2O. This process produced 0.03% of the H_2 used in chemical and energy feedstocks in 2020. More than 40% of the world's installed electrolyser capacity is in Europe, with Canada (9%) and China (8%) as shown in Figure 5. The PEM, alkaline, solid oxide electrolysis cells (SOECs)[90], and anion exchange membranes are the four main electrolyser technologies currently available Table 4. depicts the techno-economic properties of various electrolyzer technologies (Buttler & Spliethoff, 2018). In 2020, alkaline electrolysers accounted for 61% of installed capacity, while PEMs accounted for 31%. The remaining capacity is made up of SOECs and electrolyser technology that has yet to be determined (an installed capacity of 0.8 MW).

The alkaline electrolysis is a mature commercial method that has been applied for H_2 production in the chlorine and fertiliser industries since the 1920s. Alkaline electrolysers have a wide operating range, from a 10% load to full design capacity. The capital costs are low compared to other electrolyser methods because they do not require precious materials. PEM electrolyser systems have a smaller footprint than alkaline electrolyser systems, making them potentially more appealing in dense urban or industrial areas. Because of the high cost of current materials for membrane materials, bipolar plates (titanium), electrode catalysts (platinum, iridium), and overall costs for PEMs (USD 1750/kW) are higher than for alkaline electrolysers (USD1000-1400/kw). The PEM techniques also have a shorter lifespan at the moment (Brauns & Turek, 2020).

2.4.2. Future advances in electrolysis technology

Given the capacity under construction and planned, global installed electrolyser capacity could reach 54 GW by 2030 as shown in Figure 6. By 2030, capacity could reach 91 GW if all projects in the early stages of development are counted. With 22 GW and 21 GW currently under construction or planned, respectively, Europe and Australia lead the way, followed by Latin America (5 GW) and the Middle East (3 GW). Many projects rely on renewable energy as a sole source of electricity, and a dozen demonstration projects (with a combined electrolyser capacity of 250 MV) are investigating the use of nuclear power for H_2 production (China, Canada, Russia, the United States, and the United Kingdom). Only 4 GW (7%) of the total are currently under construction or have made a final investment decision, leaving 50 GW in various stages of development (example: at the front-end engineering design, concept phases, and feasibility study) (Hydrogen projects database 2021). The average project size is growing as global electrolyser capacity expands. The largest alkaline electrolyser plant in operation (the 25 MW Industrial Cachimayo plant in Peru, which is linked to the electricity grid) and the largest PEM electrolyser plant in operation utilising dedicated renewables (20 MW using hydropower, inaugurated in 2020 by Air Liquide in Bécancour, Canada) are both included in the average of 0.6 MW in 2020. There are 80 projects under construction or in the planning

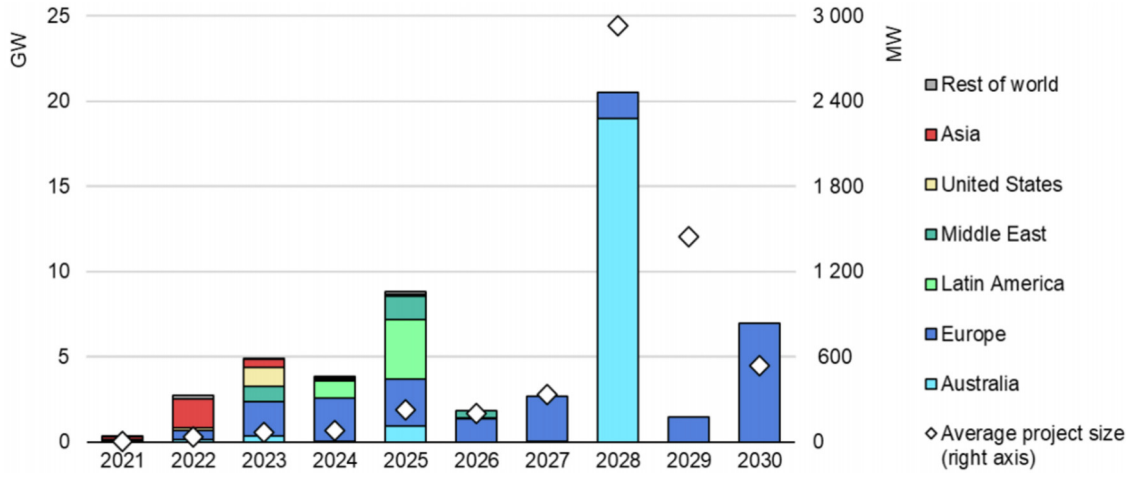


Figure 6. 2021-2030 New electrolyser capacity installed as a result of ongoing or planned projects (Hydrogen projects database 2021).

stages with a capacity of more than 100 MW and 11 projects with a capacity of more than 1 GW. The proposed Western Green Energy Hub (Australia) is on a GW scale: with up to 50 GW of solar PV and wind capacity, it will generate 3.5 Mt H_2/yr for conversion into 20 Mt of ammonia for export. Economies of scale and learning effects are expected to reduce electrolyser costs as the average project size grows to 230 MW by 2030 (Hydrogen projects database 2021).

The following are some of the research preferences that could advance the efficiency and lower the cost of electrolysis future fuelling technologies:

- Reducing the membrane's ionic resistance: Novel membranes will be thinner and integrate enhanced ion-conducting formulations, which will reduce the membrane's resistance and induce additional electrical energy supplied to the membrane to be converted into H_2 chemical energy and a lesser amount of into heat. Ionic resistance is lower in alkaline (KOH) systems than in PEM processes, but KOH schemes have complex material handling and pressurisation regimes.
- Minimising system-wide (parasitic) energy losses: Through system redesign and optimization, parasitic loads like power conditioning can be minimized. The power conditioning is one sections where efficiency is lost; present systems lose up to 10% electrical efficiency when using presently available inverters. With novel inverters reconfigured to address the different needs of electrolyzers, these losses will be cut in half or more. Before those redesigns can take place, power supply companies will want to see sufficient market assurance. Other cost savings can be obtained by optimising a variety of components as well as the total operating system. Manufacturing pricing and volume are significant cost factors. When the efficiency costs of direct current/ alternating current/ (dc/ac) power conversion are considered, one benefit of renewable energy becomes apparent. Renewables produce direct current power, which can be used directly to the direct current utilising electrolyzer cell stack without inversion. This iterative efficiency benefit linked with renewables could become significant as the price of renewable energy continues to fall.
- Lowering current density: Because conversion proficiencies are proportional to electric current density, substituting additional electrolytes or increasing cell surface area reduces total power needs per unit of H_2 produced. An enhanced catalyst deposition system will also reduce the number and cost of materials required for each unit of H_2 production. Another area of cost efficiency opportunity is operating process redesign for optimization. Beyond the current level of efficiency, technological advancements will be required. Higher temperatures, which lower ionic resistance within the cell environment, are one part that promises to enhance efficiency.
- High temperature: Because of membrane durability limitations, PEM techniques usually operate at low temperatures (below 100°C). High-temperature PEM is being developed; they should be able to withstand considerably high temperatures and thus provide high performance (efficiencies).

Electrolytic H_2 production is a proven technique that currently serves a high-value industrial chemical market (Ito et al., 2018). The strategy to adapting these systems to meet future energy-related applications is a reduction in costs and performance improvement. Hydrogen (H_2) can be produced from renewable sources, allowing for a completely sustainable energy pathway. The declining expense of renewable energy resources, as well as the enhancing efficiency and cost outlook for electrolysis, contribute to the possibility that renewably sourced electrolytic H_2 may be viable with other H_2 supplies in some cases. Electrolyzers generally operate on grid-quality power, so new power control and conditioning equipment must be implemented for electrolyzers to function effectively from renewable sources. Because electrolyzers need dc, and renewables produce dc, there are no losses connected with dc/ac conversion (Wang et al., 2014).

2.5. *Wind energy*

A mature hydrogen economy's long-term goal is frequently stated to be H_2 production from renewable energy sources (Tashie-Lewis & Nnabuife, 2021). As a result, the advancement of cost-efficient renewable techniques should be prioritised in the H_2 programme, particularly given the significant progress needed before these techniques achieve the levels of economic and productivity feasibility required to compete efficiently with conventional options. As a result, basic renewable research must be expanded, and the advancement of renewable H_2 production technologies must be speeded up. The wind has arguably the maximum prospective in the near to medium term of all the renewables currently under consideration as an efficient source of pollution-free H_2, using the electricity produced by wind turbines to electrolyze H_2O into H_2 and O_2. Three challenges must be addressed for its effective development and implementation: more reduction in the price of wind turbine technique and the cost of wind-generated electricity; lowering the price of electrolyzers, and optimising the wind turbine-electrolyzer with H_2 storage facility.

The H_2 produced by wind power has apparent environmental benefits. It produces no hazardous, solid, or radioactive waste; it does not depend on H_2O, and it is primarily emission-free, emitting no carbon dioxide or other criteria pollutants like nitrogen oxides and sulphur dioxide. Furthermore, it is a local energy source. As a result, it solves the primary concerns driving the current push toward a H_2 economy: energy secu-

Table 4
The technological and economic characteristics of various electrolysis processes (Buttler & Spliethoff, 2018).

	Alkaline electrolyser			*PEM electrolyser*			*SOEC electrolyser*		
	Current	2030	Longterm	Current	2030	Longterm	Current	2030	Longterm
The electrical efficiency (%LVh)	63-70	65-71	70-80	56-60	63-68	67-74	74-81	77-84	77-90
Operating pressure (bar)	1-30			30-80			1		
Temp. (operating) (°C)	60-80			50-80			650-1000		
Stack lifetime (operating hours)	60,000-90,000	90,000-100,00	100,000-150,000	30,000-90,000	60,000-90,000	100,000-150,000	10,000-30,000	40,000-60,000	75,000-100,000
Load range (%, relative to nominal load)	10-110			0-160			20-100		
Plant footprint (m2/Kwe	0.095			0.048					
CAPEX (USD/KWe)	500-1400	400-850	200-700	1100-1800	650-1500	200-900	2800-5600	800-2800	500-1000

rity and environmental quality. However, wind energy is not without issues (Martinez-Burgos et al., 2021).

Wind energy is among the utmost cost-effective renewable energy techniques currently available, and it is starting to compete with novel fossil fuel electricity generation in some areas. The yearly energy throughput, which is easily affected by the on-stream capability factor and wind speed, is a key factor in determining wind turbine economic success. The present price of producing electricity from wind at good wind sites ranges from 4–7 cents per kilowatt-hour (kwh) (without monetary incentives), with a rated capacity of about 30% (Ishaq & Dincer, 2020). Wind energy has several distinct benefits as a H_2 source. It satisfies the two primary motivations driving the current push toward a H_2 economy: lowering CO_2 emissions and reducing the requirement for hydrocarbon imports. Furthermore, it is the most cost-effective renewable method currently in use, with costs expected to continue to fall. Because renewable technologies efficiently handle two of the major public advantages of transitioning to a H_2 energy scheme and wind energy is the nearest to practical utilisation with the technological possibility to produce a sizable portion of future H_2, it merits continued, undivided attention.

2.6. Solar energy

According to estimates, solar energy has the capacity to achieve the human race's energy needs for the foreseeable future. Photovoltaic (PV) cells are one method of recapturing solar energy. PV cells generate electricity when they are illuminated by sunlight. PV modules for sale are available for a variety of applications. They do, however, make a negligible contribution to the production of electricity in the States. The current cost of PV module electricity is 6 to 10 times that of natural gas or coal electricity. As a result, the cost of producing hydrogen using PV electricity would be substantially higher than using fossil fuels (Ishaq & Dincer, 2020).

2.6.1. The present state of solar technology

Roughly 85% of present commercial PV modules are made from polycrystalline silicon or single-crystal. Polycrystalline silicon cells are usually 10-15 centimetres (cm) in size. They can be rectangular or circular in shape. A module is made up of multiple cells that have been soldered together. Each cell has a maximum throughput voltage of 0.6 volts (V), and the overall module output is close to 20V. In bright sunlight, the output current of each cell ranges between 2 and 5 amps. Single-crystal silicon cells are created from wafers acquired through continuous wire sawing of Czochralski-grown single-crystal ingots (Appel et al., 2020). Similarly, the majority of poly-crystalline silicon cells are made from ingots formed by the directional solidification of silicon within a mould. Wafer thicknesses typically range from $250 - 400\,\mu m$ (microns). It is noteworthy that nearly half of the silicon is lost during cutting as "kerf" loss. Polycrystalline silicon cells can also be made from silicon sheets or ribbons grew using other methods. This method avoids the expense of cutting silicon ingots into wafers. The silicon wafers or ribbons are then processed further to create wire contacts and p-n junctions. To create the final PV module, the array of cells is laminated with glass and a transparent polymer known as ethylvinyl acetate (EVA). The components are well-known for their long lifespan (10-25 year warranty from the manufacturers). The present technology provides approximately 15% module efficiency and 18% cell efficiency.

The other type of PV technique is based on the deposition of thin films. PV cells are made by the deposition of amorphous and microcrystalline silicon using various of processes such as plasma-improved chemical vapour deposition, hot wire chemical vapour deposition, etc. Thin-film solar cells have been made using polycrystalline thin-film compounds based on groups II–VI of the periodic table, such as cadmium telluride (cdTe), and ternary mixtures based on groups I–III–VI for example, copper-indium-diselenide (CIS) (T-Raissi et al., 2007). The

Table 5
Calculated cost of H_2 production in solar cases.

Case	Installed Cost ($/kW)	Electricity Cost ($/kWh)	H_2 Cost with Electrolyzer ($/kg)
Current (Dist PV-C)	3285	0.319	28.19 (Dist PV Ele-C)
Future (Dist PV-F)	1011	0.098	6.18 (Dist PV Ele-F)

thickness of the deposited layers is much less than 1 micron. When compared to crystalline silicon solar cells, thin-film technology has several significant manufacturing advantages: (a) reduced material consumption; (b) lesser processing stages; (c) automation of processing stages; (d) integrated, monolithic circuit design, resulting in the removal of individual solar cell assembly into final modules; and (e) fast roll-to-roll deposition. The overall process for crystalline silicon solar cells is projected to involve more than a dozen distinct steps in preparing and processing circuit, ingots, cells, and wafers components before a module are complete. Thin-film module production, on the other hand, requires half the number of processing steps and simplified material management.

Thin-film techniques seem to hold more potential for cost-saving, prompting study by numerous laboratories over the last two or three decades. Few of the outcomes include increased effectiveness of small laboratory research-size cells, basically 1 cm^2 in size. Copper-indium (gallium)-diselenide (CIGS) research cells have demonstrated efficiencies of up to 21.5 percent. Similarly, CdTe research cells have been reported to have a high efficiency of 16.5 percent. Silane (SiH4) and hydrogen mixtures are used to deposit amorphous silicon. The maximum efficiencies obtained in laboratory-scale amorphous silicon cells are around 12% (Sattler et al., 2017). One significant drawback for thin-film solar cells is to resolve the significant drop in efficiency from a laboratory-scale cell to a real module. Commercial modules of CdTe and CIGS, for example, have efficiencies ranging from 7%–12% (as compared with laboratory-scale cell efficiencies of 16.5 percent and 21.5 percent). Similarly, the efficiencies of commercial amorphous silicon modules are less than 10% The efficiency decreases significantly as cell size increases. Dual and triple junction cells are being developed to improve the efficiency of microcrystalline silicon and amorphous cells. This modification results in multiple layers, each with a different optimal band gap. However, the deposition of multiple layers increases the number of processing steps and thus the cost. Finally, when exposed to sunlight, amorphous silicon modules undergo light-induced degradation, resulting in lower, stabilised efficiency. Despite its promise, thin-film systems have been unable to lower the cost of solar modules due to low deposition rates, which have resulted in low capital utilisation of expensive machines. The throughputs and yields have been disappointing. These plants require improved inline controls. Some corporations have recently shut down their thin-film industrial systems due to manufacturing issues (Appel et al., 2020). Simpler and faster deposition technologies that produce reproducible results are required. Deposition technology that does not result in a significant drop in efficiency from laboratory to module scale is also needed. There is no clear "winner technology" today. Solar modules are manufactured by more than a dozen companies. Even the largest of these companies lack world-class, large-scale manufacturing facilities (>100MWp worth of solar modules per year). This size restriction prevents solar cell production from benefiting from economies of scale. Many businesses make use of a variety of technologies. Solar modules currently cost between $3 and $6per peak watt (Wp). For solar cells to be competitive with traditional electricity generation techniques, module costs must fall below $1/Wp Table 5. estimates the cost of producing both electricity and hydrogen (Ji & Wang, 2021).

Comparing to H_2 production from natural gas plants or coal, all existing approaches and anticipated techniques for producing H_2 from solar energy are significantly more expensive (by a factor of 3). Due to a lower annual utilisation factor of about 20% (as opposed to, say, a wind of 30-40%). This puts massive pressure on manufacturers to decrease the price of solar energy recovery devices. While projected future installed module price of about i$1/Wps appealing for electricity production and merits a significant research effort, it falls short of providing hydrogen at a competitive value. There is no clear winner when it comes to harnessing solar energy. Though, it seems that new competitive technologies may emerge (Ji & Wang, 2021).

Development and research priorities

The large-scale application of solar energy to the H_2 economy will necessitate multi-faceted research and development efforts. The cost of thin-film solar cells must be reduced in the short term. This will necessitate the development of robust silicon deposition methods with high throughput rates. For high efficiency, new deposition strategies using microcrystalline silicon structures at moderate pressures are required. Manufacturing costs can be reduced through inline detection and control, as well as by developing more efficient roll-to-roll coating methods. Increased automation will also help to bring down costs. It is necessary to address issues concerning a significant reduction in proficiency from small laboratory samples to the module level. In the near term, thin-film deposition techniques may profit from a new perspective on the overall process as it moves from the laboratory to the manufacturing scale. This type of research is costly. Further academic research centres with industrial alliances could be beneficial. Such studies will necessitate the formation of multifunctional teams from various engineering disciplines. The organic polymer-based solar cells offer hope for mass production at a reduced cost in the medium to long term. They are appealing because they can be cast as thin films at high speeds using well-known polymer film casting methods. Presently, the effectiveness of such a system is quite low (around 3-4%or less) and its stability in sunlight is reduced. Though, due to incredible progress in conducting polymers and other related electronics applications, it is expected that research in this area will be fruitful. Comparably, the quest for a more sustainable dye material and a superior electrolyte material in dye-sensitized cells has the potential to result in low-cost solar cells. There is a requirement to improve such cells' stable efficiency; a stable efficiency of around 10% possibly will be beneficial. In the future, the success of using photons to directly split H_2O molecules are quite appealing. This could be a fruitful area for research.

2.7. Biomass and photo-biological method

Solar renewable energy is the main energy source for producing H_2 from biomass (Wu Chunfei et al., 2011) or through direct photobiological systems. The photobiological H_2 production concept is illustrated in Figure 7. There are two kinds of biomass feedstock for H_2 production: (a) cost efficient residues like organic waste from normal wood processing (biomass residues) and agricultural farming (b) bioenergy crops (Ji & Wang, 2021). Water is cleaved directly by photosynthetic microorganisms in direct photobiological H_2 production, with no intermediate biomass formation. Since energy (solar) is a renewable energy source,H_2 production through biological means is appealing (Pal, Singh & Bhatnagar, 2021).

2.7.1. Biomass availability and cost

Hydrogen H_2 production through biomass is a thermodynamically ineffective and costly process in which 0.2–0.4% of solar energy is converted to H_2 at a current price of around $7.05/kg via gasification in

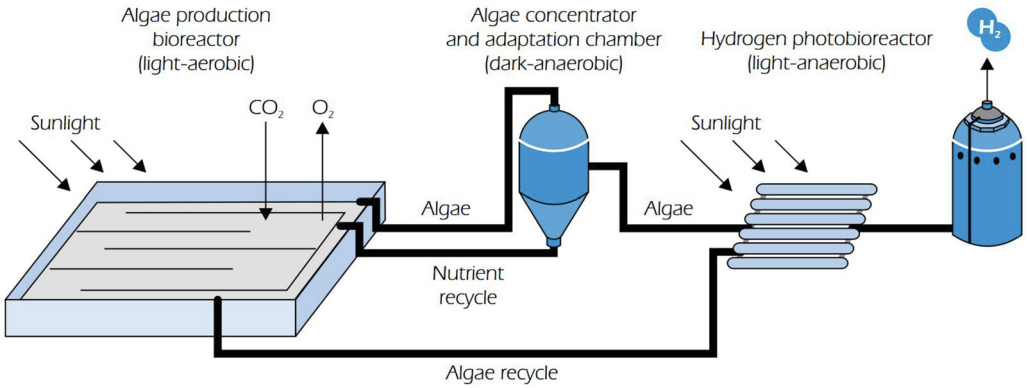


Figure 7. The photobiological H_2 production concept (Hydrogen projects database 2021).

a midsize plant. All renewable hydrogen production technologies and feedstocks compete for the land area with other societal requirements such as recreation, land conservation, agricultural goods, and services. To reduce land use and minimise competition, biological methods for hydrogen production must be thermodynamically reliable, kinetically fast, and efficient. Crop yield is projected to increase by 50% in the future techniques case, and proficiency is expected to increase by 40%, up from 26% in the present technology case (inclusive of distribution, conversion, and dispensing energy efficiencies). The number of biomass needed to meet 100% of H_2 demand in an all-electric-vehicle economy would necessitate approximately 282000 square miles of bioenergy crop farming (T-Raissi et al., 2007). This part of land accounts for roughly 40% of the cropland presently utilised for crop production in the States (USA). Farming bioenergy crops on such a large scale is probable to experience major environmental effects on biodiversity, H_2O sources, soil, and eutrophication, as well as affect agricultural commodity prices. It is estimated that the potential future technology cost for H_2 from biomass gasification is $3.60/kg hydrogen, which is non-competitive in comparison to other hydrogen production techniques (Pal, Singh & Bhatnagar, 2021).

2.7.2. Enhanced direct photobiological production of H_2

The H_2 production via direct oxidative cleavage of H_2O, facilitated by photosynthetic microorganisms without the use of biomass as an intermediate, is a new process in the early phases of development. By avoiding biomass formation and resulting gasification, the production of solar energy conversion to H_2 via direct photobiological methods is theoretically 1 to 2 orders of magnitude higher than biomass gasification (Yao et al., 2016). The efficiency of direct photobiological H_2 discharge could be on the order of 10% compared to 0.5-1% for biomass-to-H_2 conversion. It is possible that bioengineering attempts on the light-harvesting complex and reaction centre chemistry could enhance this efficiency further over the next few decades, bringing the total effectiveness (solar-to-H_2) of direct photobiological H_2 production into the 20–30% range (Touloupakis et al., 2021). Before considering photobiological technologies for large-scale H_2 production, however, significant fundamental research must be conducted.

- The following are the main challenges for producing H_2 using biological technologies:
  Low thermodynamic proficiency of biomass-to-H_2 conversion, the increased cost of biomass gasification and bioenergy crop production, and the massive demand for, and impact on, natural resources and land use for bioenergy crop farming;
- The engineering of microorganisms and mechanisms for direct photobiological H_2 production at higher kinetics rates and thermodynamic efficiency without the use of biomass as an intermediate.

3. Hydrogen production technology comparison and future projections

3.1. Hydrogen production projections

Hydrogen technology is not a new concept. In a variety of industrial methods, the world already generates and utilises more than 55 Mt of H_2 each year. Currently used hydrogen applications will be outpaced by new hydrogen applications (see Figure 8). Around 2050, H_2 could power a global fleet of over 400 million cars, 15-20 million trucks, and about 5 million buses, accounting for 20-25%of their separate transportation segments on average (Ishaq, Dincer & Crawford, 2021). In the automotive industry, hydrogen vehicle adoption will range from 10% for small cars to 20-25%for trucks and large cars and 35% for vans. About 20% of the world's diesel trains could be replaced by H_2-powered trains. By 2050, H_2 could account for 5% of the world's fuel supply for planes and cargo ships. Imported or domestic H_2 could produce 1,5000 TWh of electricity in the power generation sector (U.S.D. of Energy 2015). It has the potential to provide about 10% of the power and heat needed by the global household and industrial sectors combined. In areas where winter heating demand is high, these shares for residential heat and power are higher (15 to 20% of heat demand).

Natural gas infrastructure is common in these areas, which H_2 can use. They're also higher in industrial applications that rely on high-grade heat (20-25% of total heat demand), which is more difficult to decarbonize than lower-grade heat. H_2 could be completely decarbonized as an industrial feedstock. Furthermore, instead of methane, H_2 can be employed to generate 30% of CH_3OH and derivatives from captured carbon, recycling more than 350mt of carbon dioxide into products. It can also be used in low-carbon direct reduction processes to produce about 10% of steel (approximately 200 Mt). By 2050, annual hydrogen demand could have grown tenfold, from 8 EJ in 2015 to nearly 80 EJ in 2050 (see Figure 9), enough to meet the increasing world energy demand for two and a half months (Tashie-Lewis & Nnabuife, 2021, The role of green hydrogen in global decarbonization 2018). This massive increase is because of the rise in feedstock used in the residential, industrial, power, and transportation sectors, also a global rollout from priority markets to the rest of the world that is projected to begin after 2030 (Capurso et al., 2022).

In the 2050 two-degree case, producing nearly 80 EJ of H_2 would achieve 18% of expected overall energy demand and 12% of overall primary energy demand. The energy system would benefit from an extra energy carrier with appealing properties in the form of H_2. It can be produced in a variety of ways, stored for long periods at a low cost, and transported across borders. It can connect industries by converting electricity into fuel for generating heat and likewise. Its flexibility would allow higher renewable energy shares in the power system to be cost-

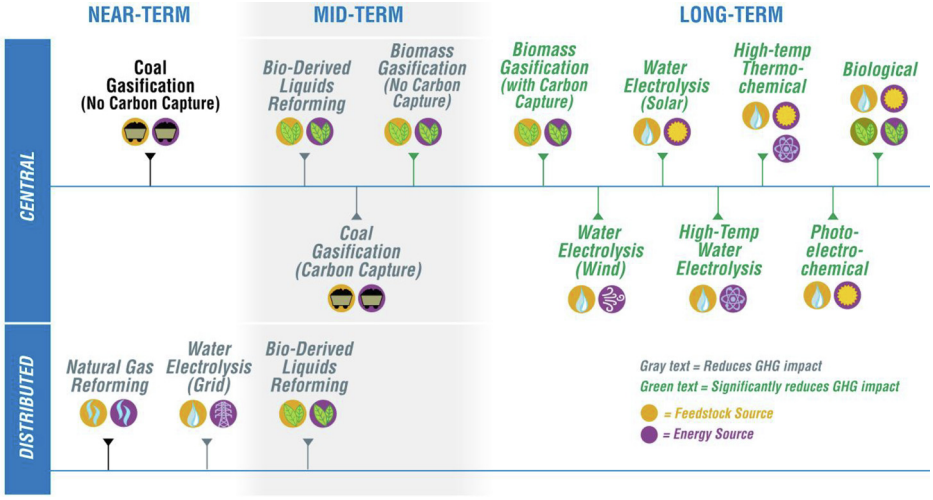


Figure 8. Timelines for the commercialization of various types of H_2 production (U.S.D. of Energy 2015).

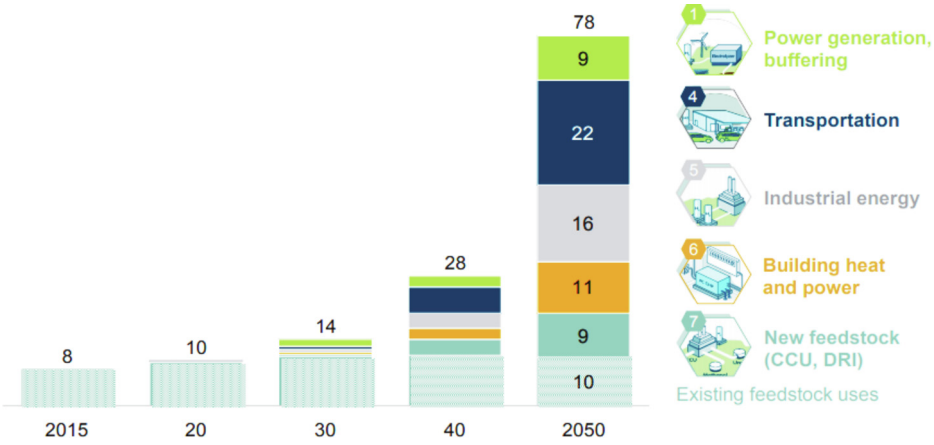


Figure 9. Projected increase in hydrogen demand by 10-fold in 2050 (The role of green hydrogen in global decarbonization 2018).

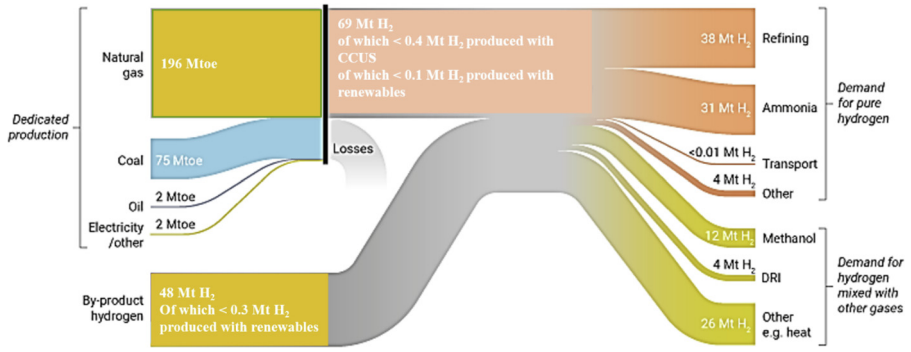


Figure 10. The current H_2 value chain (Hydrogen projects database 2021).

effective where they would likely be prohibitively expensive (The role of green hydrogen in global decarbonization 2018). When compared to today's energy composition, its deployment potential would save roughly 20 million barrels of oil per day. It would drastically reduce the amount of time and energy needed to do so.

In 2019, the demand for pure H_2 was 39 million tonnes for oil refining and 32 million tonnes for ammonia NH_3 production (80% of which came from fertilizers). Methanol (CH_3OH) production utilised 14 mt of the 45 Mt of H_2 in syngas for chemical production or iron reduction. In 2020, total H_2 consumption was expected to be around 115 Mt. See Figure 10 for the H_2 value chain (Hydrogen projects database 2021).

According to the International Energy Agency's (IEA) Net Zero by 2050 and Global H_2 Review 2021 reports, annual H_2 demand will be slightly over 200 million tonnes in 2030 and 530 Mt in 2050. From electrolysers and gas with CCS, the proportion of this that is low-carbon rises to 70% in 2030 and around 90% in 2050 (Masoudi Soltani et al., 2021). By 2050, H_2 is projected to account for about 10% of global final energy consumption. In transportation, H_2 accounts for one-third of truck fuel and 60% of shipping fuel, with a 48 Mt demand in 2050. According to the IEA, $37 billion has been pledged in national H_2 strategies for 2021, as well as $300 billion in private H_2 production initiatives, with low-cost

Table 6
Comparison of various hydrogen production processes (Kayfeci, Keçebaş & Bayat, 2019).

Methods	Energy source	Feedstock	Capital cost (M$)	H_2 cost ($/kg)
SMR with CCS	Fossil fuels (standard)	Natural gas	226.4	2.27
SMR without CCS	Fossil fuels (standard)	Natural gas	180.7	2.08
CC with CCS	Fossil fuels (standard)	Coal	545.6	1.63
CG without CCS	Fossil fuels (standard)	Coal	435.9	1.34
ATR of CH4 with CCS	Fossil fuels (standard)	Natural gas	183.8	1.48
Methane pyrolysis	Fossil fuels (standard)	Natural gas	–	1.59–1.70
Biomass pyrolysis	Fossil fuels (standard)	Woody biomass	53.4–3.1	1.25–2.20
Biomass gasification	Fossil fuels (standard)	Woody biomass	149.3–6.4	1.77–2.05
Direct biophotolysis	Solar	H_2O + algae	50 $/m2	2.13
Indirect biophotolysis	Solar	H_2O+ algae	135 $/m2	1.42
Dark fermentation	–	Organic biomass	–	2.57
Photofermentation	Solar	Organic biomass	–	2.83
Solar PV electrolysis	Solar	H_2O	12–54.5	5.78–23.27
Solar thermal electrolysis	Solar	H_2O	421–22.1	5.10–10.49
Wind electrolysis	Wind	H_2O	504.8–499.6	5.89–6.03
Nuclear electrolysis	Nuclear	H_2O	–	4.15–7.00
Nuclear thermolysis	Nuclear	H_2O	39.6–2107.6	2.17–2.63
Solar thermolysis	Solar	H_2O	5.7–16	7.98–8.40
Photoelectrolysis	Solar	H_2O	–	10.36

Table 7
Hydrogen production processes' cost and performance properties (T-Raissi & Block, 2004).

Methods	Energy consumption (kWh/m^3)		Tech. current state	Performance %	Costs Relative to SMR
	Ideal	**Practical**			
SMR	0.78	2–2.5	mature	70–80	1
CH_4/Natural gas (NG) pyrolysis			R&D to mature	72–54	0.9
Hydrogen sulfide (H_2S) CH_4 reforming	1.5	–	R&D	50	<1
Photocatalytic decomposition of H_2O			early R&D		
Landfill gas dry reformation			R&D	47–58	~1
POX of heavy oil	0.94	4.9	mature	70	1.8
Naphtha reforming (NR)			mature		
Thermochemical H_2O splitting			early R&D	35–45	6
Coal gasification (TExaco)	1.01	8.6	mature	60	1.4–2.6
Steam-iron process			R&D	46	1.9
SMR of waste oil			R&D	75	<1
Photo-electrochemical decomposition Of H_2O			Early R&D		
POX of coal			Mature	55	
Chloralkali electrolysis			Mature		by-product
Grid electrolysis of H_2O	3.54	4.9	R&D	27	10-Mar
Photolysis of H_2O			Early R&D	<10	
Electrolysis of H_2O (High-Temp.)			R&D	48	2.2
Biomass gasification			R&D	45–50	2.0–2.4
Solar & PV-electrolysis of H_2O			R&D to mature	10	>3
Photo-biological			Early R&D	<1	

clean electricity being a core component (Hydrogen projects database 2021).

According to the IEA Energy Technology Perspectives 2020 in its Sustainable Development Scenario, global H_2 production will increase rapidly to around 445 Mt for energy use plus 75 Mt for process employed by 2070. In conjunction with CCS, the 520 Mt of H_2 would be produced using 58 percent electrolysis and 40 percent fossil fuels. Transportation accounts for 60% of total energy demand, and chemical and steel production account for 60% of total energy consumption (Hydrogen projects database 2021).

3.2. Different hydrogen production comparisons

Table 6 shows variables such as feedstock, investment cost, energy source, and H_2 production cost (per Kg of H_2) to qualitatively measure the costs derived from each H_2 production method (fossil fuel and renewable-based). The cost of H_2 production is subject to some uncertainty. This cost is heavily influenced by the level of technological advancement, the accessibility of present structure, and the feedstock price. According to the table, the most cost-effective methods of producing H_2 are coal, biomass gasification, and steam CH_4 reforming. Nuclear thermochemical cycles (Cuecl and Sel) appear to be price competitive with fossil fuels and biomass. Solar and wind electrolysis have the highest cost per kg of H_2 produced. Because one of the primary benefits of electrolysis is its capability to be employed locally, the price of electrolysis is estimated using a small-scale, distributed production assumption (Kayfeci, Keçebaş & Bayat, 2019).

Table 7 compares the cost and efficiency properties of various H_2 production methods, ranging from naphtha reforming, SMR, coal gasification, landfill gas dry reformation, H_2S methane reforming, steam reforming of waste oil, steam-iron process, POX of heavy coal and oil, high-temperature H_2O electrolysis, grid electrolysis of H_2O , photolysis of H_2O , chloralkali electrolysis, solar and biomass gasification, PV H_2O electrolysis (Shayan, Zare & Mirzaee, 2018, Ishaq & Dincer, 2021, Faheem et al., 2021).

In the short term, probably 2030, the competitive edge of fossil fuels is likely to persist, with H_2 via natural gas without CCUS expected to cost in the range of USDI-2/kg H_2dependent on local gas values. Apart from the case of coal-derived H_2, fuel costs are the most expensive part of H_2 production costs (Figure 11). Future H_2 costs will thus be influ-

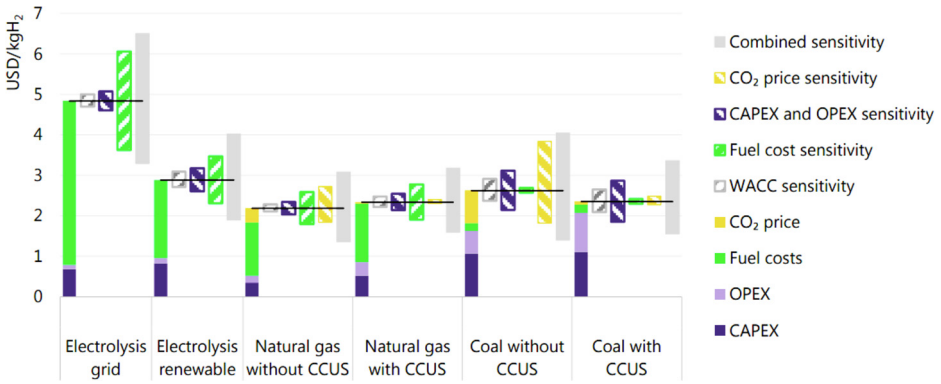


Figure 11. Estimated costs of hydrogen production in 2030 for various technology options. Renewable electricity price = USD 40/MWh at 4,000 full load hours in best locations; sensitivity analysis based on +/ − 30% variation in OPEX, CAPEX, and fuel costs; +/-8% change in default WACC; and a USD40/tCo_2 price variation to USD0/t$CO_2$and USD100/tCO_2levels (Hydrogen projects database 2021).

enced heavily by gas and electricity costs, as well as cost-influencing parameters like conversion efficiencies. The cost of production can be affected by CAPEX requirements, especially if plants operate at less full load hours (Hydrogen projects database 2021).

4. Conclusions and future research priorities

There are significant obstacles to attaining the vision of H_2 production; the route will not be easy or simple. Many of the research findings apply to the whole H_2 production process: the H_2 system must be safe, cost-competitive, reliable, and appealing to consumers, and it should ideally provide benefits in terms of energy security and carbon dioxide emissions. Particularly for the transport sector, significant advances in the fuel cells development, storage systems, and distribution systems are critical. There is no guarantee of extensive success.

The following are the utmost fundamental economic and technological challenges that must be addressed:

- Significant improvement has been made in lowering the cost of producing electricity from renewable energy sources. However, producing H_2 from renewable energy via the intermediate step of producing electricity, a premium energy source, necessitates further developments to be competitive. In essence, these hydrogen production technology pathways generate electricity, which is then converted to H_2, which is then converted back to electricity by a fuel cell. These stages add costs and operational losses that are especially significant when H_2 enters the market as a commodity transportation fuel, leading the researchers to believe that most present approaches, with the possible exception of wind energy, need to be redirected. It is worth noting that the necessary cost drops can be attained through targeted essential and experimental research on H_2 production via thin-film solar, photochemical, and photo-biological processes.
- To build the infrastructure needed to supply hydrogen to light-duty vehicle users. Hydrogen (H_2) is presently produced on a large scale and at a sensible cost for industrial use. When the development has reached a mature stage, H_2 can be produced for use in fuel cell vehicles at a practical cost in the future. The massive cost of supplying hydrogen to dispersed locations is a challenge for both current industrial H_2 and future H_2. This difficulty is exacerbated during the initial periods of a transition when demand is more dispersed. The total cost of a fully developed H_2 pipeline system would be spread across many users, much like the cost of a natural gas pipeline system today. However, the transition is hard to visualise in detail. Many technical innovations are required in the establishment of small processing facilities. Non-technical factors such as site selection, security, financing, environmental impact, and the safety of dispensing systems and the hydrogen pipelines will also be important. All of these obstacles must be overcome before widespread use can occur. It appears that an early stage in which H_2 is produced on a small scale near a small user is possible. In this instance, the operating costs for small processing facilities must be drastically reduced, which may be feasible with additional research.
- To sequester (store) and capture the CO_2 byproduct of coal-based H_2 production. Coal is a huge domestic energy resource in the United States with the capacity to produce cost-efficient and competitive H_2. However, coal processing emits a significant amount of carbon dioxide. Enormous number of carbon dioxide would have to be captured safely and effectively sequestered for hundreds of years to minimise emissions of carbon dioxide from coal processing in a carbon-constrained future. The achievement of broad public acceptance, as well as further technological development, for CO_2 sequestration, is critical to the commercialization of a large-scale, coal-based H_2 production process and also for the natural-gas-based process.
- More emphasis should be placed on options for accomplishing water splitting with no CO_2 emissions. At this preliminary phase of laboratory-scale research, the programme should include numerous alternatives for promising cycles, including catalysts to improve reactions at low temperatures and material compatibility issues. The expansion of high-temperature steam electrolysis should be pursued in tandem with the thermochemical cycles. Material durability, overvoltage reduction, operating pressure effects, and the separation of gas products efficiently and safely should all be studied. If the research is successful, one or two methods should be chosen for a few-year demonstration of the integrated method.
- An investment in research that develops near-term techniques while investigating novel approaches must be maintained. For a few years, the overall budget for electrochemical, thermochemical, and other options should be increased to allow for the selection of the most promising methods for demonstration. There is a requirement to encourage industry participation in evaluating the economic ability of different options.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Present and projected developments in hydrogen production: a technological review

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