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An Overview on The Design, Operation and Levelized Costs of Hydrogen Refuelling Stations for Fuel Cell Electric Vehicles

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ABSTRACT

Interest in hydrogen economy is developing rapidly and spearheaded by developed countries to mitigate the combined effects of volatile fossil fuel market and environmental pollution. The transportation sector is a key area in the transition from fossil-based fuels to a clean hydrogen fuel. Fuel cell electric vehicle (FCEV) technology has matured and successfully tested on a wide range of transportation platforms. To enable FCEV as commercially viable, an important factor is the availability of hydrogen refuelling stations (HRS) at fuel cost that is affordable. This article provides a general overview of hydrogen transportation economy for stakeholders, policymakers, and investors to facilitate informed decision-making. It explores the expansion of HRS designs and operation based on the emphasis on green energy concepts towards achieving improvements in the Levelized Cost of Hydrogen (LCOH). It is acknowledged that the success of a green HRS operation in meeting targeted LCOH is highly dependent on the cost of the energy source, where solar and wind power are the current central solutions. LCOH is seeing a visible reduction as the new cost-effective technologies emerge, as well as greater emphasis is given on optimizing the operation. The review concluded that green HRS is capable of meeting a commercially attractive LCOH within five to ten years mainly through the optimization of operation strategy.

Keywords: Hydrogen Refuelling Station; Fuel Cell Electric Vehicle; Levelized Cost of Hydrogen

1.0 INTRODUCTION

Hydrogen is the first-ranked among all the known elements and it is the most abundant in the universe. One of its attractive properties is its high energy density, where one kg of hydrogen substance has an equal energy density of 2.8 kg of natural gas [1]. Transition towards hydrogen fuel is seen as the natural next step in the advancement of civilization that puts greater emphasis on sustainability. Hydrogen is no longer deemed as fuel for the future since hydrogen-based technologies are primed to contribute a substantial percentage of the current global energy demand. The Institute of Renewable Energy (IRENA) estimates that hydrogen will account for up to 12% of global energy use by 2050, as well as significant reductions in the cost of hydrogen infrastucture by 40% to 80% in the coming years [2].

Hydrogen economy is an economic model relying on hydrogen fuel to deliver a substantial fraction of the global energy and service needs in an industrial environment where hydrogen-based technologies are central in balancing the energy demand and supply stresses, as well as reducing harmful emissions while stimulating economic growth and creating new jobs [3]. It reduces the dependency on fossil fuels, as well as capable in migitating global carbon dioxide emissions by 24% through the transportation sector alone [4].

Greater concern on the effects of global warming due to greenhouse emissions, as well as volatile fuel market, has pushed developed countries to spearhead the energy transition from fossil fuel towards hydrogen fuel. Countries committed to the transition towards hydrogen economy have increased as energy independency is achievable by individual countries compared to the oil and gas economy model. As shown in Figure 1, Asia, Europe, Africa and North America are seriously planning and developing the groundwork for the energy transition. Significant carbon reduction targets by 40 to 65% by these nations are strongly backed by large-scale investments up $10 trillion USD by 2050 [5, 6]. Hydrogen economy transition among developing countries are inclined towards long-term transition (20 to 30 years plan) with low financial commitments due to constraints in infrastructural development costs. Oil and gas producers are the least committed to the hydrogen transition, but visible shifts in business models towards large-scale hydrogen production by major oil companies such as Shell [7] and Petronas [8] are currently developing.

Central to the hydrogen economy is sustainable and affordable hydrogen production. The global hydrogen production is estimated at 70 million tonnes and rapidly growing. The resources for mainstream industrial hydrogen are hydrocarbon fuels. Approximately 6% of global natural gas and 2% of global coal have been utilized

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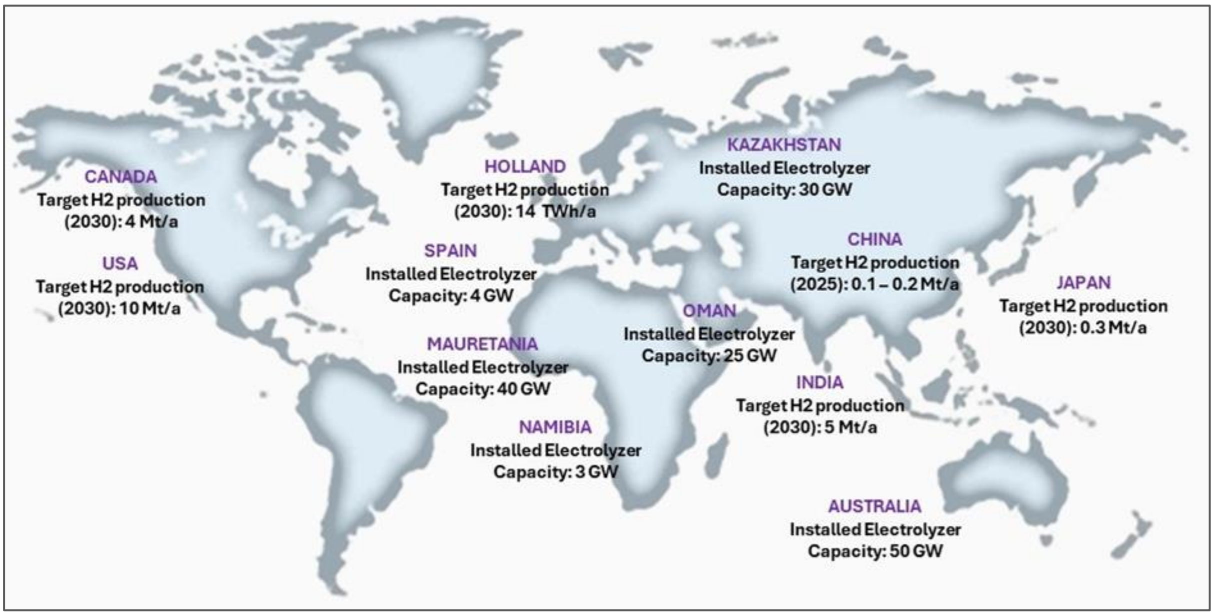


Figure 1. Global hydrogen infrastructure deployment

to sustain the hydrogen supply chain, while hydrogen produced using water electrolysis is less than 5% from the global production [9]. Hydrogen is needed in end-user industrial segments such as electronics and semiconductors, chemicals, petroleum, power plants, and pharmaceuticals. By market share, the chemicals segment is the largest followed by the pharmaceuticals segment. The rising demand for hydrogen in the chemical industry is due to the manufacturing of ammonia. Hydrogen is also used in making other compounds such as cyclohexane, aniline, and hydrochloric acids [10]. Driven by its high energy density and potential mitigation of harmful emissions, hydrogen is estimated to contribute up to 12% of global energy use by 2050 [11]. In order to achieve a green chemical industry, hydrogen produced via water electrolysis is a key factor and would see a rise in global demand in the future as industries need to meet sustainable agendas in order to be compliant with demanding environmental regulations.

Hydrogen-based technologies are becoming integral in balancing energy demand and supply while fostering economic growth and job creation. Developed countries like China, Japan, and Germany lead the charge, investing heavily in hydrogen infrastructure to meet ambitious carbon reduction targets. Despite challenges such as infrastructural costs and resistance from traditional fuel industries, major companies are shifting towards large-scale hydrogen production, leveraging sustainable methods like water electrolysis. Crucially, hydrogen's role extends beyond energy production, finding applications in diverse industries such as electronics, chemicals, and pharmaceuticals, where demand is rising in tandem with the need for sustainable practices to meet environmental regulations. In essence, the hydrogen economy presents a promising pathway towards a cleaner, more resilient future, contingent upon collaborative efforts across sectors to realize its full potential.

Hydrogen Refuelling Station (HRS) is an integral component in the hydrogen transportation economy. Since the first pilot logistics study of hydrogen fuel cell vehicles (FCEV) in California, the chosen hydrogen production technology is a major factor in the production cost, known as the Levelized Cost of Hydrogen (LCOH). In turn, the selling price of hydrogen is dictated by the LCOH, and the targeted acceptance of FCEV is dependant on the operating fuel cost to be burdened on consumers. Therefore, in this energy transition era, it is important to understand the potential HRS designs and operation approaches and identify the current level of LCOH for the reference of policy makers and potential business owners.

FCEV is being developed as a clean and sustainable alternative to traditional gasoline and diesel vehicles. However, for FCEV to be widely adopted, a sufficient number of HRSs must be in place to support them. Therefore, understanding the current state of HRS infrastructure is important for assessing the feasibility and scalability of hydrogen-powered transportation. This article aims to provide a brief overview on the current technologies of HRS designs related to on-site hydrogen production using renewable resources. The HRS designs are discussed together with green energy operation strategies and its effect on the LCOH. The information and discussion provides an introductory level of understanding on the technological progress of HRS and its constraints towards enabling a competitive hydrogen economy, providing a general overview for stakeholders, policymakers, and investors to facilitate informed decision-making towards establishing a robust and sustainable hydrogen infrastructure.

2.0 FUEL CELL ELECTRIC VEHICLE

The automotive industry is a major economic driver, producing approximately 40 million cars and trucks annually and consumes half of the world's energy consumption [12]. Hydrogen is the ultimate solution in decarbonizing the transportation sector as it produces only water and heat as its process byproducts. Hydrogen FCEV has similar power drive architecture to battery-powered electric vehicles (BEV). An on-board fuel cell is capable of electrochemically converting hydrogen into electrical power with zero carbon emission. Technically, FCEV has greater driving range, faster refuelling time, and flexible hydrogen generation from existing gas or water grid infrastructure [13]. As listed in Table 1, studies have shown that FCEV is economic for long-range vehicles such as trucks and buses or when continuous electrical supply is needed for clean public transport such as trains and ferries [14].

The race to produce commercially viable and environmentally healthy FCEV has gained rapid momentum as the technology matures. In Table 2, China leads the FCEV race as it has targeted a million on-the-road FCEV by 2030 [15]. Its strong domestic demand and low-cost technological progress capability are the key strengths in its planning. By 2035, China is expected to exceed 50% on the market share of New Energy Vehicles (NEVs), indicating a substantial presence and growth trajectory for FCEVs in the Chinese market. China's commitment to boosting green hydrogen production and establishing a large number of hydrogen refueling stations aligns with its goal to lead in the global FCEV market, especially in mass transport and heavy-duty vehicle sectors [16]. These efforts position China as a key player in driving the adoption and market share of FCEVs within the country and globally. U.S market share is significant, driven by the government initiatives and policies aimed at reducing carbon emissions and adopting renewable energy technologies [17]. A modest FCEV market share in Japan was recorded in 2020 but accounting only 0.1% of sales from 1.4 millions EV. Despite the moderate market share, the government has set a 100% target of EV by 2035 which potentially could drive greater adoption of FCEV [18]. In Germany, the total number of passenger FCEV in 2022 is 2364 units, a small figure when compared to the more than 1.4 million BEV in the country [19].

Progress of FCEV technology is allowing powerful models that supersede the performance of BEV, particularly on the specific driving range. The Nikola One model is capable of reaching a 800 km range on a 70kg hydrogen tank compressed at 700 bar, which is 36% better than the range of Ford F-10 model in the BEV segment [30]. The extended range of FCEV and its powerful motor torque have made it economically attractive for heavy vehicles and electrically-driven public transportation such as speed trains.

Table 1: FCEV models and specifications

Vehilcle type	Model	Manufacturer	Power (kW)	Storage	Range (km)	Ref
PC	Mirai	Toyota	114	Compressed H2	650	[20] [21] [22]
	NEXO	Hyundai	120	Compressed H2	600	
	Clarity	Honda	100	Compressed H2	483	
	iX5	BMW	125	Compressed H2	400	
	GLC	Mercedes	125	Compressed H2	400	
	Golf	Volkswagen	100	Compressed H2	400	
	Equinox	General Motors	100	Compressed H2	400	
	Cadillac CT6	General Motors	100	Compressed H2	400	
	Focus	Ford	100	Compressed H2	400	
	MX-30	Mazda	100	Compressed H2	400	
	Ariya	Nissan	120	Ethanol fuel using reformer	500	
CV	Xcient	Hyundai	190	Compressed H2	400	[23]
	Kenworth T680	Kenworth	310		724	[24]
	Profia Z light duty	Hino	N/A	Compressed H2	600	[25]
	Nikola one	Nikola	200	Compressed H2	805	[26]
	Sora	Toyota	114	Compressed H2	200	[27]
	Elec city	Hyundai	180	Compressed H2	500	[28]
	Urbino 12	Solaris	70	Compressed H2	350	[29]

Note : PC – Passenger car; CV – Commercial vehicle

Table 2: Current capacity and future targets of FCEV

Country	**FCEV Demand**	**Key information**
China	High	•Current market is over 1 million •Targets 1,000 HRS by 2030.
U.S	Significant	•Policy landscape supports FCEV production and sales
Japan	Moderate	•Current market is 140 thousand •Aims for carbon neutrality by 2050
Germany	Moderate	•Lack of infrastructure to support

Studies have shown that buses and trucks powered by hydrogen fuel cells are not necessarily capable of significant savings compared to diesel engines. In fact, there is evidence suggesting that hydrogen fleets, including fuel cell trucks, can be much more expensive to maintain than battery-electric or even diesel vehicles [31]. An analysis comparing battery-electric and hydrogen fuel cell buses revealed that battery-electric buses are more efficient in terms of overall energy efficiency, with a higher efficiency rate of about 85-90% compared to 60-70% for hydrogen fuel cell buses [32].

Additionally, the maintenance costs for hydrogen fuel cell vehicles can be significantly higher than those for battery-electric vehicles. For example, a study found that maintenance cost for a fuel cell fleet is 2.5 times higher than for an older compressed natural gas (CNG) fleet. Overall, while hydrogen fuel cell technology may offer benefits in certain areas, such as range and refueling time, the operational and maintenance costs associated with these vehicles can be considerably higher compared to battery-electric alternatives [33].

3.0 HYDROGEN PRODUCTION TECHNOLOGIES

Hydrogen production encompasses various pathways, including Steam Methane Reforming (SMR), electrolysis of water, and gasification of coal or biomass. In 2020, global hydrogen demand reached 90 million tonnes (Mt), primarily filled by fossil fuel-based hydrogen production [34]. Dedicated hydrogen production plants contributed 72 Mt of hydrogen, accounting for 79% of the total supply. The remaining 21% was generated as byproduct hydrogen in facilities primarily focused on other products, particularly in refineries where naphtha reformation for gasoline production produces hydrogen [35].

Of the total demand, 72 Mt of hydrogen was used in its pure form, mainly for ammonia production and oil refining purposes. Additionally, 18 Mt of hydrogen was mixed with other gases for applications such as methanol production and Direct Reduced Iron (DRI) steel production [35].

Natural gas played a central role in hydrogen production, primarily through steam methane reformation, which dominated processes in the ammonia, methanol, and refinery industries. Approximately 240 billion cubic meters (bcm) of natural gas, constituting 6% of global demand in 2020, accounted for 60% of annual global hydrogen production. Coal, particularly significant in China, contributed 115 million tonnes of coal equivalent (Mtce), representing 2% of global demand and constituting 19% of hydrogen production [36].

The reliance on fossil fuels for hydrogen production resulted in substantial direct CO2 emissions, totaling nearly 900 Mt in 2020. This accounted for 2.5% of global CO2 emissions from energy and industry, equivalent to the combined emissions of Indonesia and the United Kingdom. Reducing emissions from hydrogen production is essential for facilitating a clean energy transition. The remaining portion of dedicated hydrogen production utilizes oil and electricity as fuel sources [35].

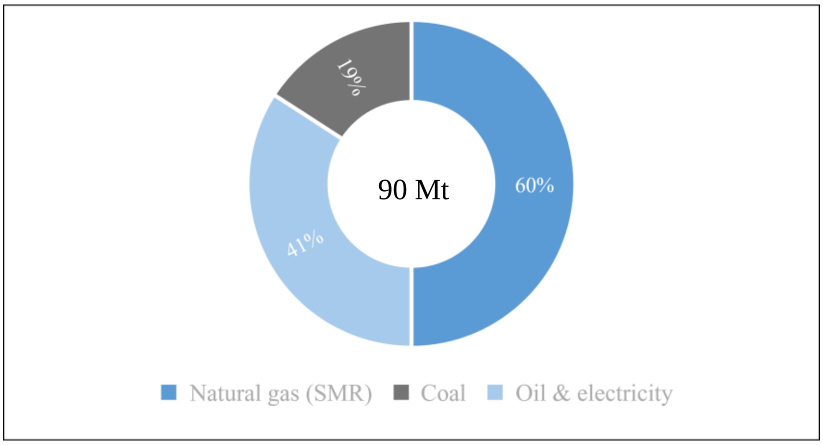


Figure 2. Global hydrogen production technologies

Hydrogen is mainly available in hydrocarbon substances as well as water. The separation of hydrogen from its molecular partners are normally performed through the thermochemical or electrochemical process pathways. Hydrogen is thermochemically obtained by reacting a hydrocarbon substance with steam. The high temperature process promotes the separation of the hydrogen, carbon and oxygen elements from its molecular bonds to form new substances typically carbon dioxide and hydrogen gas. Natural gas is highly used in the steam reforming process, while sustainable approaches use waste flue gases from boilers and furnaces as the reactant for the hydrogen production. Steam reforming is the cheapest approach in hydrogen production, where the levelized cost of hydrogen (LCOH) is approximately as low as USD 1/kg up to USD 2/kg which depends on location, natural gas prices and value of carbon captured for use or storage [37]. However, carbon dioxide produced from this method is increasing yearly, where SMR is responsible for about 3% of global industrial sector [38] which contributes from 8.4 to 9 Gt as depicted in Figure 3.

The electrochemical pathway is the eletrolysis process. It is the cleanest route to produce hydrogen compared to other methods that release carbon-based substances to the atmosphere. The main challenge for electrolyzers is the cost of operation to supply sufficient electrical power for the splitting of water into hydrogen and oxygen. The minimum energy needed for water electrolysis is 4.4 kWh/kg (15.8 kJ/kg) of water [39].

Relatively, the demand for water electrolysis systems is improving. According to the Market Research Future (MRFR) report, the global water electrolysis market share is projected to grow exponentially at 6% Compound Annual Growth Rate (CAGR) up until 2030. These encouraging market trend boosts the growth of hydrogen-related industries [40]. The main technologies that contribute to the market uptrend is alkaline electrolysis and the more efficient, but costly is polymer electrolyte membrane (PEM) electrolysis. Currently, the established alkaline electrolysis technology is the leading electrolyzer technology due to its greater technological maturity, durability and relatively low cost [41]. However, the operation of electrolysers is subjected to the quality of its power supply [42]. Fluctuating and intermittent behaviour of solar and wind power energy affects the performance of an electrolyser; thus, dynamic power supply operational strategies such as partial grid-dependency must be adopted if renewable energy is to be used [43].

In 1987, a reservoir containing pure hydrogen or white hydrogen was discovered in Mali, which is the first ever found on earth and the latest discovery was in 2023 found in France. It remains relatively understudied as a primary energy source created underground through chemical reactions. During the Regalor Project in Lorraine, researchers unexpectedly discovered increasing percentages of native hydrogen with excavation depth. The project, concluded in December 2023, showcased this unique find alongside methane extraction. The revelation prompts ongoing European studies to identify additional hidden sources of native hydrogen, contributing to the growing interest and exploration of this unconventional energy resource [44]. However, hydrogen production through steam reforming and electrolysis would continue to be important due to the high volumetric demand to drive planned hydrogen economies globally.

3.1 Hydrogen refuelling station (hrs) designs

The market penetration of FCEV is dependent on the availability of supporting hydrogen production and supply infrastructures [45]. A HRS is an integral part in the necessary infrastuructural development for FCEV to be successful with the function to safely supply hydrogen under appropriate pressure and temperature conditions for the refuelling of FCEV. The typical hydrogen tank pressure of a FCEV is between 35 and 70 MPa [46]. Currently, there are about 200 HRS in the world and 5300 new HRS are planned by 2030 [47].

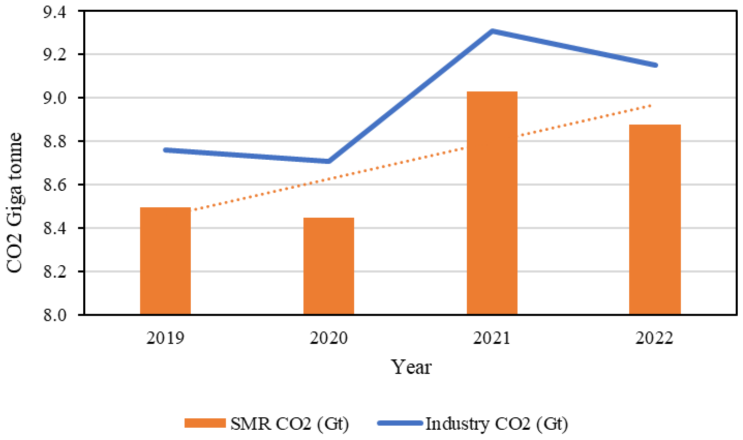
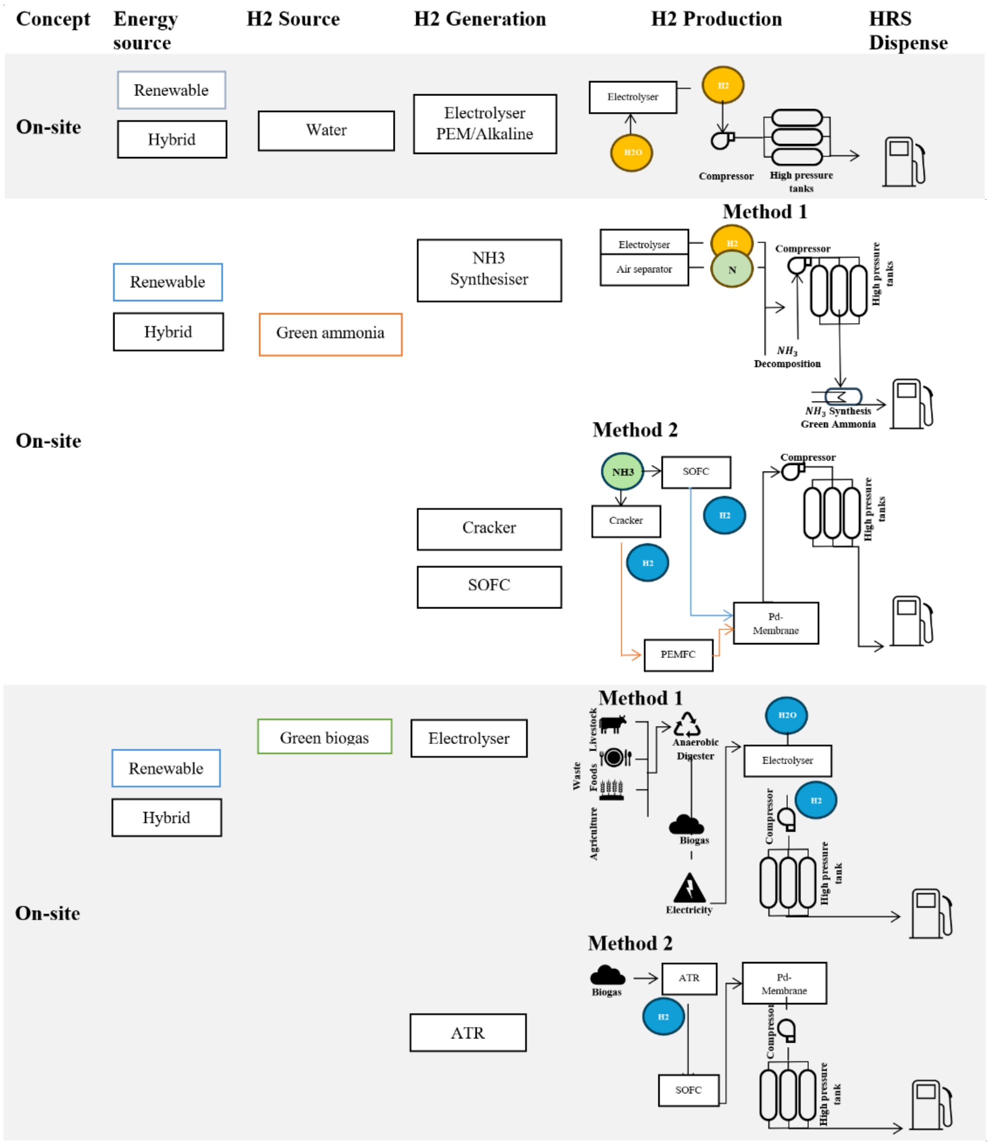


Figure 3. SMR’s carbon dioxide emission trend

There are two basic design and operation models of HRS – on-site and off-site hydrogen production. An on-site HRS produces hydrogen within its vicinity using small-scale technologies for localized use. This approach offers a more a consistent and convenient supply of hydrogen for fueling vehicles, while enhancing sustainability and operational control. An off-site HRS depends on hydrogen supply from a large-scale hydrogen plant for its operation. The produced hydrogen is then compressed or liquefied and transported to the refueling stations via dedicated pipelines, trucks, or tankers. This off-site production and delivery process involves storing hydrogen in high-pressure tanks at the refueling stations until it is dispensed to fuel cell electric vehicles. Off-site hydrogen production is a common method globally which provides a reliable supply of hydrogen to support the growing demand for fuel cell vehicles [48].

An on-site HRS design relies on the use of electrolyzers and is usually integrated with renewable energy sources to meet a green HRS concept. Typically, a green HRS utilizes solar and wind to generate electricity for the hydrogen production process. It is a solution that allows demand-based and self-dependent hydrogen production with low or zero carbon dioxide emissions, which is a highly suitable approach for the development of green cities.

Figure 4 provides a simplified process of an on-site solar-powered hydrogen production HRS using electrolyzers. The basic configuration comprises of the energy harvesting system, power supply and management, hydrogen production system, storage, mechanical, electrical and safety devices, as well as dispensers [49]. Electrical power generated by the solar PV panels is stored in battery banks.



Note : Illustrations are based on main components in a single HRS

Figure 4. Schematic process of an on-site HRS

The DC power supply regulates the power requirement of the electrolyzer based on the hydrogen production demand. The main power source is the green energy stored in the battery banks, while power from the grid is applied according to green power availability and operating strategy. The produced hydrogen is stored in tanks at high pressure and is supplied to the FCEV through hydrogen dispensers. Table 3 presents a comparative analysis of diverse HRS system designs from Gökçek and Kale [50] and Perna et al. [51], focusing on their key characteristics. The designs encompass wind-PV-battery HRS, wind-battery HRS, green ammonia, green biogas, and water H2 production. Each system is evaluated based on its hydrogen production method, energy source, storage and dispensing technologies, cost analysis, infrastructure integration, scalability, reliability, and technological innovations.

The wind-PV-battery HRS and wind-battery HRS employ hybrid configurations with renewable sources and storage solutions, showcasing optimal designs tailored to meet a daily demand of 125 kg of hydrogen. In contrast, the green ammonia system stands out with its innovative storage approach, relying on liquid storage at 8.7 bar and 20°C, making it a promising hydrogen carrier. Green biogas demonstrates reliability through its production using BEKON dry fermentation technology, coupled with an autothermal reforming (ATR) process.

The water hydrogen production system utilizes a modular electrolysis unit with nine modules, each at 118 kW, highlighting scalability and efficiency. The comprehensive cost analysis includes levelized cost of hydrogen (LCOH), net present cost (NPC), and levelized cost of electricity (LCOE), offering a holistic economic perspective. Overall, this comparative analysis aids in understanding the distinctive features and trade-offs associated with each HRS system, providing valuable insights for researchers, policymakers, and industry stakeholders in the pursuit of sustainable hydrogen infrastructure.

Table 3: HRS system design analysis

System design characteristic	Wind-PV-battery HRS	Wind-battery HRS	Green ammonia	Green biogas	Water
H2 production method	650kW PEM electrolyser	550kW PEM electrolyser	Cracking	ATR	1,062kW (118kWx9) Modular electrolyser
Energy source	Hybrid - Wind, PV & batteries	Hybrid - Wind & batteries	Renewable	Renewable	Hybrid: PV & grid
Storage & dispensing technology	High pressure tanks & lead-acid batteries. Compressors, cooling systems & dispenser.	High pressure tanks & lead-acid batteries. Compressors, cooling systems & dispenser.	Liquid Storage at 8.7 bar, 20°C.	Pressure Swing Adsorption (PSA) at 900 bar.	Compression at 900 bar after Electrolysis. Compressors, cooling systems & dispenser.
Cost analysis	LCOH: USD8.92/kg NPC: USD8.4mil LCOE: USD1.90/kWh	LCOH: USD11.08/kg NPC: USD11mil LCOE: USD2.50/kWh	LCOH: USD7.76/kg NPC & LCOE not avaialable	LCOH: USD8.17/kg NPC & LCOE not avaialable	LCOH: USD8.92/kg NPC & LCOE not avaialable
Infrastructure intergration	Optimal design for 125kg/day H2: 904 kW PV, E-53 Wind Turbine, Lead-Acid Batteries, 492 kW Converter, 650 kW PEM Electrolyzer, 900 kg H2 Tank.	Optimal design for 125kg/day H2: Three E-53 Wind Turbines, Lead-Acid Batteries, 535 kW Converter, 550 kW PEM Electrolyzer, 800 kg H2 Tank.	Optimal Design for 450 kg/day H2: Synthesis of Hydrogen and Nitrogen with Ammonia Feeding SOFCs.	Optimal Design for 450 kg/day H2: ATR Process for Hydrogen Production with Biogas Composition (60% CH4, 40% CO2).	Optimal design for 450 kg/day H2 : 9 Modules, 118 kW each, Producing 450 kg/day at 10 bar.
Scalability	Expandable based on demand	Expandable based on demand	Expandable based on demand	Expandable based on demand	Expandable based on demand
Reliability	Multiple renewable sources & storage for continuous power supply	Multiple renewable sources & storage for continuous power supply	Reliable Liquid Storage of Green Ammonia	Reliable Production from BEKON dry fermentation technology	Reliable modular electrolysis unit
Technology innovation	Effective integration of renewable energy sources with H2 production	Effective integration of renewable energy sources with H2 production	Ammonia as liquid carrier, direct SOFC feeding	Production from BEKON, ATR process for H2.	Modular architecture for scalability
Reference	Gökçek & Kale [50]		Perna, Minutillo, Di Micco S & Jannelli E. [51]		

4.0 LEVELIZED COST OF HYDROGEN (LCOH)

The LCOH is a metric to benchmark the cost-competitiveness of hydrogen production. It is the equivalent cost per unit of hydrogen evaluated along its projected life cycle to obtain a Net Present Value (NPV) equal to zero. The LCOH provides a reference on the cost to be charged to customers to enable a profitable and sustainable hydrogen production over its life cycle. The variables accounted in the production of green hydrogen and LCOH evaluation are presented in Fig. 5.

1. Production curve of the renewable energy: The technology chosen for the renewable resource critically affects the amount of available energy for the hydrogen plant. It is normally dictated on the selected geographical location and its meteorological conditions, such as the level of solar irradiation and/or the wind resource. A reliable or accurate production curve information leads to a more precise calculation of the LCOH,
2. The capital cost (CAPEX): Accounts for the cost of developing a holistic infrastructure for the planned hydrogen production, inclusive of the renewable energy system, the hydrogen production technology, auxilliary equipment or services such as water treatment, the compression and cooling system or hydrogen storage, as well as the upgrading of existing equipment. A reliable LCOH depends on the precision of the engineering design that comprises the technology selection, system integration and system sizing.
3. The OPEX cost is operating and maintaining the production facility. It is the expenditure incurred in the normal operation of the plant's production. This estimate considers water consumption, the cost of renting the land, or the annual maintenance required for all the assets. An important factor to consider in this cost is the potential use of energy from the electricity grid. When the business model believes that this consumption is desirable, the Power Purchase Agreement (PPA) must be very well detailed as it will affect not only the taxonomy of the Hydrogen produced but also the financial modelling.

The Levelized Cost of Hydrogen (LCOH) per kilogram (kg) of hydrogen determined by the Department of Energy (DOE) is $1.69/kg for Steam Methane Reforming (SMR) with Carbon Capture and Storage (CCS) and $1.64/kg for Autothermal Reforming (ATR) with CCS [52]. These values are based on a detailed assessment of the cost components involved in hydrogen production using these technologies, including capital costs, fixed and variable operation and maintenance costs, fuel costs, and CO_2 transport and storage costs. The Department of Energy (DOE) has not explicitly provided a specific LCOH/kg for electrolysis in the report. However, the report mentioned various LCOH values achieved or projected for hydrogen production using different technologies and energy sources, such as wind energy, solar PV, and electrolysis. The LCOH values range from USD 1.14/kg by 2030 using electrolysis technologies to USD 3.29/kg to USD 4.15/kg for PV-powered electrolysis with specific cost reduction strategies [53], [54]. These values reflect the ongoing efforts to reduce the cost of hydrogen production and make green hydrogen more competitive with conventional hydrogen production methods.

As presented in Table 4, the LCOH for each HRS differs due to the cost of resources and energy conversion technologies. Minutillo et al. [55] evaluated that the the calculated LCOH values range from USD 10.46/kg to USD 14.10/kg and is proportionate to the grid-dependency as well as the hydrogen production capacity. Gökçek and Kale [50] evaluated the LCOH for servicing 25 vehicles per day, each has a 5 kg tank with USD 8.92/kg for the hybrid wind-photovoltaic-battery system. A study by Zhao and Brouwer [56] evaluated the LCOH to be USD 9.14/kg, whereas Barhoumi et al. [57] estimated an LCOH of USD 3.74/kg for a hydrogen capacity of 150 kg/day without considering the costs of auxiliary facilities.

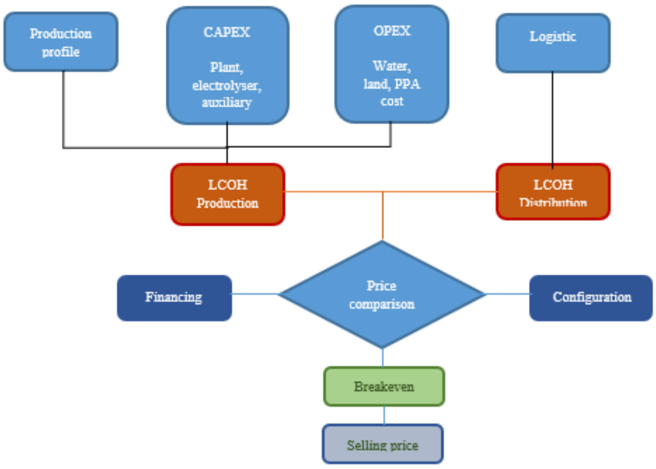


Figure 5. Process flow of LCOH calculation

Table 4: Comparison of LCOH

Analysis by	**Energy source**	**HRS Capacity (kg/day)**	**H2 source**	**H2 production**	**LCOH/kg (USD)**	**Remark**
Gökçek & Kale [50]	Wind-PV-battery	125	Water	Electrolysis	8.92	
	Wind-battery	125	Water	Electrolysis	11.08	
Zhao & Brouwer [56]	Wind-PV	n/a	Water	Electrolysis	9.14	
	Wind	n/a	Water	Electrolysis	6.71	
Barhoumi [57]	PV	150	Water	Electrolysis	3.74	Exclude auxilary machineries
Perna, Minutillo, Di Micco S & Jannelli E. [51]	SOFC	450	Green ammnonia	SOFC - Pd-Membrane	7.76	
	PEMFC	450	Green ammonia	Cracker – PEMFC – Pd-Membrane	7.07	
	SOFC	450	Green biogas	AutoThermal (ATR) & Pd-Membrane	8.17	
	PV	450	Water	Electrolysis	8.92	
Gu [15]	PV	500	Water	Electrolysis	7.12	
Bahou [58]	Hybrid – PV & grid	152	Water	Electrolysis	9.18	
	Hybrid – PV & grid	30.4	Water	Electrolysis	12.56	
Minutello [55]	PV	50	Water	Electrolysis	10.46	
	Hybrid – PV & grid	200	Water	Electrolysis	14.10	
Micena [59]	Hybrid – PV & grid	185.4	Water	Electrolysis	8.96	
	Hybrid – PV & grid	19.8	Water	Electrolysis	13.55	

The LCOH of small-scale HRS based on solar PV-electrolyzer varies based on the estimated hydrogen load and accounted auxiliary facilities such as the compression, storage, and dispensing units. Perna et al. [51] presented a techno-economic assessment of a large scale on-site HRS producing 450 kg per day of hydrogen from green ammonia, biogas, and water hydrogen sources. The ammonia-based configuration was found to be the best solution in terms of hydrogen production energy efficiency with a LCOH in the range of USD 7.07/kg to USD 7.76/kg. The LCOH using solar PV-electrolyzer configuration was evaluated at USD 8.92/kg, or 26% higher than ammonia-based hydrogen, due to the investment (62% from total), maintenance and operational costs (35% from total). The main advantage of solar PV hydrogen is the low value of replacement cost as it was analysed that no replacement of PV panels is needed during the plant lifetime.

Other strategic techno-economic studies of local HRS using renewable solar PV have been conducted by Gu et al. [15] for Shanghai in China, Bahou [58] for Rabat in Morocco, Minutello et al. [55] for Naples in Italy, and Micena et al. [59] for Guaratingueta in Brazil. These research studies evaluated the LCOH of hydrogen by considering cross-regional and on-site hydrogen supply paths. Strategically operated grid-connected solar PV HRS is deemed as a suitable solution for regions with high solar irradiance and low electricity tariffs.

There are various design concepts of Hydrogen Refueling Stations (HRS) and their potential to reduce the LCOH/kg. These design concepts focus on optimizing the efficiency and cost-effectiveness of hydrogen production and distribution. One key aspect highlighted is the importance of scaling up electrolysers to enhance efficiency, minimize losses, and reduce costs in green hydrogen production. Larger systems achieve economies of scale, operating more efficiently with reduced downtime. Improved design and integration of renewables minimize energy losses by optimizing resource utilization. Economies of scale lead to lower production costs per unit of hydrogen, driving competitiveness against fossil fuels. Technological advancements driven by scaling up improve stack efficiency and durability, further enhancing green hydrogen's viability. Overall, scaling up electrolysers is crucial for advancing the efficiency and cost-effectiveness of electrolysis systems, facilitating the transition to a sustainable energy future [60].

In the long term, a study by the Economic Research Institute for ASEAN and East Asia (ERIA) in 2022 positively indicated the potential of electrolyser technology to be the cheapest hydrogen production route in the future as the technology matures and the market demand increases [61]. Electrolysers are crucial for producing low-emission hydrogen from renewable or nuclear electricity, offering a sustainable energy source for various applications.

The potential of renewable hydrogen production costs to decrease over time is due to technological advancements in renewable electricity generation (solar, wind or hydro) and electrolysis. The progress in solar photovoltaic (PV) technology has been significant in recent decades, with research and development leading to highly sophisticated solar cells that generate more electricity per unit area. The cumulative photovoltaic (PV) installations experienced a remarkable Compound Annual Growth Rate (CAGR) of 30% from 2011 to 2018, signifying a rapidly expanding market. Technological advancements have played a pivotal role, yielding solar cells characterized by heightened efficiency, reduced costs, and enhanced performance across diverse environmental conditions. Recent research and development efforts have significantly contributed to these improvements [62] [63]. Furthermore, advancements in heliostat technologies focus on enhancing system efficiency, reducing material costs, and optimizing operations in solar-thermal power systems. Improved tracking capabilities and AI-powered solutions increase solar energy collection rates, while novel materials like modified silicon carbide lower maintenance costs. Integration of advanced control systems enables operational optimization by minimizing downtime and maximizing energy output. These advancements collectively contribute to reducing the LCOH/kg by enhancing overall system performance and cost-effectiveness in concentrating solar power plants [64].

In a bid to ascertain the long-term performance of PV equipment in various climates across the United States, the PV Lifetime Project conducted by the National Renewable Energy Laboratory (NREL) is actively investigating these aspects. The results are crucial in understanding the durability and reliability of PV systems [65]. Emphasizing its global impact, the innovation within the PV sector is anticipated to wield substantial influence over the future energy landscape. The Department of Energy's focused research and development program in photovoltaics aims to propel advancements in solar cell technologies, striving for an overall enhancement in PV system performance [62]. Providing essential insights into the solar industry, the Solar Energy Industries Association (SEIA) is a key resource, offering data and research encompassing market trends, policy evolution, and technological breakthroughs. Together, these factors underscore the dynamic nature and promising future of the photovoltaic industry [66].

5.0 CONCLUSION

Globally the transition towards hydrogen economy is gaining positive momentum driven by the needs to mitigate environmental issues and towards zero carbon initiative. Fuel cell electric vehicles or FCEVs powered by hydrogen is the highly potential aspect towards the transition. However for FCEVs to be commercially viable, the availability of hydrogen refuelling stations or HRS at affordable costs is vital. This review has explored the expansion of HRS designs and operations, focusing on the integration of green energy concepts to improve the Levelized Cost of Hydrogen (LCOH). The success of green HRS operations in achieving targeted LCOH is heavily reliant on the cost of energy sources, with solar and wind power emerging as central solutions. Additionally, advancements in technology and optimization of operational strategies are contributing to visible reductions in LCOH.

The comparison of various HRS designs, including on-site and off-site production models, underscores the importance of integrating renewable energy sources for sustainable hydrogen production. The analysis of LCOH across different HRS systems reveals the economic viability of green hydrogen production, with costs varying based on energy sources, production capacities, and technological innovations. A HRS based on the PV-wind configuration is the central option for the initial phase in the energy transition due to its established technology, with hydrogen from ammonia suitable to be installed at later stages of the energy transition at a larger scale.

In conclusion, the transition to a hydrogen economy, particularly in the transportation sector, holds immense potential for reducing carbon emissions and fostering sustainability. With continued advancements in technology and increasing investments in renewable energy infrastructure, green HRS operations are poised to become commercially attractive within the next five to ten years. However, concerted efforts from policymakers, industry stakeholders, and researchers are essential to overcome challenges and accelerate the adoption of hydrogen as a clean and sustainable energy carrier.

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