Hydrogen Technologies and Policies for Sustainable Future: A Review

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ABSTRACT

Hydrogen has recently attracted considerable attention as a promising alternative for addressing energy and environmental issues. Hydrogen is a flexible and clean energy carrier that can be used in various industries, including transportation, manufacturing, and power generation, without emitting harmful emissions. This study provides a detailed review of hydrogen technologies and policies in the context of a hydrogen economy. Hydrogen production is examined with its cost analysis and current technological challenges, in addition to the key aspects of hydrogen storage, transportation and applications. This review also provides a critical discussion of global policies and roadmaps that have been proposed or implemented to achieve a hydrogen-based future economy. These policies include funding for R&D, financial incentives, tax credits, and frameworks. Finally, two key areas that can be exploited to expedite global hydrogen adoption are proposed. First, technological challenges can be addressed by employing an integrated system approach to produce hydrogen for various applications, along with vigorous investment in research on material development in handling/storing hydrogen. Second, policies to accelerate hydrogen adoption should focus on public-private partnerships, media awareness campaigns, and the introduction of green credit scores.

Keywords: Hydrogen Economy, Hydrogen Technologies, Hydrogen Production, Clean Energy, Energy Policies, Sustainability

1.0 Introduction

The global energy sector, which relies mostly on fossil fuels (Ff), is worth an estimated $1.5 trillion yearly. Nonetheless, there are major issues to be addressed, because Ff is not renewable [1]. Energy is essential to the expansion of the global economy. The British Petroleum (BP) Energy Forecast predicts that the global population will increase to 9.2 billion in 2040 and that between 2017 and 2040, the gross world product (GWP) would rise by 3.2% yearly if social preferences, government policies, and technological advancements continue to advance at their current rates and in the same way. Global energy demand will rise by 0.8% to 1.2% annually, reaching 16.4 to 17.9 Gt (gigatons of oil equivalent (Gt) in 2040 as a result of the expansion of the world economy [2].

Energy resources are mostly utilized to meet human needs and improve quality of life, although they occasionally have an adverse effect on the environment [3]. According to the United Nations, successful policies to protect the atmosphere must focus on the energy sector by boosting efficiency and switching to environmentally friendly energy sources [4]. Increasing efficiency, reducing the amount of Ff in the energy mix, incorporating alternative energy sources [3], and implementing carbon capture, utilization, and storage (CCUS) in existing facilities [5] are all direct ways to reduce CO_2 emissions..

It is now generally acknowledged that H_2 may be the best source of energy for the future because it burns cleanly and produces only water vapor during combustion [6, 7]. The direct splitting of certain hydrocarbons using various physical and chemical approaches (thermochemical, electrochemical, and photochemical) to create hydrogen based on carbon catalysts has recently been demonstrated to be a feasible alternative to conventional processes [8]. Methane is a promising fuel for producing hydrogen because it has a high hydrogen-to-carbon ratio, and there are numerous deposits on earth. Conventional techniques for hydrogen generation include fractional methane oxidation and methane steam reforming (SR). Unfortunately, greenhouse gases such as CO_2 are produced by both techniques and should ideally be eliminated or minimized [9].

The vision of the Hydrogen Economy" (HE), which has been proposed [10], refers to an economy in which hydrogen acts as the primary source of energy. To replace the current usage of Ff in the industrial, commercial, transportation, and residential sectors, HE aims to produce hydrogen primarily from readily available energy sources. This economy has been suggested as a long-term solution to the following problems faced by the world is currently facing:

(i) Resources depletion
(ii) Lack of food and malnutrition in underdeveloped nations
(iii) Growing population of the world
(iv) Environmental issues around the world

Effective expansion of HE will have significant positive effects on the economy, energy security, environment, and final consumer [11-13]. The transition from the Ff economy to a hydrogen energy system is hampered by significant scientific, technological, and social obstacles despite its apparent advantages. Hydrogen storage is a serious issue during this transition because of its extremely low density [14, 15]. However, the enormous rewards of HE are thrilling, and governments are enhancing the prospects of this energy model by investing heavily in it [16]. Substantial investments and research on hydrogen production technologies, as well as a fully developed HE value chain, are required to make hydrogen a fundamental component of the energy market [17]. The objective is to improve all aspects of hydrogen production systems, including cost, reliability, safety, and suitability for various end-user requirements, including small-and large-scale, mobile, and stationery. There is a need to develop a highly developed hydrogen infrastructure because current systems for producing hydrogen rely on existing technologies [18]. Strong policies across the entire hydrogen value chain [19] can aid in improving the capacities of hydrogen production techniques and consequently lowering costs, which would result in widespread adoption by the general public, businesses, and governments [20]. Table 1 encompasses the pros and cons of conventional and hydrogen-based economies as well as the challenges associated with each.

This study focuses on the advancement of a hydrogen-based economy by examining the vital factors that influence the adoption of scalable H_2 transitions. The distinctive contribution of this research lies in its evaluation of the intricacies and quality of both technical and policy aspects required to navigate a hydrogen economy. This study attempts to bridge the gap in the literature on the technological status and challenges of the hydrogen economy and policies adopted to enhance global hydrogen adoption. The authors believe that no such review is currently present in the literature that could assist readers of wider interests in understanding the status of a hydrogen-based economy by covering technological as well as policy aspects. Overall, this review serves as a valuable resource for researchers and policymakers interested in learning about the prospects and technical challenges of the hydrogen economy as well as its potential impact on a sustainable future.

Table 1: Comparison between hydrogen economy and fossil fuel economy

Economy	Advantages	Disadvantages	Challenges
Hydrogen	• Potential to solve the humanity's issues regarding environment, energy, population, and poverty [21] • Low carbon emissions and higher energy density per weight than petroleum fuel [22] • Superior efficiency of conversion into energy • Effective and simple conversion to different energy sources [23]	• Hydrogen concentration between (4% - 74%) in air can ignite posing safety risks [24] • Hydrogen embrittlement of metals makes storage and transport risky • The flame's transparency amplifies leak hazards, influencing public opinion and casting doubt on market growth [25] • High production and storage costs	• Existing technologies from nuclear or renewable resources would be inefficient and unsustainable [26] [27] [28] • The lack of materials for hydrogen infrastructures [29] • Delivering and storing hydrogen safely [30]
Fossil fuel	• Widely available, relatively inexpensive, and can be distributed and delivered using the current infrastructure [31]	• Environmental pollution, depletion of Ff, and the climate change [23, 32] • Incurring more cost due to the incorporation of CCS	• Ff depletion will cause about food, water, and security issues [33]

2.0 Hydrogen Production Methods

Hydrogen production spans from carbon-free 'green' hydrogen, generated through renewable energy, to carbon-intensive 'black' or 'brown' hydrogen, which relies on fossil fuel combustion. This production spectrum shown in Table 2 encompasses various 'colors' representing different levels of carbon intensity [34]. Although most hydrogen is currently produced through the CO_2-intensive SMR process, hydrogen can also be created using electricity. Electrolysis, a traditional method for separating water into hydrogen and oxygen using an electrical current, produces hydrogen with no direct emission of carbon dioxide. The power used in electrolysis can be obtained from renewable energy sources and in this case produced hydrogen is referred to as “green hydrogen” [30].

Table 2: The spectrum of hydrogen colors [35-37]

<table>
<tr><th>Specific terms</th><th>Technology</th><th>GHG Footprint</th></tr>
<tr><td>Green hydrogen</td><td rowspan="2">Electrolysis</td><td>Minimal</td></tr>
<tr><td>Yellow hydrogen</td><td>Minimal</td></tr>
<tr><td>Purple/pink hydrogen</td><td>Processes fueled by nuclear energy</td><td>Medium</td></tr>
<tr><td>Blue</td><td>Natural gas reforming + CCUS gasification + CCUS</td><td>Low</td></tr>
<tr><td>Turquoise</td><td>Pyrolysis</td><td>By product of solid carbon</td></tr>
<tr><td>Gray</td><td>Natural gas reforming</td><td>Medium</td></tr>
<tr><td>Brown</td><td rowspan="2">Gasification</td><td>High</td></tr>
<tr><td>Black</td><td>High</td></tr>
<tr><td>Aqua</td><td>Extraction from oil sands (natural bitumen) and conventional oil fields</td><td>Nil</td></tr>
<tr><td>White</td><td>Naturally occurring underground hydrogen and produced by fracking</td><td>Nil</td></tr>
</table>

Because methane constitutes most of the natural gas, hydrogen can be produced using the SMR method, which has an efficiency ranging from 65-75%. Natural gas can also be partially oxidized, resulting in a 50% lower efficiency [38]. The dominant technology for coal gasification is the Koppers-Totzek method, which can generate hydrogen with a purity of up to 97%, and using carbon sequestration, it would be viable to maintain fossil-based hydrogen generation in the short and medium term [39, 40]. Table 3 enlists lists the various processes and methods reported in the literature for producing hydrogen using different feed sources.

Table 3: Description of some process of producing hydrogen

Production Methods	Description
Electrolysis	Electrolysis of water is the process of splitting the water molecule into hydrogen and oxygen using electrical and thermal energy [7]. Solid oxide, alkaline, and polymer membrane electrolyzer are the three main cell types [41] Alkaline electrolyzer is currently the most mature technology for water electrolysis [42]

Thermochemical Water Splitting	Water-splitting thermochemical cycles use repetitive chemical processes to break water into hydrogen and oxygen. The intermediate reactions and chemicals are recycled during the process [43]
Plasma Arc Decomposition	Plasma can release high-voltage electric current due to its electrically charged particles. Natural gas, primarily methane, is broken down by thermal plasma activity into hydrogen and carbon black (soot) [44]
Water Thermolysis	Reaction requires temperatures over 2500 K, at 3000 K and 1 bar dissociation is 64%. Industrial processes fail to separate H_2 and O_2. After cooling to 2500 K, semi-permeable membranes separate the mixture [45]
Gasification of Coal	In a high-temperature, high-pressure reactor, coal is partially oxidized by steam and oxygen, producing mostly H_2, CO, steam, and CO_2 (syngas). The hydrogen production from this syngas is increased using a shift process [46]
PV Electrolysis Methods	PV-based electrolysis requires electrolyzer, accumulator battery set, DC bus bar, AC grid, PV panels, and hydrogen storage canisters. Solar electrolysis costs 25 times more than fossil fuel alternatives to produce hydrogen. Nonetheless, this process's cost has been decreasing and is predicted to drop to 6 [47]
Photocatalytic	Solar radiation-derived photonic energy is transformed into chemical energy through the photocatalysis process [48]
Photoelectrochemical cells (PEC)	In a PEC, at least one photoelectrode is a semiconductor, and one or both photoelectrodes absorb solar light to trigger electrochemical reactions, such as water splitting. Both chemical and electrical energy can be produced by PECs [49]. Heterogeneous photo-catalysts are used in photo-electrolysis at a single electrode that is exposed to sunlight. The electrodes of the electrolysis cell are also powered electrically. Photonic radiation has the effect of reducing the amount of electrical energy needed [50]
Bio-photolysis	Biochemical techniques that produce hydrogen from water are photo-fermentation and bio-photolysis. Indirect and direct photo fermentation are different types of this process as categorized by Kotay and Das [51]. Several microorganisms that are sensitive to light can be used as biological converters.
Fossil Fuel Reforming	At high temperatures, steam or CO_2 and hydrocarbons react to produce H_2 and CO in the steam (or dry) reformer (SR or DR) [52]. Hydrocarbon fuels are converted into H_2, CO, and other compounds by endothermic reforming and exothermic partial oxidation (PO) reactions [53]. Autothermal reforming (ATR) comprises in situ exothermic partial oxidation with O_2, which generates energy for the endothermic reforming reaction [54]. Due to its lower carbon to hydrogen ratio, methane (refined natural gas) is the optimum fuel for hydrogen-rich syngas production [55].
Biomass Gasification	Converts organic compounds into a solid and a gas phase. The solid phase, called "char," consists of the organic fraction that was not gasified with additional inert materials from biomass. The gas phase also known as "syngas", which is first purified from gas compounds containing sulfur and nitrogen, has high heating value and can be used for power generation or biofuel production [56].
Pyrolysis of Natural Gas	This is a thermal decomposition process completed in the absence of oxygen that produces multiple products. It can generate carbon black and has the potential to contribute to carbon dioxide-free hydrogen production in the future, if the carbon by-product is effectively utilized or sequestered [57].

Microbial Decomposition	Anaerobic digestion is a promising process for generating hydrogen and methane through microbial decomposition of organic wastes and conversion of metabolic intermediates [58].

Currently, there are several methods for producing hydrogen, as discussed in the section above. However, the selection of a feasible production method is a complex process constrained by various factors, such as cost, environmental impact, and resources. It can be anticipated that the future adaptation of hydrogen production technologies will be solely dependent on their environmental friendliness and cost of production, transportation, and storage. A summary of these expenses is presented in the subsequent sections to help readers analyze the suitability of the relevant hydrogen technology.

2.1 Cost of Hydrogen Production

Estimating the cost of producing hydrogen is challenging because it strongly depends on the cost of feedstocks, accessibility of existing infrastructure, and level of production technological advancement [44]. Figure 1 and Table 4 present the findings from the literature regarding typical hydrogen-specific production costs and energy efficiency based on different production technologies.

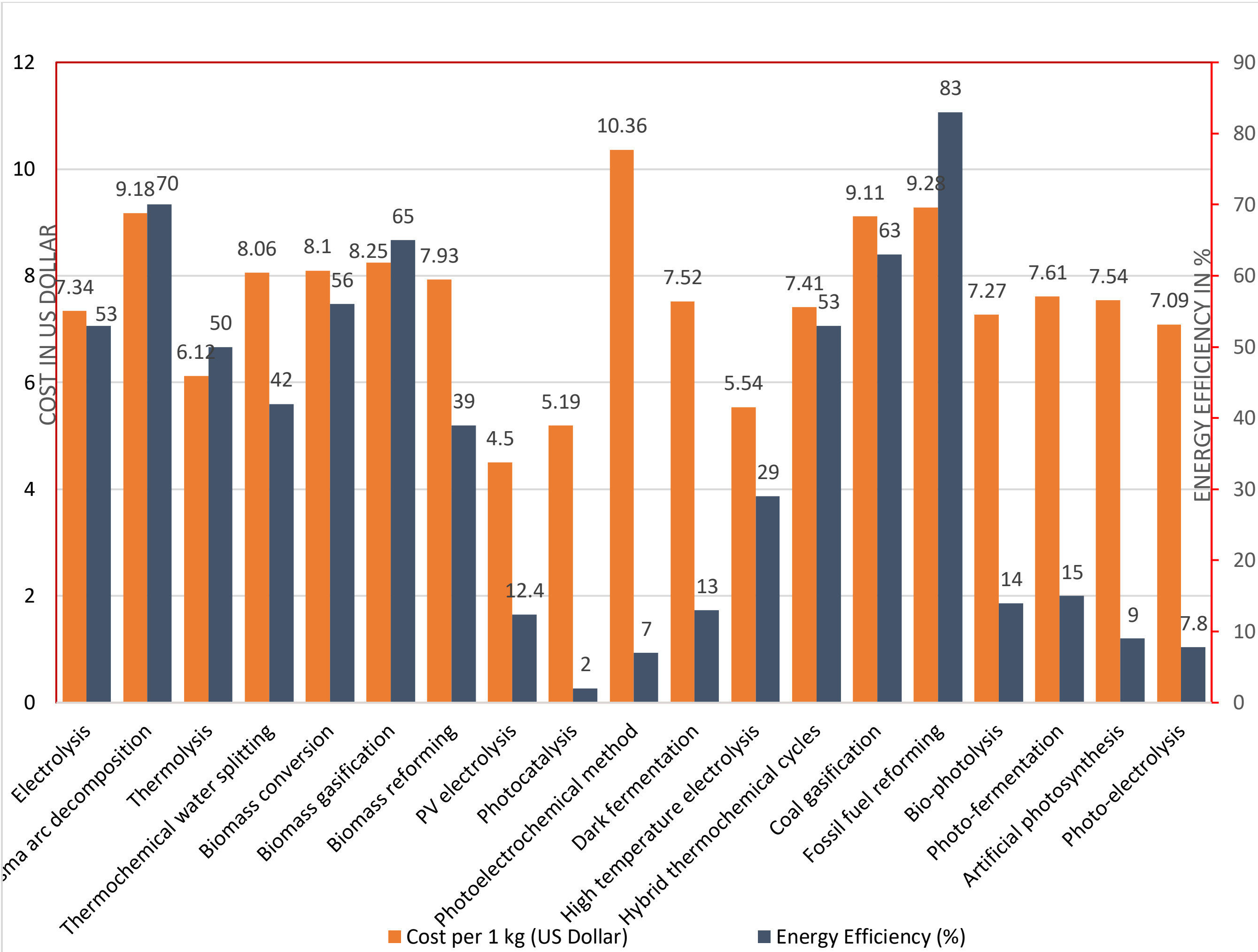

Figure 1:Cost of hydrogen production OPEX + CAPEX ($/kg) and its efficiency [44]

The costs of different technologies from research papers published in 2015 and recent studies for each production method are presented in Table 4. In 2015, an evaluation of the energy efficiency and cost of each production method showed that plasma arc decomposition, coal and biomass gasification, and fossil fuel reforming (FFR) emerged as the most economical processes for hydrogen production. The prices of the thermochemical cycles, biomass conversion, and hybrid thermochemical cycles appear to be comparable to those of Ff and biomass. The most expensive method for producing a kilogram of hydrogen is photoelectrochemical (PEC) systems, but it is still in the early stages of research and development. Hence, as PEC system technology advances, it is anticipated that the production costs of PEC operation will decline in the future [59]. In recent studies, the cost of various hydrogen production techniques has illustrated that steam methane reforming (SMR) and coal gasification (CG) are the most economically viable choices, with a proven track record. Biomass gasification is cost-effective and uses waste materials instead of fossil fuels. Microbial hydrogen production seems promising cost-wise; however, real-world capital investment remains uncertain, relying on laboratory research [60]. It is important to note that the average manufacturing costs used in this study were collected from literature.

Table 4:Cost of hydrogen production using various technologies [44, 60-63]

Denote	Production Techniques	Cost per kg in 2015 (US Dollar)	Energy Efficiency for 2015 (%)	Cost per kg in recent studies (US Dollar)
P1	Electrolysis	7.34	53.0	5.73–8.54
P2	Plasma arc decomposition	9.18	70.0	NA
P3	Thermolysis	6.12	50.0	2.17–8.40
P4	Thermochemical water splitting	8.06	42.0	NA
P5	Biomass conversion	8.10	56.0	2.8
P6	Biomass gasification	8.25	65.0	1.77–2.77
P7	Biomass reforming	7.93	39.0	1.83–2.35
P8	PV electrolysis	4.50	12.4	5.78–23.27
P9	Photocatalysis	5.19	2.0	18.32
P10	Photoelectrochemical method	10.36	7.0	18.98
P11	Dark fermentation	7.52	13.0	2.57–6.98
P12	High temperature electrolysis	5.54	29.0	2.89–6.03
P13	Hybrid thermochemical cycles	7.41	53.0	1.99–14.85
P14	Coal gasification	9.11	63.0	1.34
P15	Fossil fuel reforming (SMR)	9.28	83.0	2.08
P16	Bio-photolysis	7.27	14.0	1.42-2.13
P17	Photo-fermentation	7.61	15.0	2.83
P18	Artificial photosynthesis	7.54	9.0	NA
P19	Photo-electrolysis	7.09	7.8	NA

The UK (BEIS) has published a technical report on the present and anticipated levelized costs of hydrogen (LCOH) production utilizing various technologies for *small plant capacity*. These technologies include steam methane reform (SMR) with CCUS, autothermal reforming (ATR) with CCUS, ATR and gas heated reformer (GHR) with CCUS, electrolysis, and biomass gasification with CCUS [64]. Costs of hydrogen production discussed in the report are summarized here in Table 5.

Table 5: Present and anticipated hydrogen cost for some technologies with CCUS [64]

Technology	Cost of H_2 (£/MWh)		Year
SMR with CCUS (300MW plant capacity)	59		2020
	66		2035
	67		2050
ATR with CCUS (300MW plant capacity)	62		2020
	66		2035
	65		2050
SMR + GHR with CCUS (300MW plant capacity)	60		2025
	61		2035
	60		2050
Alkaline Electrolysis	180*	65**	2020
	161*	53**	2035
	157*	50**	2050
Proton Exchange Membrane Electrolysis	197*	80**	2020
	159*	45**	2035
	155*	42**	2050
Solid Oxide Electrolysis	168*	135**	2020
	135*	75**	2035
	125*	67**	2050
Biomass Gasification with CCUS (59 MW plant capacity) i.e., wood pellet as feedstock	70		2030
	27		2040
	-4		2050

* Grid electricity, price for industrial retail.

**Curtailed electricity with 25% load factor (LF) assumed to be 0 £/MWh

Table 5 shows some comparative LCOH for each technology under the specified conditions. This provides valuable insights into the economic viability and competitiveness of various hydrogen production pathways, and CCUS-enabled methane reforming is currently the cheapest. However, as time passes and fuel prices change, different electrolysis configurations may become cost competitive. The report assumed that negative carbon emissions are as valuable as carbon emissions, allowing production costs to be partially or completely offset by the value of negative emissions [64]. Negative emissions mean capturing and storing CO_2 emissions in such a way that it offsets the CO_2 that would have been released into the atmosphere through natural decay without carbon capture, contributing to the natural carbon cycle. Further sections will delve into a comprehensive discussion regarding action plans, covering policies, technological advancements, and funding strategies aimed at achieving these specific targets to further the hydrogen economy development agenda.

3.0 Hydrogen Economy Development

The decreasing costs of renewable energy and improvements in electrolyzer technology make it possible for green hydrogen to be commercially viable by 2030 [37]. However, this can only occur with significant innovations in the hydrogen industry [38]. Figure 2 shows the "18S approach, " which Dincer and Acar introduced in relation to the elements and dimensions of innovation in hydrogen systems. This approach could motivate both private and public investors to evaluate, comprehend, and implement actions and strategies that would achieve a seamless shift towards a hydrogen economy [65]. Policy must "look definite and credible" for investors to invest in low-carbon, long-lived capital stocks and prevent cost sinking [66]. Kovac et al. stated that without global market and hydrogen acceptability, investment will be wasted, emphasizing that the transition is a global challenge that requires industrial and public acceptance [67].

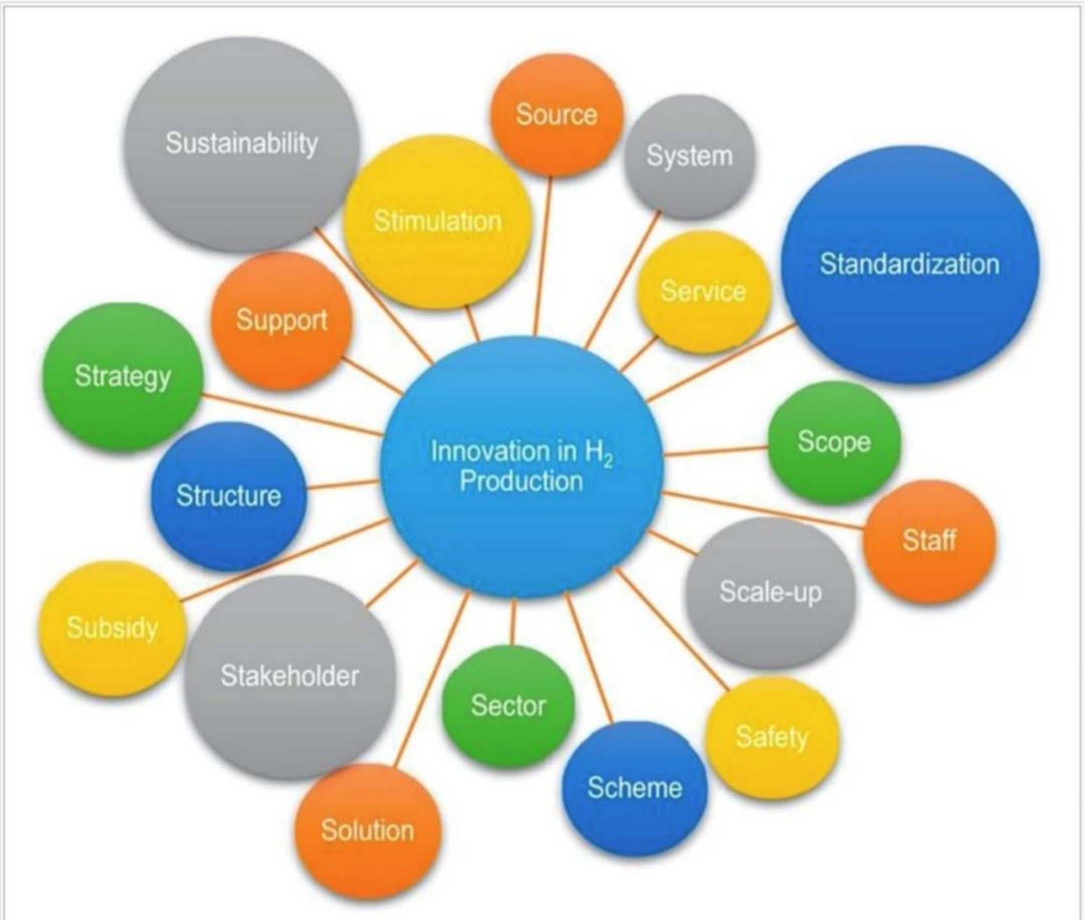

Figure 2:The 18S strategy to developing a hydrogen economy [256]

It is envisaged that developing the hydrogen economy in tackling the global warming issue not only demands a public-private partnership but also emphasizes driving this agenda through friendly policies encouraging the transition from conventional energy resources to hydrogen-based resources. Such a process would require a fool-proof plan in all aspects of the hydrogen economy from its production, distribution, transportation, and storage, thus highlighting the key investment and funding areas for policymakers to ponder upon. Furthermore, a detailed strategy is needed to address public concerns, resulting in more support and acceptance.

3.1 Distribution and Storage for Hydrogen

Hydrogen energy storage and transportation are critical and evolving aspects of the hydrogen economy and are just as vital as production. Their role is to ensure safe and efficient utilization of hydrogen anywhere and at any time [68]. In its pure state, hydrogen possesses a low volume energy density but a high weight-based energy density [13]. Several solutions for hydrogen distribution and transportation are available, depending on the delivery distance, local conditions, and amount of hydrogen. Three techniques have been employed for hydrogen storage: physical storage in the form of compressed gas, physical storage as cryogenic liquid hydrogen, and solid-state storage approaches [68]. The most important methods are the delivery of compressed gaseous hydrogen (CGH2) through pipelines and liquid hydrogen (LH2) via trucks [69]. Hydrogen can be safely pressurized to 700 bar and stored as gas in various structures, including cylinders, containers, and underground cavities [70]. These containers are typically constructed from materials like steel, aluminum, and carbon fiber-reinforced composites [13].

Salt caverns, formed through water-dissolving underground salt rock formations, are composed mainly of halite (NaCl), a chemical sedimentary rock. These caverns exhibit low permeability, limited porosity, strong plasticity, and self-repairing ability after damage. Consequently, they serve as global storage solutions for natural gas and crude oil, and they stand as the sole underground structures proven effective for large-scale hydrogen storage to date [71].

The optimal choice for large-scale offshore hydrogen storage is depleted hydrocarbon fields. These fields, abundant in size, have a proven track record of effectively containing natural gas and oil. In fact, worldwide, 74% of natural gas is already stored in such depleted hydrocarbon fields [72]. Typically, hydrogen (H_2) is injected and withdrawn as the working gas in storage when needed. Meanwhile, cushion or base gases like CO_2, CH_4, N_2, and sometimes even H_2 itself, are stored within the facility to sustain pressure through compression and expansion during injection and withdrawal phases [73].

Compressed gaseous hydrogen technologies vary in operating capacity, including Metal hydride (1-12 m^3/hr), Electrochemical (5-280 m^3/hr), Ionic (750m^3/hr), Turbo (>1000 m^3/hr), Membrane (1-4000 m^3/hr), Screw (200-100000 m^3/hr), and Piston (10-115000 m^3/hr) [74]. They offer benefits for fuel storage, increasing energy density by volume [75, 76]. However, these technologies face challenges such as maximum flow rates, availability, maintenance, and the risk of hydrogen contamination from compressor lubricants [74]. Liquefying hydrogen at 20 K yields a colorless, non-corrosive liquid, offering advantages like higher energy density, compact storage, streamlined hydrogen refueling station (HRS) designs, and reduced hydrogen compression effort [74, 77]. However, research is required to address limitations related to hydrogen uptake and release rates, liquefaction rates, hydrogen boil-off, and tank cost [78]. Table 6 provides an evaluation of different technique for hydrogen storage.

Four types of vessels are used for compressed hydrogen storage:

Type I: The most affordable option, constructed from metallic materials (commonly steel or aluminum alloy) capable of withstanding up to 30 bar of pressure.

Type II: These vessels feature metallic walls wrapped with fiber resin composites on the cylindrical section. They are 30–40% lighter than Type I but cost 50% more.

Type III: Made from carbon fiber composite materials (carbon fiber reinforced plastic, CFRP) with a metal lining, often aluminum.

Type IV tanks consist of primarily composite materials, with the liner typically composed of materials like high-density polyethylene (HDPE) and minimal metal content.

A variation of Type IV includes reinforcement with space-filling skeletons, aiming to achieve even higher hydrogen volumetric and gravimetric densities [79].

Table 6: Assessment of different techniques for storing hydrogen [79]

Storage method	Hydrogen content (wt% H_2)	Volumetric density (g/L)	Volumetric energy density (MJ/L)
Compression			
• 1 bar, RT	100	0.0814[a]	0.01
• 350 bar, RT	100	24.5[b]	2.94
• 700 bar, RT	100	41.4[b]	4.97
• 700 bar, RT, (inlc. Type IV tank)	5.7	40.8	4.9
Liquid hydrogen			
• 1 bar, - 253 °C	100	70.8	8.5
• 1 bar, - 253 °C (inlc. tank)	14	51	6.12
Cryo-compression			
• 350 bar, -253 °C	100	80	9.6
Metal hydrides			
• MgH_2	7.6	110	13.2
• $FeTiH_2$	1.89	114	13.7
Complex hydrides			
• $NaAlH_4$	7.5	80	9.6
Physical adsorbents			
• Activated carbon @77 K and 30–60 bar	5.0	38.5	2.4
• Zeolite (NaX) @77 K and 40 bar[c]	2.55	20	2.4
• MoF (MOF-210) @77 K and 80 bar	25.8	25.8	3.1
Liquid hydrogen organic carriers			
• Methylcyclohexane/ Toluene	6.2	47.3	5.68
• perhydrobenzyltoluene/ benzyltoluene	6.2	56.0	6.72

[a] Calculated from ideal gas law.

[b] Calculated from the standard form of the Peng-Robinson equation.

[c] Assuming same density as activated carbon.

Research on hydrogen storage is being carried out on a more extensive scale in order to develop materials that are secure, reliable, compact, and cost-effective for use in fuel cell technology and in the transportation of hydrogen from its place of production to the end user [77].

Hydrogen storage is the primary technological hurdle in a sustainable hydrogen economy [80]. For hydrogen to be practical for transportation, its energy density should be increased. Currently, hydrogen can be stored in different forms such as compressed hydrogen and liquid hydrogen [81]. Similarly, techniques such as chemical bonding, molecular adsorption, diffusion, van der Waals attraction, and hydrogen release from materials have been extensively studied for the capture and release of hydrogen, as discussed in Table 7 [77]. Moreover, global efforts are underway to resolve transportation and storage issues for the wider adoption of hydrogen fuel. In one such example, Germany suggested that a suitable delivery and distribution infrastructure must be incorporated to guarantee balanced growth of hydrogen technology throughout the nation. Studies on pipeline networks supported by truck transport are excellent endeavors to ensure various potential solutions [82, 83]. The early distribution of hydrogen to hydrogen refueling stations is expected to be dominated by gaseous trailers, with liquid trucks bridging the gap to pipelines. In the distant future, liquid hydrogen carrier ships, which are now being developed in Japan, might potentially pave the way for hydrogen transport by sea. The latter may allow the import of fossil hydrogen (such as from coal) from areas with high CCS potential, as well as renewable hydrogen from remote locations with abundant renewable energy sources but small hydrogen demand centers [84].

Ongoing research and development efforts are focused on enhancing the efficiency of hydrogen production and storage technologies, which could significantly improve the viability and competitiveness of hydrogen transportation. Investing in these technological advancements is crucial to promote the widespread adoption of hydrogen as a mainstream fuel source. Moreover, Government-backing, and supportive policies are vital for advancing the hydrogen transportation sector. Offering incentives, subsidies, and regulatory frameworks can hasten the establishment of a hydrogen infrastructure, spur investment, and drive the adoption of hydrogen as an alternative fuel. Collaboration between governments and industry stakeholders is crucial for fostering an environment conducive to the growth of hydrogen transportation. The subsequent section presents a review of policies and frameworks adopted globally by different governments and planning sectors to transition to a hydrogen-based economy is argued in detail.

Table 7: Different storage mechanisms for hydrogen

Mechanism of Storage	Medium	Description
Chemical	Ammonia	Synthesis, distribution, and catalytic breakdown of ammonia are well-developed [85]
	Formic acid	HCOOH is selectively converted into H_2 and CO_2 by ruthenium catalysts in aqueous solution [86]
	Metal Hydride	At room temperature or after being heated, hydrogen can be absorbed and released later [87] [88].
	Carbohydrate	Liquid hydrogen with high storage density that can also be kept as solid powder [89].
	Liquid Organic Hydrogen Carrier (LOHC)	Unsaturated organic molecules having gravimetric storage capacities of 6 wt.% can store massive amounts of hydrogen, e.g., *N*-ethyl carbazole [90].
Physisorption	Carbon Materials • Fullerenes • Nanotubes • graphenes	• Charge polarization traps of molecular hydrogen on carbon fullerene's metal ion, Li_2C_{60} [91] • 2 nm-thick carbon tubes that store hydrogen in their pores [92] • Hydrogen is stored between graphite layers and released at 450 °C [93]
	Zeolites: • Metal organic framework • Covalent organic framework • Microporous metal coordination materials • Clathrate	• Using MOFs doped with electropositive metals, e.g., Li-MOF [94] • COFs designed with pore diameters equivalent to hydrogen's molecules [95] • Structures with metal building components which can be adjusted for hydrogen uptake and adsorption/desorption [96] • Clathrate hydrates can accommodate guest molecules in their hydrogen-bonded water-molecule polyhedral cages [97]
	Glass capillary arrays	Steel vessels with glass capillary arrays. H_2 is added until the steel vessel attains storage pressure [98]

	Glass microspheres	Hydrogen is injected into glass microspheres at 350–700 bar, 300°C, then rapidly cooled to ambient temperature. For controlled hydrogen release, the spheres are then moved to the low-pressure vehicle tank and reheated to 200–300 °C [99]

3.2 Hydrogen Applications

The majority of current research focuses on the use of hydrogen in all spheres of our social lives, including industrial, residential, and space applications [100, 101]. Their adaptable qualities make them a possible fuel choice for transportation and power production. It can be utilized in the transportation industry as fuel [102, 103], as a carrier of energy [104, 105], and as a medium for storing energy [106-108]. In general, hydrogen is utilized in the production of ammonia [109], petroleum refining [110], and the refining of metals, including nickel, tungsten, molybdenum, copper, zinc, uranium, and lead [111]. Figure 3 visually represents the utilization of hydrogen in both energy generation and as a feedstock in various applications. Nearly all applications where Ff is currently employed are likely to use hydrogen as fuel in the future. Hydrogen would provide immediate environmental and pollution-reduction advantages, especially for transportation [112].

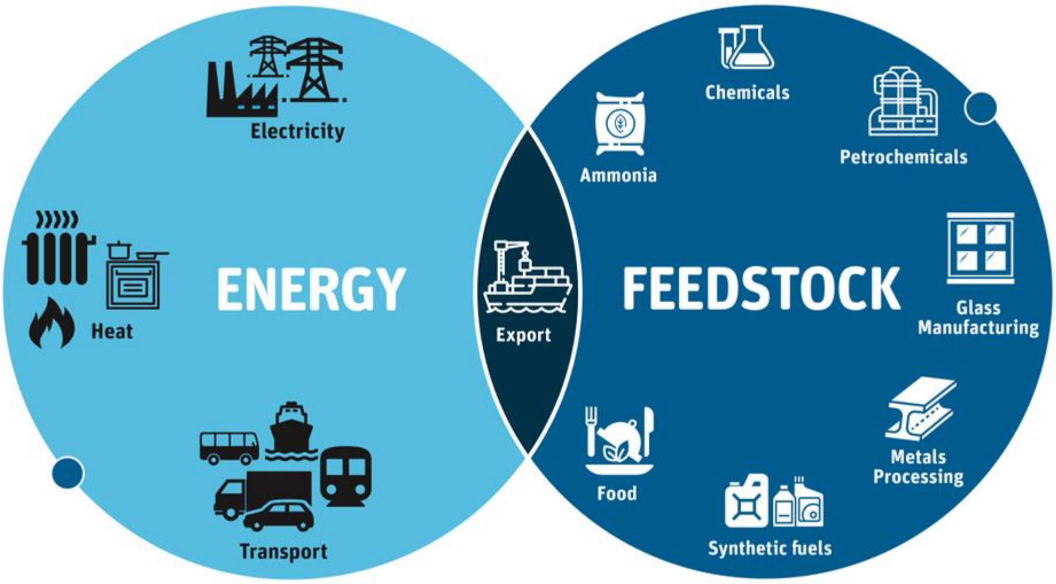

Figure 3: Applications of hydrogen [113]

A recent study on the different uses of hydrogen confirms its major significance for the production of electricity, food preparation, automotive fuel, industries powered by hydrogen, aircraft, and hydrogen villages, as well as for all residential energy needs [113].

The Hydrogen Council evaluated the total cost of ownership (TCO) of low-carbon hydrogen solutions from 2020 to 2050 across various applications, as shown in Figure 4. They compared these costs to those of other low-carbon and conventional technologies. Hydrogen is a primary low-carbon option for certain applications, such as ammonia production and hydrocracking, competing with "grey" hydrogen derived from fossil fuels. 22 applications were identified, in which hydrogen could be cost-competitive by 2030 under specific conditions and assuming scale-up. These applications, including long-distance transport and regional trains, represent a significant portion of the global energy consumption. However, the competitiveness of hydrogen in certain applications relies on the availability of carbon capture and storage (CCS). Hydrogen has the potential to compete with traditional energy carrier alternatives in various applications, including SUV, trains, long-range passenger cars, and long-distance buses. In all cases zero or low-carbon hydrogen is needed with a cost that breaks even with traditional alternatives to make hydrogen competitive against conventional fuels, however, applications regarding industrial feedstock or synthetic aviation fuel would need to be taxed at least 100 USD per ton of CO_2 emission [114].

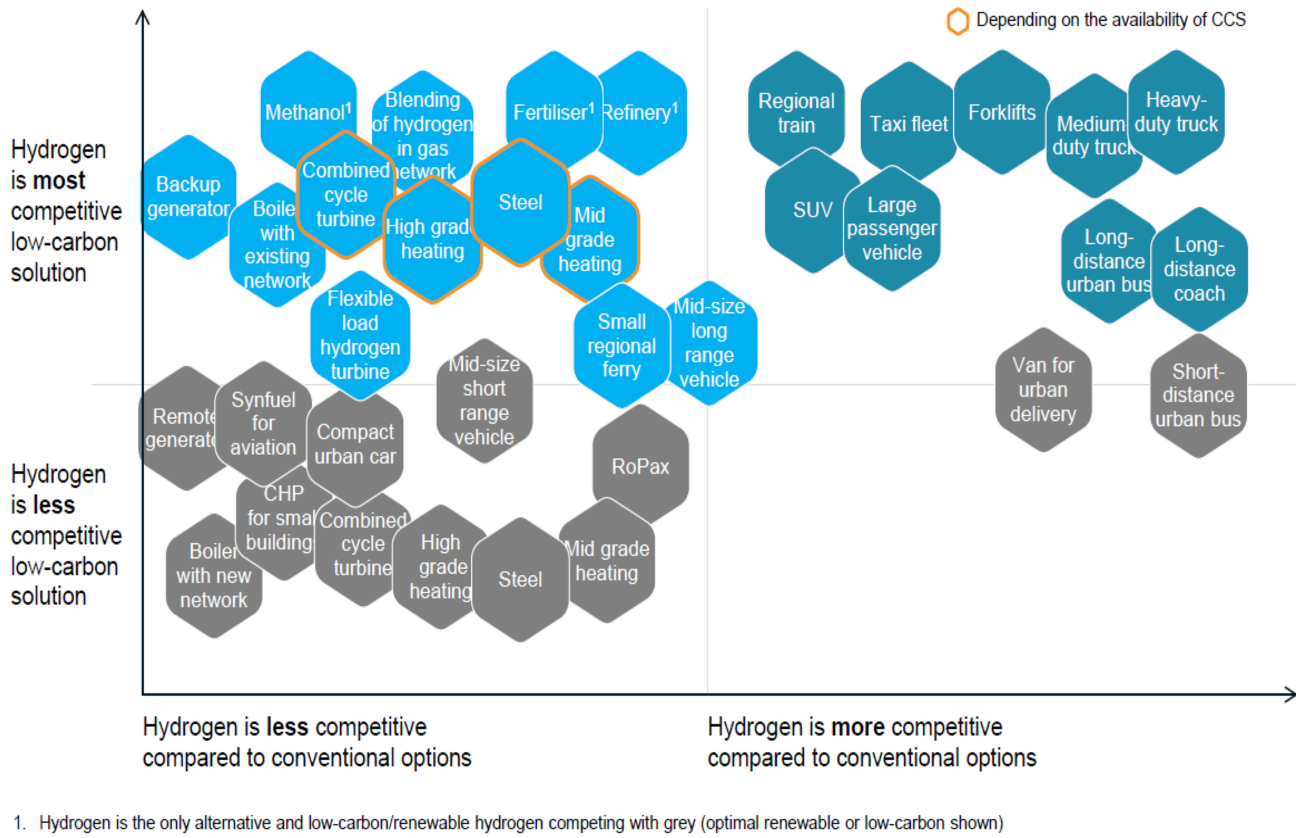

Figure 4: Comparison of hydrogen applications with low-carbon and conventional alternatives in terms of competitiveness [114]

3.3 Policy Development on Hydrogen Economy

Government action is required to adopt hydrogen as a new energy vector to advance at the rate required to support global climate goals. A substantial shift in the way government decision makers and business executives search for clean fuels and renewable energy for their respective nation-states is currently taking place, signaling a huge paradigm shift [115]. When creating policy instruments, one must consider the objectives and constraints of different nations, such as the available resources and the condition of the infrastructure. Several policy alternatives are available. Five major areas were outlined in the IEA Future of Hydrogen Report to make tracking easier. These topics are used yearly by the Global Hydrogen Review to advise decision makers about advancements and implementation shortcomings [19, 116]. The five areas are as follows.

- Provide a vision for the role of hydrogen in the overall energy policy framework to give stakeholders confidence that there will be a future market for hydrogen.
- As a vital tool to encourage its use as a clean energy vector, policies that assist demand generation for low-emission hydrogen are needed.
- Policies to lower investment risks in initiatives along the entire hydrogen value chain, make it easier to acquire financing, and hasten deployment.

- Encourage R&D, innovation, targeted demonstration projects, and knowledge-sharing, all of which are crucial for reducing costs and boosting the competitiveness of hydrogen technology.
- Create suitable regulatory frameworks, standards, and certification systems to ensure best practices, reduce barriers to trade, promote investor and consumer confidence, and facilitate the market for low-emission hydrogen.

These visions typically show a future in which institutional, technological, and infrastructural developments coexist, with a trend towards greener social ideals and a more equal society. In extreme cases, "the redistribution of power on Earth is what the hydrogen economy promises [117]. The potential social benefits of a hydrogen economy are regarded to be the key forces behind the shift, particularly with relation to climate change, but also with reference to energy security, air pollution, the depletion of fossil resources, and "geo-political dominance". Nonetheless, at a micro level, governmental actions, and policy measures, such as funding for demonstration projects, tax structures, and education initiatives are viewed as crucial to influence the establishment of a hydrogen economy. Additional "micro" factors include the advancement of hydrogen and renewable technologies, as well as possible energy-use synergies between buildings and vehicles [118]. The EU prioritizes green hydrogen production by water electrolysis utilizing RES, the strategy involves three steps, (a) From 2020 to 2024, deploying at least 6 GW of electrolyzer to produce 1 Mt of green hydrogen, (b) targets 40 GW of electrolyzer and 10 million tons of green hydrogen, and (c) from 2030 to 2050, green hydrogen technology will reach all hard-to-decarbonize sectors [67]. After the release of the IEA Global Hydrogen Review 2021 more nations are implementing hydrogen policies and nine nations (Austria, Belgium, China, Colombia, Denmark, Luxembourg, Poland, Slovak Republic, and South Africa) have unveiled national hydrogen programs. As a result, a total of 25 nations, including the European Commission, have declared strategies that incorporate hydrogen as a clean energy vector in their plans for the transition to clean energy. When China and the other rising economies are combined, they make up approximately 40% of the emissions currently addressed by national policies, compared to 17% for advanced nations [19].

By the mid-century mark, it is anticipated that hydrogen will be crucial in supplying the energy required to achieve carbon-free global warming. Hub's global integrated assessment models, such as the REMIND model, recently began to include the implementation of hydrogen demand and supply technologies as a research area. Several of the first findings provide some indication of the rising global demand and its timeframes in the context of the implementation of the Paris Agreement targets [119]. For the first half of 2022 through the end of 2021, there has been little progress in adopting strategies to boost demand generation. Most current hydrogen demand generation policies are centered on transportation. Because industry offers the strongest immediate opportunity to generate demand for low-emission hydrogen, very few programs specifically target industrial applications [19]. The EU acknowledged that adequate hydrogen infrastructure and additional R&D are required to increase demand and production [120]. Table 8 outlines the strategies and measures implemented by certain countries to stimulate the generation of demand.

Table 8:Policies adopted by some countries [19]

Countries	Policies
Canada	• Refineries to employ low-emission hydrogen via low-carbon fuel requirements or renewable transportation mandates.
China	• Newly announced regulations for the creation of new sustainable models in the petrochemical and chemical industries, but there aren't any actual rules in place just yet.
Germany	• For a decade, the circulation tax is waived for all electric and hydrogen-powered vehicles.
India	• Impose mandatory quotas for renewable hydrogen in the manufacturing of fertilizers (5% of demand from 2023–2024, up to 20% in the next 5 years), and that the usage of quotas would soon be extended to the steel industry.
Korea	• The number of stations receiving subsidies for the cost of purchasing hydrogen has increased, albeit the amount of support per station has decreased; these stations now provide the largest subsidies for fuel cell electric passenger cars and buses.
Netherland	• In 2022, refineries will be permitted to employ renewable hydrogen as part of their 2025 renewable fuel transportation requirement. • Cabinet's climate policy calls for using hydrogen to reduce CO_2 emissions in industry and transportation by 2030. • Started a program of subsidies for trucks using hydrogen
Norway	• Charge reductions for FCEVs on ferries, toll roads & public parking lots
Switzerland	• Waived road tax fees for Zero Emission Vehicles (ZEVs) that was applied to trucks weighing more than 3.5 tons.
USA	• The adoption of low or zero emissions ferries, including hydrogen, and programs to assist the acquisition of hydrogen buses. • Refineries to employ low-emission hydrogen via low-carbon fuel requirements or renewable transportation mandates (California).
United Kingdom	• Refineries employ low-emission hydrogen via low-carbon fuel requirements or renewable transportation mandates. • It advocates blending an increasing amount of SAF into aviation fuel starting in 2025, with a secondary goal for fuels derived from hydrogen. • Purchased zero-emission buses as part of the ZEBRA program's extended scope.

Investment in new technologies is a common challenge as it is necessary to build a supporting infrastructure that promotes widespread uptake and user satisfaction. A significant barrier to the growth of the hydrogen economy is the continued lack of investment in the hydrogen value chain [121]. Value chains for emerging hydrogen are extremely complicated, and businesses may need government assistance to mitigate investment risks at each stage. The rapid adoption of hydrogen in the economy calls for massive investments in study, pilot projects, and infrastructure construction [122]. Governments across the world are launching programs, such as grants, loans, tax incentives, or contracts, to lower the risks associated with early initiatives and to stimulate private participation. The EU Commission is also adopting Smart

Specialization to promote European regions and cities for financial distribution and development [123].

Countries and companies that take proactive measures to secure reliable technical capabilities in the field of hydrogen technology are anticipated to reap enormous economic benefits because of the long-term effects of constructing relevant infrastructure for the anticipated revolution in future energy systems. Therefore, to make effective R&D investment decisions, governments and corporations worldwide must first understand where their biggest competitors are placing their R&D investments [124]. Several Croatian universities and research institutions are now working on hydrogen projects and have invested a lot of effort to join the top nations in the use of stationary power generation, production, and co-generation technologies for transportation [67]. In addition to numerous business and industrial organizations, the Commonwealth Government and state governments formed several agencies and taskforces linked to hydrogen. Moreover, financial initiatives from federal and state governments have been launched to advance research, feasibility analyses, and project demonstrations connected to hydrogen [125].

The involvement of hydrogen in clean energy transition depends on appropriate rules, standards, trade barriers, and certification systems to ensure its sustainability. These categories serve various purposes. For example, the International Organization for Standardization (ISO) can calculate the carbon footprint of hydrogen production paths and transit from well to gate using a defined technique. The carbon footprint of the hydrogen unit was verified using a certification scheme. Governments have the authority to set standards for hydrogen emissions [19].

An overview of global policies reveals that establishing hydrogen as a central component of energy policy requires a clear vision to ensure stakeholders of its future market potential, which in turn would stimulate the demand for low-emission hydrogen, thus catalyzing its adoption as a clean energy source. In addition, measures to reduce investment risks, streamline financing, and accelerate deployment across the hydrogen value chain are vital for successful policy implementation. Thus, creating an environment that supports research, innovation, and knowledge-sharing is crucial for cost reduction and competitiveness enhancement in hydrogen technology. Finally, establishing regulatory frameworks and standards is essential to ensure adherence to best practices, reduce trade barriers, and foster confidence among investors and consumers, thereby facilitating the growth of the low-emission hydrogen market.

4 Conclusions and outlook

In summary, the hydrogen economy has emerged as a promising solution to fossil fuel challenges, such as pollution and resource depletion, although obstacles remain in the technology, science, and policy realms. Despite these hurdles, hydrogen offers unique benefits, including potential solutions to global energy and environmental issues, and low carbon emissions. Effective production, transportation and storage methods are crucial for safe hydrogen use and compliance with standards. This review assesses various hydrogen production techniques and identifies gasification, and steam methane reforming as cost-effective methods so far and highlights the technological challenges faced by the modern methods such as fuel cell, water electrolysis, biomass gasification especially in terms of cost and efficiency. Comparisons with CCUS-enabled methane reforming indicate cost competitiveness, whereas evolving fuel prices may affect electrolysis configurations. Additionally, the review examines hydrogen storage and application, compares the total cost of ownership with traditional alternatives, and highlights cases of cost parity. It is concluded that the long-distance transportation of hydrogen poses logistical hurdles. Utilizing pipelines, akin to those employed for natural gas may offer an efficient and economical means of hydrogen distribution. Nonetheless, the adaptation of current pipelines or the development of new infrastructure demands meticulous planning and substantial investment.

This review also delineates key areas crucial for decision makers regarding advancements and implementation gaps within the hydrogen industry. These areas provide a clear view of the role of hydrogen in the energy policy framework, implementing policies to stimulate demand, mitigating investment risks, fostering research and innovation, and establishing appropriate regulatory frameworks, standards, and certification systems.

Finally, it is envisaged that the actualization of the hydrogen economy will depend on the implementation of appropriate policies and technological advancements, which will make it competitive with fossil fuels. Overall, the development of clean and affordable hydrogen fuel, cost-effective hydrogen storage, and feasible infrastructure for the transportation of hydrogen remain critical areas of research that require continued innovation and investment to overcome the current limitations and achieve a sustainable future.

Declaration of Competing Interests

NONE

Authors Contribution

Oluwatobi Agbadaola: Original draft writing

Danial Qadir: Conceptualization, Data collection

Faizan Ahmad: Funding Acquisition and Supervision

Humbul Suleman: Funding Acquisition, Project administration

Evangelos P. Favvas: Formal Analysis and Review

Dionysios S. Karousos: Manuscript Review and Editing

Funding Details

Authors greatly acknowledge the European Regional Development Funding Authority for their financial support (No. 34R17P02147).

Acronyms

AC	Alternating current
ATR	Autothermal reforming
BEIS	Department for business, energy and industrial strategy
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CCUS	Carbon capture utilization and storage
CFRP	Carbon fiber reinforced plastic
CG	Coal gasification
CGH_2	compressed gaseous hydrogen
DR	Dry reformer
EU	European union
FCEV	Fuel cell electric vehicle
Ff	Fossil fuel
GHR	Gas heated reformer
HE	Hydrogen Economy
Hf	Hydrogen fuel
IEA	International energy agency
ISO	International organization for standardization
LCOH	Levelized cost of hydrogen
LF	Load factor
LH_2	liquid hydrogen
MH	Metal hydride
MOFs	Metal organic frameworks
OPEX	Operating expenditure
PEC	Photoelectrochemical cells
PO	Partial oxidation
PV	Photovoltaics
R&D	Research and development
REMIND	Regional model of investment and development
RES	Renewable energy system
RT	Room temperature
SAF	Sustainable aviation fuel
SMR	Steam methane reforming
SOEC	Solid oxide electrolyzer cell

SR	Steam reformer
TCO	Total cost of ownership
ZEBRA	Zero Emission Building Research Alliance
ZEVs	Zero emission vehicles
ZIFs	Zeolitic imidazolate frameworks

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