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REVIEW

Policy Implementation Roadmap, Diverse Perspectives, Challenges, Solutions Towards Low-Carbon Hydrogen Economy

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Abstract: Hydrogen is a nearly emission-free energy carrier with many enticing qualities, including wide availability, environmental friendliness, and a high calorific value. There have constantly been a lot of challenges to establish an entire fledge low carbon hydrogen economy in the past century. This study aims to critically analyse the economic, environmental, technological, and policy implementation and division of low-carbon hydrogen to find novel solutions, bridging the gaps and giving a perspective approach to the study. Differentiation of various low carbon hydrogen (LCH) components, including green and blue hydrogen, was also proposed based on the life cycle assessment emissions (LCAE). Current policy perspectives and Promised Pledged Perspectives are considered to project hydrogen demand in 2030. A thorough economic analysis of low-carbon hydrogen system technologies is also conducted from both hydrogen production and storage perspectives by comparing various production and storage systems. Current Policies towards LCH were critically viewed from policymakers, consumers, and R & D perspectives, through which several challenges, gaps, and keynote necessities were also stated.

Keywords: low carbon hydrogen, hydrogen economy, hydrogen production, hydrogen storage, green hydrogen, hydrogen policies, carbon hydrogen economy framework

Abbreviations

LCH	Low Carbon Hydrogen
LCAE	Life Cycle Assessment Emissions
LCHEF	Low Carbon Hydrogen Economy Framework
PV	Photovoltaics
FCEV	Fuel Cell Electronic Vehicles
KT	Kilo Tonnes
CPP	Current Policies Perspectives
PPP	Promised Policies Perspectives
NZE	Net Zero Emissions

CCUS	Carbon Capture Utilisation and Storage
HRS	Hydrogen Refuelling Station
SR	Steam Reforming
PO_x	Partial Oxidation
ATR	Autothermal Reforming
O&M	Operation and Maintenance
LCA	Life Cycle Assessment
OSG	Origin Scheme Guarantees
LCHVC	Low Carbon Hydrogen Value Chain
FCV	Fuel Cell Vehicles
R&D	Research and Development
MOP	Mission-Oriented Policy
GHG	Greenhouse Gases
SDO	Standard Development Organisations
LCHEPF	Low Carbon Hydrogen Economy Policy Framework
BAGS	Bi-Annual Global Summit

1. Introduction

Hydrogen was discovered in 1776 by Cavendish, who then named it phlogiston, which means ‘inflammable air’ (Wright 1858). Since then, there have been several advances towards the production and properties of hydrogen, particularly derived from conventional energy sources like natural gas (*Grey hydrogen, Blue hydrogen and Turquoise hydrogen*) (Hermesmann & Müller, 2022) and coal (*Black hydrogen*) to contemporary energy sources like renewable energies (*Green hydrogen*) (Panchenko et al., 2023; Liu et al., 2022; Yu et al., 2021; Clark & Rifkin, 2006), nuclear energy (*Pink hydrogen*) and solar energy (*Yellow hydrogen*). If we analyse the overall matter of the universe, then hydrogen consists of 75 % of the total matter (Veziro & Barbir, 1992).

Hence, in today’s world, to thoroughly apply hydrogen in our daily lives, hydrogen research should be aligned in the following pathways: a) hydrogen production (electrolysis, catalysis, CO_2 capture, ammonification etc.), b) hydrogen transformation (synthetic fuels, green ammonia etc.), c) hydrogen transport (Shipping, Trucks, Pipeline and Storage) and d) hydrogen end-use (Steel, Chemical, Refineries, Shipping, Aviation, Heating, Power Generation etc.). Once the research is aligned with the specific pathways, then a complete integrated hydrogen eco-system (or economy) can be proposed (Modestino & Haussener, 2015; Schrotenboer et al., 2022; Gao et al., 2014; Mehrpooya et al., 2017; Ghorbani et al., 2023; Zohrabian et al., 2016).

As we all know, one of the primary reasons for using hydrogen is to limit the current global carbon dioxide emissions caused mainly by exploiting carbon-based energy sources. The carbon-based energy sources roughly entail 73.4 % of the total global emissions generated, easily divided into industrial energy, transport, energy used in buildings, unallocated fuel combustion, fugitive energy emissions and agricultural and fishing energy uses.

It is necessary to transition not only into hydrogen energy sources but also to low-carbon emitting hydrogen energy sources to limit such energy sources. For such a transition, it is essential to build a strong foundation in policy-making as well as an economic setup specifically based on low carbon hydrogen. Low Carbon Hydrogen (LCH) consists of roughly four types of hydrogen: green hydrogen, blue hydrogen, aqua hydrogen and turquoise hydrogen (Yu et al., 2021; Pleshivtseva et al., 2023). For the in-depth analysis of different colours and shades of hydrogen, it is essential to understand the overview of the various hydrogen colours, shown in **Figure 1** (Ajanovic et al., 2022). Where mostly all the possible sources of hydrogen are mentioned and differentiated by the respective colours. Further, the primary current avenues of hydrogen energy usage and its future applications, the annual hydrogen production capacity of 90 million tonnes and the corresponding investments of ~ 150B USD have been highlighted. The key to a hydrogen-based economy substantially depends upon the seamless source of inexpensive energy, which is expected to be derived from renewable resources (Yu et al., 2021).

Figure 1
Different Shades and Colours of Hydrogen for proper standardisation and regulations towards supply chain management of sustainable hydrogen types

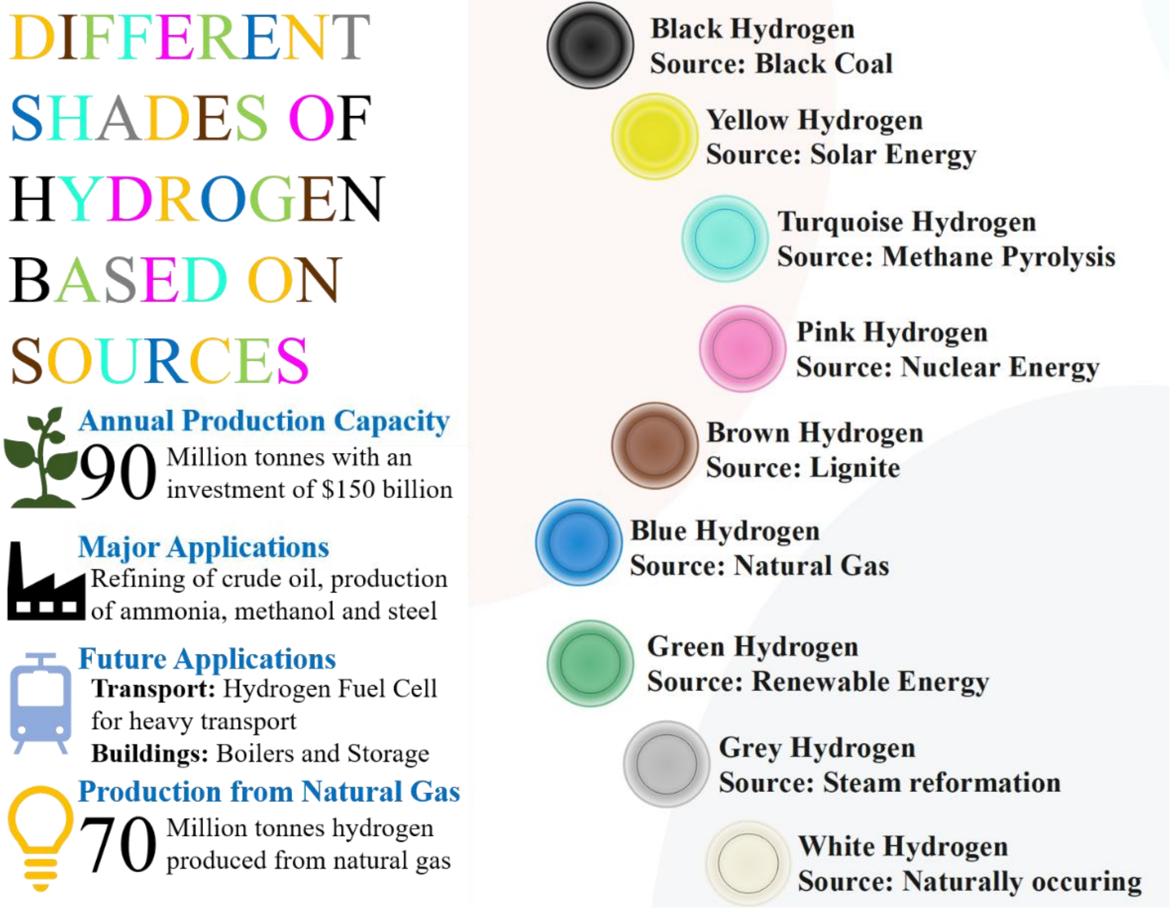
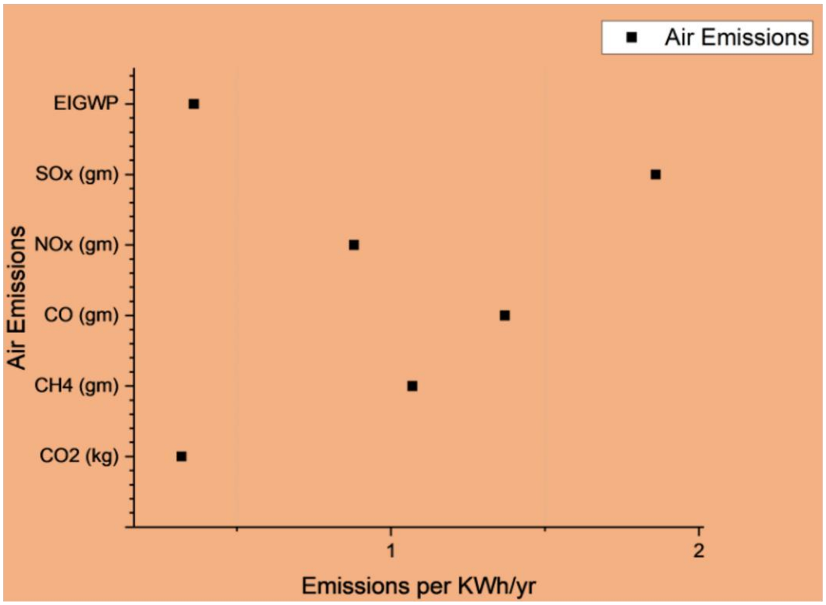


Figure 2
Generalized greenhouse gas emissions data caused by wind turbines and solar panels. (a) Wind Turbine Emissions are distinguished into air emissions and environmental impacts (KWh/year). (b) Solar Amorphous PV System Greenhouse Gases Emissions (G-CO_2/KWh). (c) Solar Monocrystalline PV System Greenhouse Gases Emissions (G-CO_2/KWh). (d) Solar Polycrystalline PV system GHG emissions (G-CO_2/KWh), where EIGWP means Environmental Impacts GWP.

a) Wind Turbine Emissions



b) Solar Amorphous PV system GHG emissions (G-CO2/KWh)

Efficiency (%)	Life Cycle (years)	Emissions (g-CO2/KWh)
6.9	30	15.6
6.3	20	34.3
5.7	30	39
7	30	50
10	20	47

c) Solar Monocrystalline PV system GHG emissions (G-CO2/KWh)

Efficiency (%)	Life Cycle (years)	Emissions (g-CO2/KWh)
8.5	30	280
14	30	60
13	20	64.8
11.5	30	44
10.6	25	165

d) Solar Polycrystalline PV system GHG emissions (G-CO2/KWh)

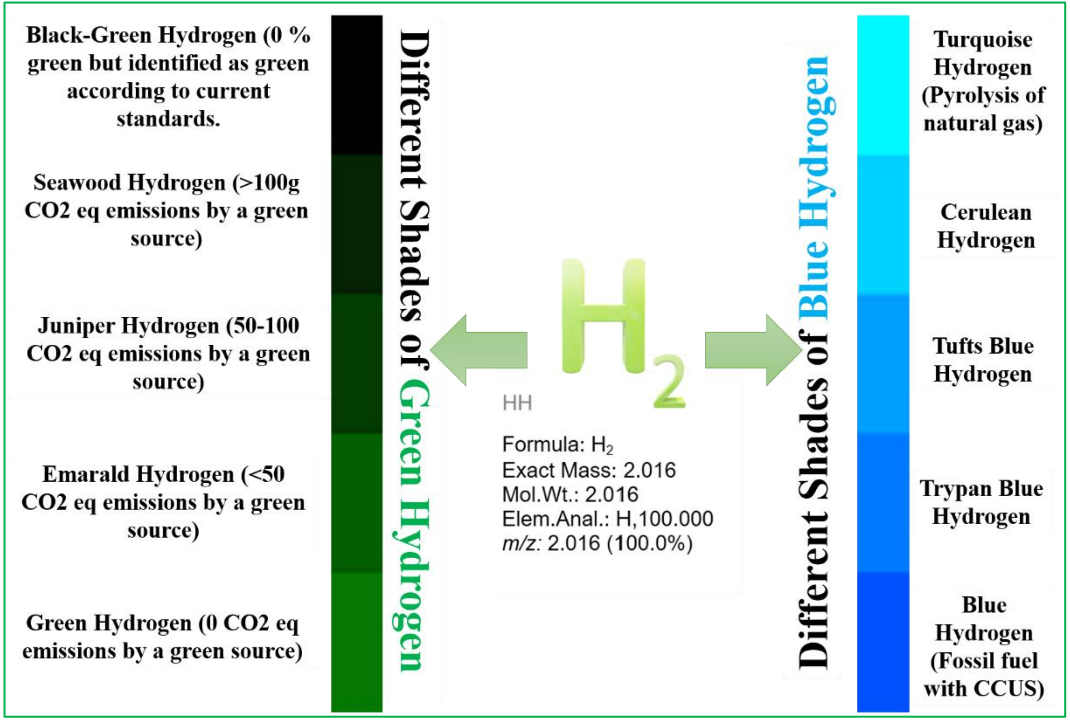
Efficiency (%)	Life Cycle (years)	Emissions (g-CO2/KWh)
12.8	30	12
10	30	53.4
10.7	20	26.4
12.92	20	72.4
12.8	30	12.1

Even though different colours and shades of hydrogen have been pre-defined in most of the cases but there emerged a necessity for the fundamental redefining in the case of several divisions and sub-divisions of hydrogen fuels based upon origin. For example, many renewable energy sources like wind energy, solar energy, biomass, etc., used in hydrogen production technologies, are expected to produce green hydrogen. However, upon close analysis and life cycle assessment data summarized in **Figure 2** (Blaabjerg et al., 2012; Blaabjerg & Ma, 2013; Chen et al., 2009; Hansen, 2012; Mazumder et al., 2013; Singh & Kushwaha, 2017; Rodriguez et al., 2014; Singh & Kushwaha, 2013; Walter et al., 2010), infers that the entire processes are not completely green and can lead to emission of harmful gases including carbon dioxide. The overview of the greenhouse gas emissions caused by wind turbines and solar panels upon analysing the life cycle assessments, life expectancy (usage time) and the types of the materials used in the photovoltaic modules are significant in deciding the carbon emissions. The data related to the emissions caused by wind turbines, and solar PV modules (Amorphous, Monocrystalline, Polycrystalline) is systematically shown in **Figures 2a and 2b, 2c, and 2d,** respectively which clearly establishes that even those process labelled as green and renewable may also contribute significantly towards the CO_2 emissions.

Significantly, the emissions produced due to the following renewable energy production technologies are less when compared to other conventional energy sources. While it is in the right direction towards carbon neutrality and energy transition, it is still not the final step towards a sustainable future and cannot be considered 100 % green. Therefore, it may be preferred to differentiate green and blue hydrogen into further sub-divisions, as shown in **Figure 3.** Meanwhile, it is expected that the researchers, policymakers, environmentalists, and governments initiate, promote and devise action plans towards a pure carbonless hydrogen economy (Mittal & Kushwaha, 2024).

Figure 3

A novel and systematic approach towards differentiating green and blue hydrogen primarily based on emission output in life cycle assessment.



The analysis of the life cycle assessment of solar panels and wind turbines was put forward along with the conventional classification and the novel classification of hydrogen based on the sustainability of the feedstock used for production. Upon such classifications, it is pretty evident that there is an exigent need to develop hydrogen policies. Such policies could only be developed once there are variable perspectives from policymakers to researchers to the public. Once such perspectives are gathered and combined with national and global surveys based on hydrogen demand and LCH economy setup, it will be very impactful to create strong hydrogen policies for the establishment of the hydrogen economy (Mittal et al., 2024).

1.1 Hydrogen demand from current policies and promised policies perspectives

In 2021, the world's demand for hydrogen increased to over 94 million tonnes (Mt), up from 91 Mt in 2019 (pre-pandemic levels) (Chu et al., 2022; da Silva Veras et al., 2017; Hawkes et al., 2002; Maestre et al., 2021). The majority of the increase was for the use of hydrogen in conventional applications, especially in chemicals, with a rise of about 3 Mt and refining, with an increase of almost 2 Mt from 2020. The COVID-19 epidemic had a significant impact on several subsectors, notably refining. In 2021, activity slowed by the lockdowns and the broader economic recession began to pick up, as seen by the rise in hydrogen consumption. Most of the provided hydrogen was made using fossil fuels, which had little value for reducing climate change; greener production was not used for hydrogen production due to the inadequacy of proper facilities, efficiency and affordability of green hydrogen production technologies.

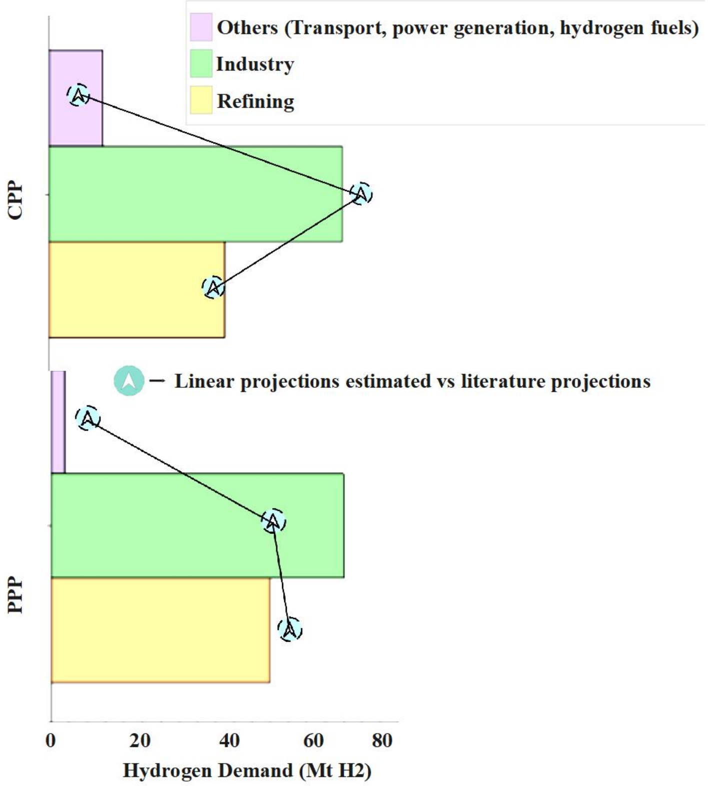
In 2021, there was very little demand for hydrogen in new and modern applications, such as heavy industry, transportation, power generation, the building sector, or the manufacturing of fuels derived from hydrogen, at only 40 kilotonnes (kt) H2 (or roughly 0.04 % of the world's need for hydrogen) (Liang et al., 2023; International Energy Agency, 2022; Trinh et al., 2023). This was mainly for usage in road transport, which saw considerable growth (60 %) even though it started from a low base. This is due to the faster deployment of FCEVs, notably in China's heavy-duty trucks.

The hydrogen demand based on sectors, which include refining, industries, transport, buildings, power generation, hydrogen-derived fuels and hydrogen blending, is shown in **Figure 4** (International Energy Agency, 2022). Although, this figure provides significant the data from 2019 to 2022 and an estimation for the year 2023 but also provides the relevant projections of 2030 hydrogen demands in million tonnes. The projections were made through the analysis of two perspectives, which include i) Current Policies Perspectives (CPP) and ii) Promised Policies Perspectives (PPP).

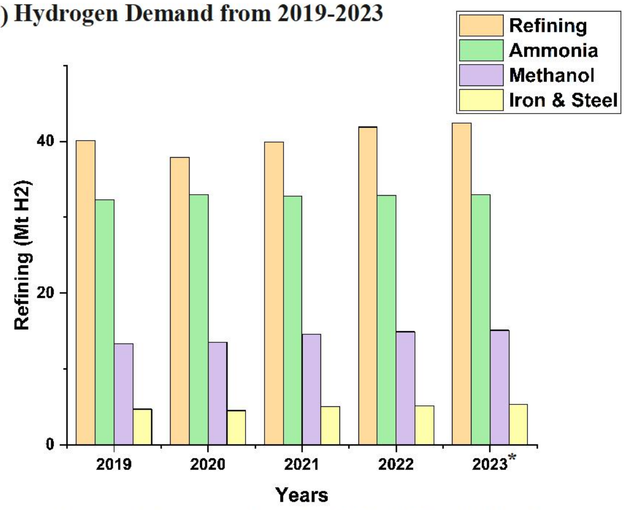
The Current Policies Projections (CPP) represent current policy settings based on assessing the policies implemented and those declared by governments worldwide, sector by sector. By 2030, the CPP's projection predicts that the global demand for hydrogen might reach 115 Mt (International Energy Agency, 2022). Most of this expansion would come from conventional usage, with little need (less than 2 Mt) for novel applications or the further substitution of fossil-based hydrogen in traditional uses.

Figure 4
The Projected Hydrogen Demands both estimated and literature projections for Ammonia, Steel, Refining and methanol production from 2019-2023, and up to 2030 based on Current Policies Perspectives (CPP) and Promised Policies Perspectives (PPP)

a) Promised Policies Perspectives (PPP) and Current Policies Perspectives Projections (CPP)



b) Hydrogen Demand from 2019-2023

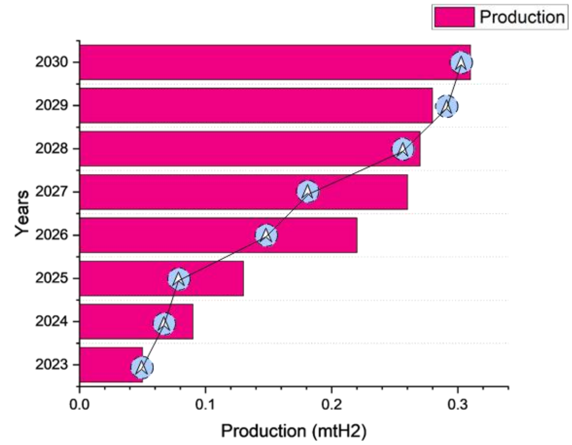


***— Estimated Projections based on 2019-2022 available data**

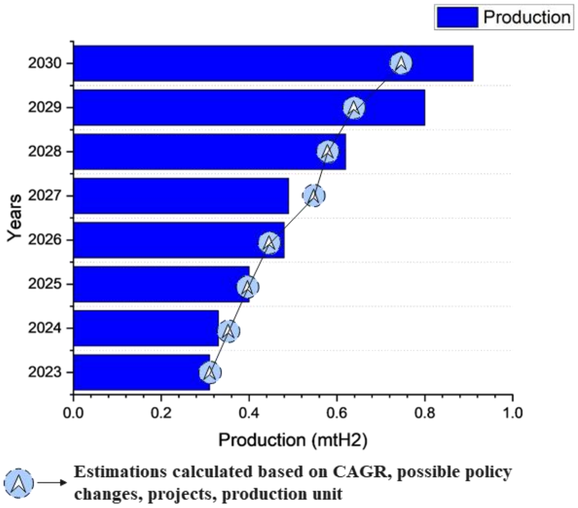
The benefits of keeping climate promises would be minimal. The Promised Pledges Policies (PPP) rely on the complete and timely fulfilment of all climate pledges made by governments worldwide, including Nationally Determined Contributions and long-term NZE objectives. It was observed that the hydrogen demand would be higher in PPP projections than in CPP projections, especially in transport, buildings, power generation and hydrogen-derived fuelling sectors.

Figure 5
Low Carbon Hydrogen Production through a) Electrolysis and b) CCUS in a million tonnes (mt) H_2

a) Production through Electrolysis (mtH_2)



b) Production through CCUS (mtH_2)



Catalytic naphtha crackers and steam crackers for specialised on-site generation utilising unrestricted fossil fuels produce the most hydrogen supply in refining today (approximately 45 % of the reserve each in 2021). Although refineries in China had over 1 Mt of hydrogen from coal gasification in 2021, the latter primarily relies on steam methane reformers fed with natural gas (Yang et al., 2022; Olateju & Kumar, 2013; Sung et al., 2016; Yadav & Mondal, 2020). To satisfy demand, acquired (merchant) hydrogen, the majority of which is created by steam methane reformers, is added to the on-site output. To find a better method for hydrogen production, it is necessary to compare and project the current techniques from 2023 to 2030; these methods include production through fossil fuels synthesised by CCUS or electrolysis, and the projections are showcased in **Figure 5a and 5b** (Yang et al., 2022).

1.2 Motivation of the review and gaps of current research

The first article ever reported on Hydrogen Production was in 1858 by R N Wright; the preparation method stated in his research was a primary decomposition of water. The procedure included passing water vapours over red hot iron bits in a porcelain gun barrel tube; pure hydrogen is obtained through this. It has been nearly 170 years since this research article was published, and still, there has not been a 100 % green, efficient and affordable process to produce hydrogen. Several obstacles and limitations that can be broadly categorised into a few pathways include but are not limited to, waste and cost management challenges, hydrogen transport and storage infrastructure requirements, and environmental safety concerns, which are currently impeding the viability of hydrogen as a viable alternative to fossil fuels (AbouSeada & Hatem, 2022; Bossel & Eliasson, 2003.; Eh et al., 2022; Falcone et al., 2021; Faye et al., 2022; Lebrouhi et al., 2022; Ren et al., 2020; Kumar & Himabindu, 2019; Tseng et al., 2005). A complete overview of the current gaps in low carbon hydrogen economy and research is showcased in **Table 1** (Benalcazar & Komorowska, 2022; Manna et al., 2021; Yue et al., 2021; Timmerberg & Kaltschmitt, 2019; Bloomberg, 2020; Bockris, 2013; Liu et al., 2020).

Table 1
Gaps, challenges and solutions of the current hydrogen economy and research

Gaps	Challenges	Solutions
Economics and Cost Management	1 Limitation of adoption and usage of green hydrogen production procedures. 2 The challenge of declining the cost of renewables for the decrease in green hydrogen generation cost.	1 Increasing end-user demand will also reduce the cost of producing hydrogen through economies of scale, leading to a decrease in LCOH. 2 Spending, regulatory framework alignment, and end-user demand development are required to scale up hydrogen supply options.
Transport and Storage Infrastructure	1 Most massive hydrogen infrastructure projects are still in the research and development stage. 2 Underground pipelines and fuelling stations not close to channels make the hydrogen economy rely on trucks and trailers for transportation.	1 Hydrogen Refuelling Station (HRS) network's density must increase to bridge the gap between remote demonstration fields and the pre-commercial stage. 2 An HRS implementation will enable speedier deployment and commercialisation of hydrogen and safe and affordable hydrogen delivery for the rearrangement of gas pipes for hydrogen transport.
Hydrogen Safety and Environmental Impacts	1 A hydrogen leak will result in an explosion when ignited or sparked. 2 Security and detection are further	1 Setting up standards for hydrogen blending. 2 A dedicated hydrogen network and market need the modernisation and harmonisation

	complicated by hydrogen's odourless, nearly invisible flame.	of regulatory rules controlling hydrogen.
Waste Management	Each year, 2.01 Gt of rubbish accumulates globally and eventually ends up in landfills and water supplies, creating severe environmental problems.	1 Recycling should be done to convert the garbage into hydrogen while boosting waste minimisation and energy conservation. 2 There is also a pressing need for more waste to hydrogen projects and agreements.
Key Technologies	1 The absence of cutting-edge technology. 2 Increasing the commercialisation of hydrogen FCVs would place a high premium and cost on fuel cell-related technology.	1 Commercialise water electrolysis using renewable energy and then work towards the advancements of other technologies.
Hydrogen Standardisation and Specification	1. The overall system and hydrogen refuelling stations' dependability haven't met the acceptable standard, or > 95%. 2. An accurate or standardised measuring technique or instrument cannot check the hydrogen meter's accuracy. 3. No formation of hydrogen quality standards, compliance, and efficient methods.	The only solution is a need for a global agreement to pass several hydrogen standardisation legislative policies to make it strict for every country to adhere to certain hydrogen quality, accuracy and safety measures in general.
Public Ignorance	There was a lot of reluctance to switch to a hydrogen economy among the public. Some of the reasons were their safety measures and comfort with conventional energy sources.	1. Social acceptance is required for successfully implementing a hydrogen economy. 2. There should be policies based on national as well as state laws for a successful implementation of the hydrogen economy.

3. Economic Analysis of Low Carbon Hydrogen Production

Hydrogen should undoubtedly be as inexpensive as feasible. However, the hydrogen economy won't take off until economically and energetically viable. If not, better options will take over the market. Infrastructures are already in place for practically all synthetic liquid hydrocarbons, but a brand-new distribution system is needed for hydrogen (Abe et al., 2019; Bockris, 2013; Bossel & Eliasson, 2003; Demirbas, 2017; Gondal et al., 2018; Bloomberg, 2020; Lee & Lee, 2008; Mah et al., 2019; Milani et al., 2020; Oliveira et al., 2021; Ren et al., 2020) . The whole energy supply and distribution system will change as the world moves towards a pure hydrogen economy. Therefore, all facets of a hydrogen economy should be explored before making investments. Due to its low density, hydrogen is far more difficult to store than fossil fuels. By 2050, 3–4 times more storage infrastructure would need to be created at the cost of $637 billion to offer the same degree of energy security as it now if hydrogen were to replace natural gas in the global economy (Ali Akbari et al., 2021; Carter, 1970; Demirbas, 2008; Eh et al., 2022; Falcone et al., 2021).

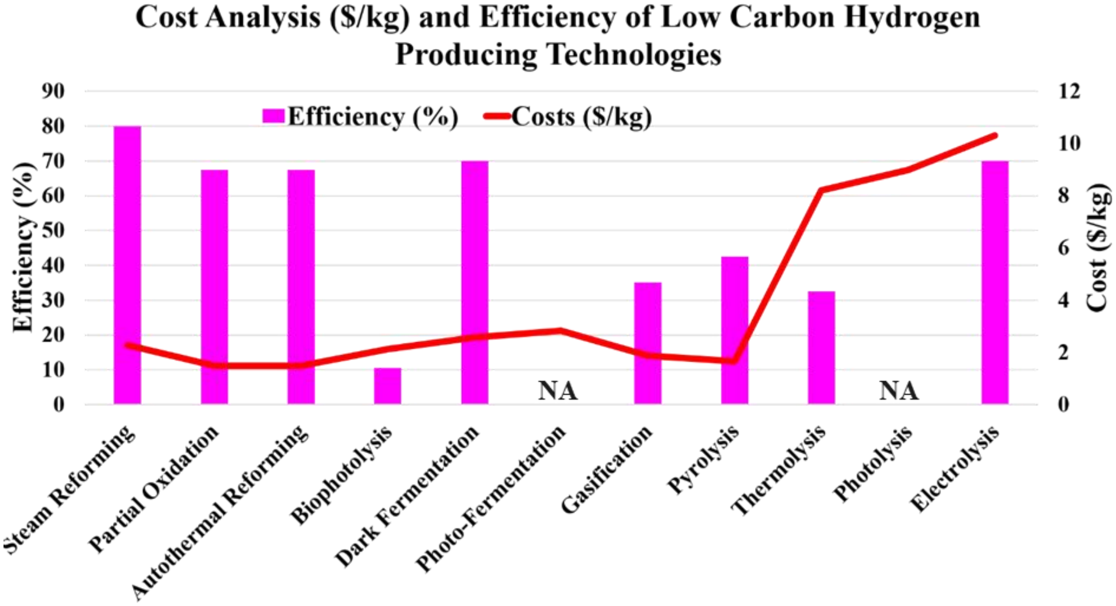
High carbon emissions (grey H_2) are created when hydrogen is produced, mostly from hydrocarbon-based sources. Moreover, while being regarded as carbon-neutral energy sources, green and blue H_2 have high production costs. The most economical option for producing hydrogen from natural gas while retaining minimal carbon emissions is said to be the SMR (Sherif et al., 2005; Tseng et al., 2005; Hasan et al., 2023). To compete with the current commercial production of grey H_2, large-scale green and blue H_2 production systems require a combination of renewable energy sources. Given the potential benefits of the new H_2 policy and carbon pricing, significant green and blue H_2 production can be expected. Due to its ability to connect the green and blue H_2 production systems, H_2 may be a viable option for multi-sectoral decarbonisation. Today, providing hydrogen to industrial customers is a significant global industry. It has been observed that the worldwide demand for hydrogen is still rising and already increased more than triple since 1975. Six of the world's natural gas and 2 % of its coal are used to produce hydrogen. As a result, the generation of hydrogen results in annual CO_2 emissions of around 830 million tonnes, equal to the combined emissions (total or yearly) of the United Kingdom and Indonesia (Green & Stern, 2017; Beasy et al., 2023a) . Large-scale hydrogen storage is one of the biggest obstacles to a future hydrogen economy. The expense of adopting alternate liquid storage methods is frequently more than the cost of creating hydrogen in the first place, and low-cost, large-scale possibilities like salt caverns are geographically constrained (Kar et al., 2023).

2.1 Economic analysis from a hydrogen production perspective

For a prosperous hydrogen economy, it is necessary to have an affordable hydrogen production system and a highly efficient hydrogen-producing facility. For example, bio-photolysis of hydrogen is a very affordable system that costs \$2.13/kg H_2 but has significantly less production efficiency (10-12%). Hence, both variables are equally crucial for a successful transition. The emission produced by the current hydrocarbon-based production pathways, such as steam reforming (SR), partial oxidation (PO_X), and autothermal reforming (ATR), primarily limits the use of H_2 as a clean energy source. Developing environmentally friendly hydrogen production methods like electrolysis has provided a cleaner option for H_2 generation. However, detractors quickly point out that the manufacturing process is energy-demanding even though it produces "green" H_2 and O_2 (Sherif et al., 2005; Clark & Rifkin, 2006; Green & Stern, 2017). Therefore, the process is not overall carbon neutral unless alternative renewable sources are used to lower the energy penalty. Another issue is that green technologies like electrolysis, which produces green hydrogen, have more significant production costs than traditional H_2 production methods, which produce grey hydrogen. **Figure 6** (Chew et al., 2023) demonstrates that the cost of producing H_2 using electrolysis (\$10.3 per kg H_2) is five times higher than that of more established methods (\$1.5–2.3 per kg H_2). As a result, another obstacle to the involvement of H_2 in the energy mix is the expense of "green" H_2 (Chew et al., 2023).

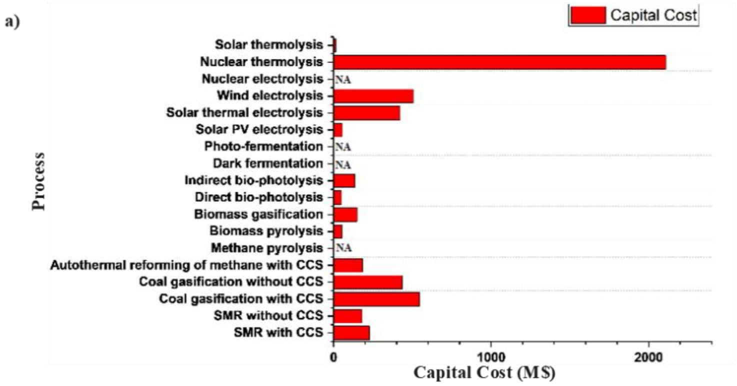
Even if we find the necessary efficiency and cost of generation techniques, we must see their environmental impacts and capital cost in millions of USD for a more secure future hydrogen economy. The ecological effects could be easily assessed by energy sources (fossil fuels, internally generated steam, solar, wind, and nuclear) and feedstock (natural gas, coal, woody biomass, water + algae, organic biomass, and water). Using natural gas with the SMR to produce hydrogen is currently thought to be the most economical option while still emitting little carbon (Chew et al., 2023; Tetteh & Salehi, 2023; Posso et al., 2023; Ferahtia et al., 2023). Large-scale green and blue H_2 production systems' techno-economic analyses indicate that integrating renewable energy sources is necessary to compete with the market's current grey H_2 output (Dillman & Heinonen, 2023; Hong et al., 2023; Zhuang et al., 2023; Akhtar et al., 2023; Khan & Al-Ghamdi, 2023)

Figure 6
Cost Analysis ($/kg) and Efficiency of low carbon hydrogen production technologies to determine the most suitable technology for LCH hydrogen economy

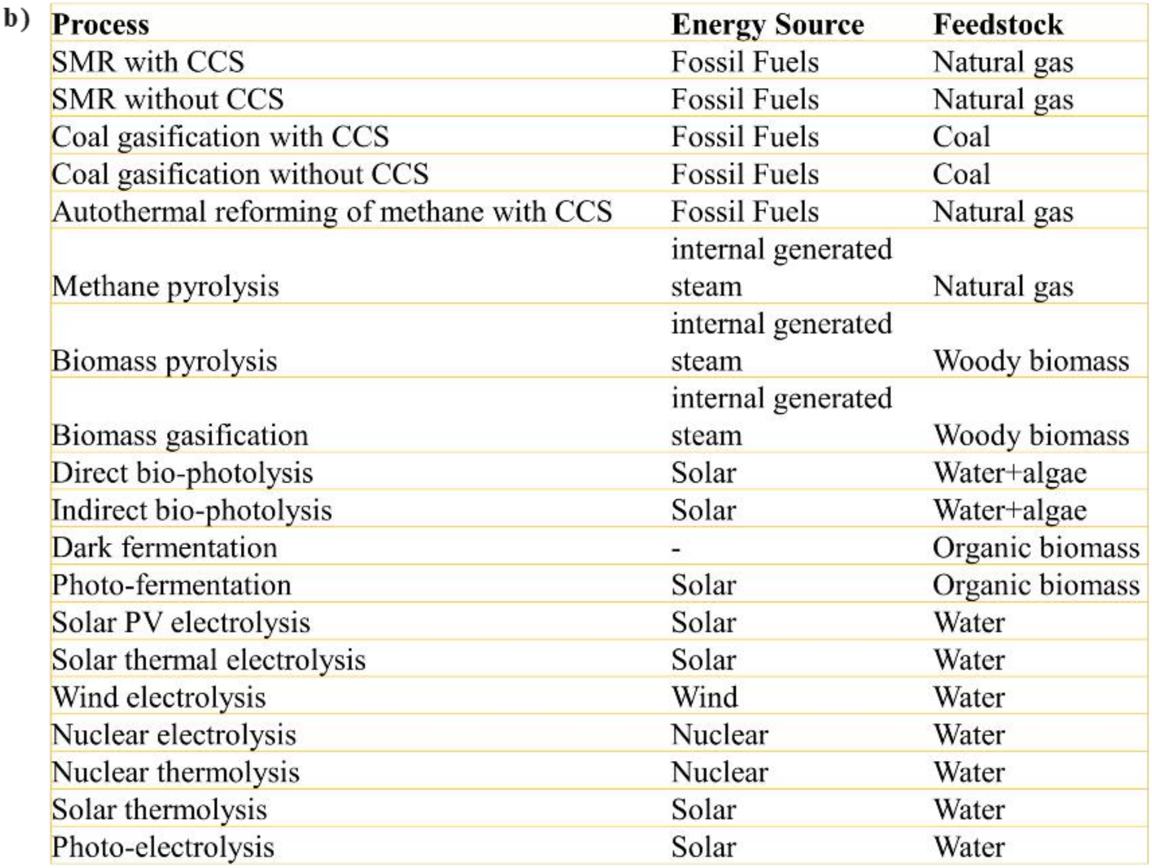


If the carbon tax is implemented, the argument will be considerably stronger. Therefore, the large-scale green and blue H_2 generation can profit from considering the new H_2 policy and carbon pricing. Since it enables connections between the green and blue H_2 production systems and the other energy sectors, H_2 may also be a promising option for multi-sectorial decarbonisation. If integrated techniques are used, the large-scale manufacturing of green and blue H_2 will be more energy-efficient and commercially feasible. Hence, a critical outlook on the processes, energy sources, feedstock, and capital cost in millions of USD is stated in **Figure 7** (Akhtar et al., 2023).

Figure 7
Comparative cost analysis of various low-carbon hydrogen-producing technologies based on capital cost, energy source and feedstock.
(a) Capital Cost for Low Carbon Hydrogen Producing Technologies.



(b) Energy Source and Feedstock for Low Carbon Hydrogen Producing Technologies.



b)

Process	Energy Source	Feedstock
SMR with CCS	Fossil Fuels	Natural gas
SMR without CCS	Fossil Fuels	Natural gas
Coal gasification with CCS	Fossil Fuels	Coal
Coal gasification without CCS	Fossil Fuels	Coal
Autothermal reforming of methane with CCS	Fossil Fuels	Natural gas
Methane pyrolysis	internal generated steam	Natural gas
Biomass pyrolysis	internal generated steam	Woody biomass
Biomass gasification	internal generated steam	Woody biomass
Direct bio-photolysis	Solar	Water+algae
Indirect bio-photolysis	Solar	Water+algae
Dark fermentation	-	Organic biomass
Photo-fermentation	Solar	Organic biomass
Solar PV electrolysis	Solar	Water
Solar thermal electrolysis	Solar	Water
Wind electrolysis	Wind	Water
Nuclear electrolysis	Nuclear	Water
Nuclear thermolysis	Nuclear	Water
Solar thermolysis	Solar	Water
Photo-electrolysis	Solar	Water

2.2 Economic analysis from a hydrogen storage perspective

The power generating (fuel cell) and hydrogen synthesis unit (electrolyser) for the hydrogen energy storage system are independent systems with separate costs which is shown in **Equation 1** (Zhang et al., 2008; Yanxing et al., 2019; Tarkowski et al., 2019; Gao et al., 2014; Furukawa & Yaghi, 2009; Lowesmith et al., 2014; Sazelee & Ismail, 2021)**.**

Total Capital Cost = Electrolyser Cost + Fuel Cell Cost + Hydrogen Tank or Reservoir Cost …………. **(1)**

Suppose a full life cycle assessment (LCA) has to be calculated. In that case, it includes the system's running expenses, such as operation and maintenance (O&M), consumables (such as power), and component replacement costs for parts that don't last the system's lifespan. The annual fee is given in **Equation 2** (Abe et al., 2019)**.**

Annual Cost (\$/KW-yr) = Capital Cost + Fixed Operation and Maintenance Cost + Variable Operation and Maintenance Cost + Replacement Cost + Consumable Cost (Fuel and Electricity)

…………… **(2)**

The lifespan of the system and the capital charge rate affect the cost of capital. Previous studies have determined the expenses of fixed and variable O&M. Throughout the plant's life; replacement costs are annualised for capital expenses. Except for CAES, which also uses natural gas, other forms of energy storage solely use electricity as a consumable. Similarly, the annual analysis of the cost to understand the present values of hydrogen storage can also be calculated as shown in **Equation 3** (Züttel, 2004; Bailera et al., 2017; Orimo et al., 2007; Bradhurst et al., 1983). The various assumptions taken for **Equation 3** are system lifetime (20 years), capital charge rate (15 %), discount rate (10 %) and inflation rate (2 %).

In **Equation 3**, PV is taken as a current value, F as future cash flow, n is the number of years, and I is the discount rate. $(1+i)^n$ is denoted as the compound amount factor.

$$PV = F_0 / (1+i)^0 + F_1 / (1+i)^1 + F_2 / (1+i)^2 + F_3 / (1+i)^3 + \ldots\ldots + F_n / (1+i)$$

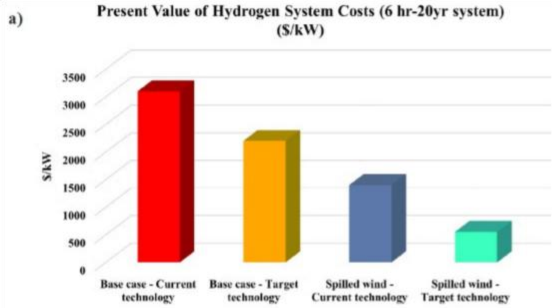
…………..**(3)**

It is essential to know that the equations stated above were taken from the literature to understand the present and future value of hydrogen system costs. Equations **(1)**, **(2)**, and **(3)** justifications and proof are thoroughly presented in the National Renewable Energy Laboratory Technical Report, 2009. (Steward et al., 2009*)*

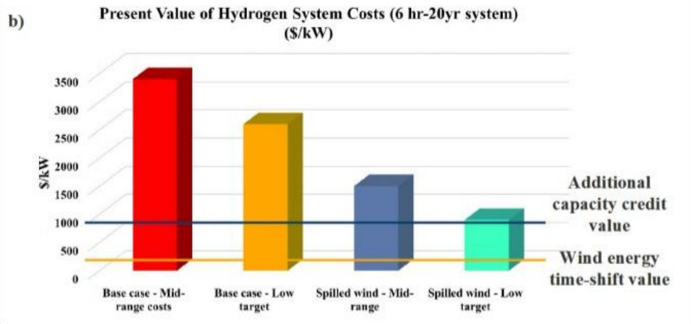
Figure 8a presents the base scenario with current technology and goal technology and the situation of spilt wind (i.e., free charging power) with the present value of expenses for bulk hydrogen systems with 6 hours of storage. **Figure 8b** (Tarkowski & Tarkowski, 2019) depiction of the 20-year current value of these advantages over the present value of expenses hints at a potential market for hydrogen if additive benefits can be realised, affordable charging is made possible, and system costs are within goal ranges.

Up to this point, cost and benefit analyses have been considered on a \$/kW basis. Utility companies frequently evaluate energy storage and production technologies, as has been the case for the past ten years. Estimation based on a \$/kWh basis facilitates comparing energy storage solutions. **Figure 8c** (Liu et al., 2020) illustrates the advantages of renewables integration and capacity credit on a per-kWh basis.

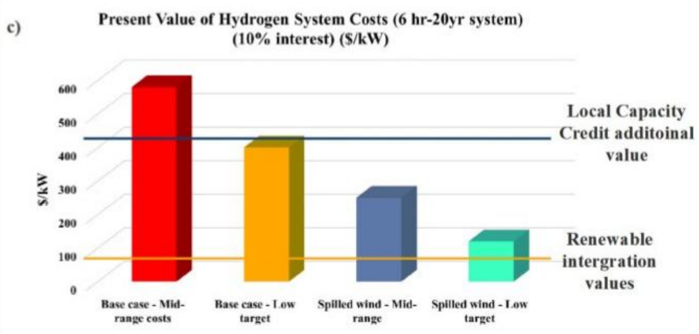
Figure 8
Present and Future Projections of Hydrogen Storage System Costs
a) Present Value of Hydrogen System Costs (6 hr - 20 yr system)



b) Present value of Hydrogen System Costs through Additional Capacity Credit Value



c) Present Value of Hydrogen System Cost through Renewable integration values and 10 % interests



3. Current Policies and Policy Implementations from a Policy Maker's Perspective

One of the significant fundamental questions is the necessity and need for energy transition and sustainability policies. The other important aspect is to project a low carbon hydrogen economy with and without policy implementations (Griffiths et al., 2021; Yang et al., 2023; Velazquez Abad & Dodds, 2020; Li & Taghizadeh-Hesary, 2022). Policymakers can have a beneficial influence on both the environment and people by putting into practice a successful sustainable policy or project. In addition to enabling businesses to make a difference, this strengthens their value chains, bottom line, and reputation on the national, international, state, and corporate levels. Some of the necessary vital notes that policymakers should use for implementations of low carbon hydrogen production are demonstrated in **Table 2** (Carlsson & Jacobsson, 1997; Demirbas, 2017; Falcone et al., 2021; Falkner, 2016; Griffiths et al., 2021; Horowitz, 2016; Savaresi, 2016; Trinh et al., 2021.; Zetterberg et al., 2012).

Table 2
Necessary Keynotes for Policy Implementations of Low Carbon Hydrogen Production and development changes

Keynote Necessities	Descriptions
Hydrogen Strategies on State, National and International Levels	Each nation must specify the extent of its vision for hydrogen, determine the degree of assistance needed, and offer a resource on hydrogen development for private financing and investment.
Prioritising of Policies	Many different end applications are possible for low carbon hydrogen economy. The applications that offer the most value should be identified by policymakers and given their attention.
Origin Scheme Guarantees (OSG)	The entire hydrogen lifecycle should be taken into account when calculating carbon emissions. Explicit hydrogen and hydrogen-based goods labels must be included in origin schemes to raise customer knowledge and support incentive claims.
Support from Governments and Policy Enabling	Policies should address low-carbon hydrogen's incorporation into the larger energy grid as it gains popularity. To maximise the advantages, industry and civil society must be involved.
Life Cycle Assessment (LCA) and Low Carbon Hydrogen Value Chain (LCHVC)	Offering sector-by-sector advice on how to develop and put into practice low-carbon hydrogen policies.

3.1 Policy Implementation Challenges from a Consumer Perspective

Several barriers must be overcome to hasten the adoption of hydrogen and fuel cells. Lack of coordination between stakeholders (such as automakers, fuel suppliers, and customers) and technology standards, which might promote economies of scale, is a significant impediment. This is a big challenge since many investments in hydrogen energy systems need a long-term horizon of at least 10 to 20 years (Li et al., 2022; Chu et al., 2022). All these problems raise the risks of long-term investments. Additionally, the absence of explicit and legally enforceable carbon reduction objectives deters prospective investment.

Policies include purchase incentives for low-emission automobiles and CO_2 taxation systems for vehicles (such as registration taxes, ownership taxes, etc.). In addition, there are also significant non-financial policies that apply to zero-emission cars, such as the unrestricted use of public parking spaces, the use of bus lanes, and free access to cities' zero-emission zones (Liu et al., 2023; Azni et al., 2023; Hassan et al., 2023) . Furthermore, as Fuel Cell Vehicles (FCVs) are a low-emission vehicle technology and help the automotive sector comply with agreements as well as, stricter fuel efficiency criteria would boost the deployment of FCVs.

Policymakers must provide a solid, long-term policy and regulatory framework that directs the transition to a clean energy economy in all sectors if they want hydrogen to play a significant role in the decarbonisation of the energy system. All parties involved in this transformation must work together to coordinate (Ballo et al., 2022; Kamshybayeva et al., 2024; Hong et al., 2023) . The advantages of economies and, subsequently, a decrease in the cost of hydrogen technologies would result from the harmonisation of standards and safety regulations for hydrogen production and its usage across geographical regions and industries; this harmonisation will occur primarily because of safer conduction of research as well free flow adaptation of the technology for industrialisation. The use of hydrogen in the energy system would also be supported by an improvement and adaption of current laws and procedures (such as CO_2 emission restrictions, tariffs, etc.) by long-term environmental goals (Beasy et al., 2023b; Lund & Mathiesen, 2009; Danov et al., 2013; Adhikari et al., 2012).

3.2 Policy implementations from a research and development perspective

Industry decarbonisation through hydrogen will necessitate establishing a supply chain infrastructure and regulatory mechanisms that encourage hydrogen supply and consumption. Although current initiatives focusing on producing and using renewable energy can be built upon, hydrogen-focused policy tools are required.

Figure 9
Top-Down Bottom-Up Mission Oriented Policy (MOP) Framework

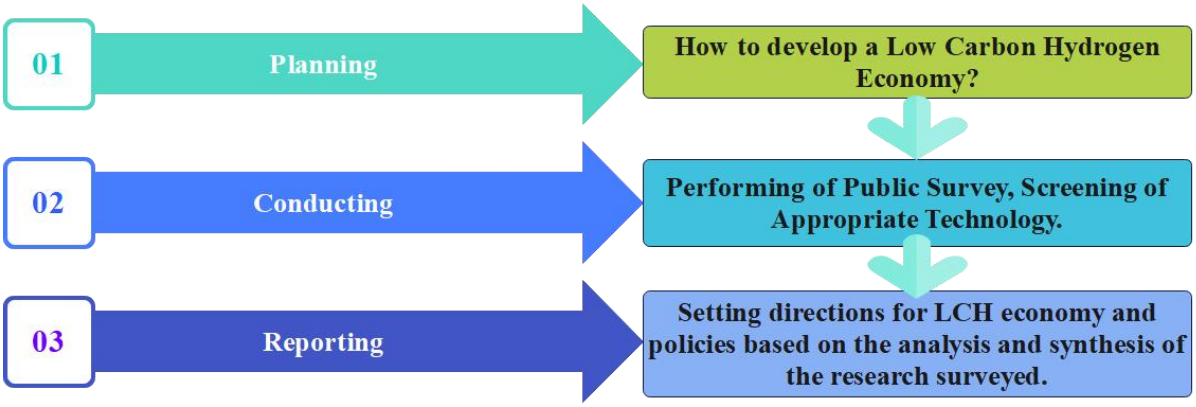


Table 3
Standards and Regulations of Low Carbon Hydrogen Economy based on Research and Development Perspective

Regulations and Standards	Overview
Carbon Dioxide Emissions	1. Foundations of current policies on Hydrogen are built on existing approaches that aim to reduce industrial CO_2 emissions. 2. A lack of solid and well-defined fiscal and financial incentives for the uptake of hydrogen for industrial decarbonisation could be overcome by such regulations.
Energy and Environmental Impacts	1. Hydrogen Policies that encourage the growth of the larger hydrogen ecosystem rather than those specifically relevant to the industrial use of hydrogen. 2. The environmental effects of using hydrogen are typically discussed in policy discussions in various industries.
Origin Scheme Guarantees (OSG)	1. Renewable energy systems currently employ Origin Scheme Guarantees (OSG) to account for lifecycle GHG emissions and allow for geographically segregated production and usage. 2. The certification programmes have also established process boundaries inside the supply chain for emissions accounting.
Low Carbon Hydrogen Safety, Quality and Control	1. Safety, quality and control are three more significant areas where regulatory frameworks for hydrogen are robust. 2. International, national and state standard development organisations (SDO) have thorough rules and standards on current hydrogen applications due to the usage of fossil hydrogen, with end-user safety, process quality assurance, and other environmental effect controls being handled.
Economical Regulations	1. As producers will only introduce hydrogen (up to the blend allowances) when renewable hydrogen is supportive, market price stabilisation for hydrogen blending reduces the price. 2. Excess renewable energy may be used to combine a prediction of renewable energy capacity with one of two hydrogen-compatible allocation strategies, either hydrogen storage or network supply.

National policies include a specific distribution of cash to encourage R&D in academia and business (Barelli et al., 2008; Ćosić et al., 2012; Bauwens & Roels, 2014; Battisti & Tucci, 2014). Providing programmes are also utilised to create specific hydrogen research centres and programmes within centres and provide research project funding. Some frameworks for regulation and certification address the hydrogen sociotechnical system's manufacturing, supply chain, and industrial usage aspects. Regarding the execution of rules, countries have had varying degrees of success in putting policy principles into practice, with many developing nations still in the early stages of building hydrogen policies, as shown in Mexico and Latin America (Jiang et al., 2020; Rose, 1990; Liu et al., 2023; Abad & Dodds, 2020).

Despite the absence of national strategies and policy frameworks (roadmaps, action plans), existing regulatory, certification, and standardisation policy frameworks have been utilised to guide the creation of technical rules on hydrogen usage in new markets. Therefore, national and sub-national (i.e., regional) regulatory bodies should work to adopt harmonised policy instruments or risk being excluded from accessing international hydrogen markets, regardless of whether a top-down (i.e., national policy-driven) or bottom-up (i.e., industry demand-driven) approach to standards-setting is observed which is also shown in **Figure 9** (Dillman & Heinonen, 2022; Park et al., 2022; Krozer, 2019; Rahimirad & Sadabadi, 2023; Ajanovic et al., 2022). The regulations and standards required for low carbon hydrogen based on a research and development perspective are showcased in **Table 3** (Sharma et al., 2023; Wang et al., 2022; Babonneau et al., 2022; Li et al., 2022; Chu et al., 2022).

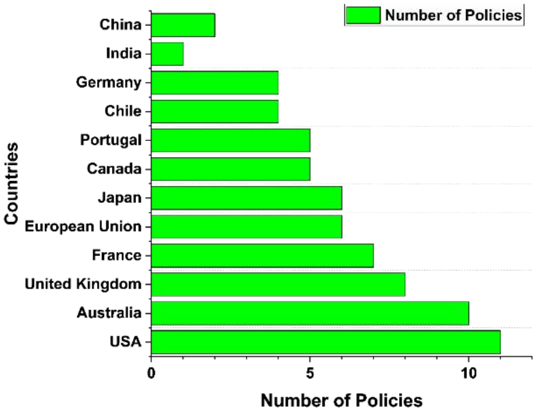
3.3 Roadmap of low-carbon hydrogen policies (LCHP)

Low-carbon hydrogen, if not the final energy transition tool, requires heavy research and development to industrialise and commercialise it. As discussed earlier, Policymaking, implementation and legislative acceptance are international, at national and state levels (Khan & Al-Ghamdi, 2023; Kar et al., 2023) . One of the first policies implemented in the earliest initiations of policies was in 1999 in Denmark, which was based on the hydrogen energy carriers. After that, a significant number of policies have been made on the hydrogen economy, which, once analysed, numbered out to 158, based both on national and sub-national levels.

The areas previously covered by policies implemented included cross-sectoral, transport, buildings, distribution infrastructure, power generation, energy system level, safety management system, industry, legislature, purification, production, etc. Whenever such policies are divided, they are divided into strategy, committee, national law, programme, scheme, funding, financial incentive, road tax exemption, innovation strategy, energy strategy, legislative decree, national plan, etc. (Akhtar et al., 2023; Azni et al., 2023; Beasy et al., 2023a; Beasy et al., 2023b; Chew et al., 2023; Dillman & Heinonen, 2023; Hong et al., 2023; Kar et al., 2023; Liu et al., 2023; Tetteh & Salehi, 2023; Zhuang et al., 2023)**.**

To better analyse the low-carbon hydrogen policies globally, it is crucial to calculate the global and national policies in hydrogen electrolysis technology, hydrogen refuelling stations, hydrogen and CO/CO_2-based chemicals, hydrogen and alternate fuels. **Figure 10** (International Energy Agency, 2022) discusses the low-carbon hydrogen policies in developed and developing countries.

Figure 10
Number of National and Global Policies Implemented in Developed and Developing Countries for Low Carbon Hydrogen



3.4 Comparative analysis of low carbon hydrogen along with alternative renewables: A global policy perspective

To understand the stance of low carbon hydrogen in front of other alternative renewable energy, it is essential to analyse the national and globalised policies implemented for the energy transition, especially for renewable energy sources (Østergaard et al., 2020; Acar & Dincer, 2014; Derksen et al., 1996; Adams & Nsiah, 2019; Uyar & Beşikci, 2017). **Table 4** (Giddey et al., 2017;

Götz et al., 2016) discusses some successful global policies implemented for renewable energy sources, including low-carbon hydrogen policies.

The four primary categories of national and international policy concerns vary by nations
1) policy uncertainties and delayed policy responses to the new macroeconomic environment.
2) insufficient investment in grid infrastructure.
3) bureaucratic administrative barriers and permitting procedures and social acceptance issues.
4) insufficient financing in emerging and developing economies. The accelerated case in this paper demonstrates how resolving those issues can boost the growth of renewables by over 21%, putting the world on track to fulfil the global pledge to triple energy production.

Table 4
Comparative Analysis of Globalised Policies towards Renewable Energy Sources

Policy	Country of Initiation	Year	Renewable Energy Sources
RePowerEu	European Union	2022	Low Carbon Hydrogen/ Solar
Australia-Germany Hydrogen Supply Chain	Australia	2021	Low Carbon Hydrogen
Israel-US Clean Energy Projects	United States of America	2022	Wind Energy
Global Bioenergy Partnership	United States of America	2006	Bioenergy
Global Methane Initiative	United States of America	2004	Biomethane
Cross-border energy infrastructure	European Union	2021	Low Carbon Hydrogen
UKEF offshore wind deal	United Kingdom	2021	Wind Energy
Solar Decathlon	United States of America	2002	Solar
Methane to Markets Partnership	United Kingdom	2004	Methane
Norway-Sweden Green Certificate	Norway	2012	Low Carbon Hydrogen (for green electricity)
Hydrogen Strategy	European Union	2020	Low Carbon Hydrogen
Strategy on offshore renewable energy	European Union	2020	Wind
European Climate and Energy Package	European Union	2011	Biofuels
European Union Biofuels Strategy	European Union	2006	Biofuels
Biofuels Energy Technology Platform	European Union	2006	Biofuels

Solar Thermal Technology Platform	European Union	2006	Solar
Wind Energy Technology Platform	European Union	2006	Wind
Biomass Action Plan	European Union	2005	Biofuels
European Photovoltaic Technology Platform	European Union	2005	Solar
Directive on Biofuels for Transport	European Union	2003	Biofuels

Once the successful ongoing global policies under implementation were analysed, one can draw multiple conclusive remarks:

1) Most ongoing globalised policies towards primary renewable energy sources come from the European Union.
2) From the early 2000s, primary renewable energy sources for which global policies were made usually involved solar, wind, and biofuels.
3) Major low-carbon hydrogen policies came in the 2020s, after the Post-Pandemic Era, in which most of the current global policies implemented globally are of low-carbon hydrogen in the overall renewable energy sources.

3.5 Net zero targets towards LCH from a global perspective

Even though different policies, techniques, life cycle assessments, environment impact analysis, sustainable labelling, climate modelling and techno-economic perspectives could be proposed for several LCH technologies for different industries and countries, it is still essential to analyse the current and recent development of net zero targets for several countries. **Table 5** (Climate Action Tracker, 2023) discusses the current net zero targets towards low-carbon hydrogen globally.

Table 5
Current Net Zero Targets towards Low-Carbon Hydrogen from a Global Perspective .

Countries	Net Zero Target Year
Chile	2050
Colombia	2050
Costa Rica	2050
European Union	2050
United Kingdom	2050
Canada	2050
Germany	2045
Nepal	2045
Nigeria	2050–2070
South Korea	2050
Switzerland	2050
Thailand	2065
United States	2050

Viet Nam	2050
Argentina	2050
Australia	2050
China	2060
India	2070
Japan	2050
Kazakhstan	2060
New Zealand	2050
Russian Federation	2060
Saudi Arabia	2060
Singapore	2050
The Gambia	2050
United Arab Emirates	2050
Türkiye	2053
Bhutan	2050
Brazil	2050
Ethiopia	2050
Indonesia	2060
Morocco	2030
Peru	2050
South Africa	2050
Egypt	No Signified Target
Iran	No Signified Target
Kenya	No Signified Target
Mexico	No Signified Target
Norway	No Signified Target
Philippines	No Signified Target

Well-crafted and ambitious net zero targets are essential to reduce greenhouse gas emissions to net zero by 2050 and 2070. This is required to maintain the 1.5°C temperature limit set by the Paris Agreement 2015. In the near and medium term, ambitious net zero targets can also guide the implementation of Paris-aligned activities, particularly 2030 carbon reduction goals (Horowitz, 2016; Falkner, 2016; Climate Action Tracker, 2023; Mittal et al., 2024). Recently, many countries, especially G20 nations, have drafted net zero promises, comprising firm commitments from various stakeholders, such as environmentalists, governments, citizens, industrialists, citizens, policymakers etc., to envision the Paris Agreement's targets. Although various initiatives and actions are taken by public and privately funded organisations regarding technological solutions, they seem insufficient to fulfil even 20% of the desired values.

The major technologies adopted by countries through which such emissions could be reduced entailed two factors: Carbon Capture Utilisation and Storage (CCUS) and lowering the current emissions. To lower the emissions, green hydrogen is one of the promising energy alternatives towards a low-carbon hydrogen economy and could also play a significant role in targeting the United Nations Sustainable Development Goals (UNSDG) and Environmental footprint (Mittal et al., 2024, Falkner, 2016).

When the G20 countries—India, China, the United States, Russia, and so on—present their net zero emissions, it becomes clear that most targets are imprecisely worded and do not yet adhere to best practices for many design components. It will take short-term solid goals and a clear action plan to reach their full potential, becoming one of the exigent challenges of low-carbon hydrogen technologies. These assessments aim to comprehensively analyse national net zero targets so that their breadth, structure, and transparency can be understood. Without this kind of examination, there's a chance that claims of net zero that aren't adequately supported could become worthless (Mittal et al., 2024).

4. Cost-Benefit Analysis of Low Carbon Hydrogen

A cost-benefit analysis of low-carbon hydrogen is necessary to identify affordable and effective environmentally benign hydrogen production technology. The other crucial element is whether or not all factors deciding whether technology is successful are considered. GHG emissions, consumption of raw materials and utilities, waste disposal, and atmospheric emissions—support renewable techniques over fossil fuel-based technology (Barghash et al., 2022; Brunton, 2021).

4.1 Strength-weakness-opportunities-threats analysis (SWOT Analysis)

To understand the Cost-Benefit Analysis of low carbon hydrogen production, it is also essential to analyse the Strength-Weakness-Opportunities-Threats (SWOT) analysis of low carbon hydrogen production as described in **Figure 11** (Rahimirad & Sadabadi, 2023; Khan & Al-Ghamdi, 2023).

Figure 11
SWOT analysis of Low Carbon Hydrogen Production

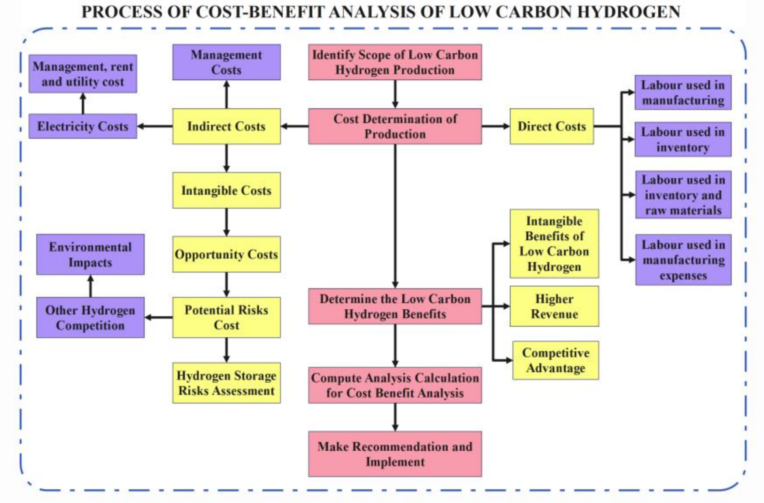
4.2 Cost-benefit analysis of low-carbon hydrogen

A Cost-benefit analysis systematically evaluates a specific plant or project's economic, technological and social performance. For Cost-benefit analysis in LCH, it is necessary to completely break down the analysis process as shown in **Figure 12.** The Process includes different steps to thoroughly analyse the cost-benefit analysis of low-carbon hydrogen which provides for:

1) Identification of Scope of Low Carbon Hydrogen Production
2) Cost Determination of Production
3) Determination of Low Carbon Hydrogen Benefits
4) Computational Analysis of Calculations for Cost Benefit Analysis towards Low Carbon Hydrogen,
5) Making Recommendations and implementing the analysis in the LCH projects or industrial plants.

A complete in-depth analysis of Cost-Benefit Analysis is shown in Supporting Information 1.

Figure 12
Step-by-Step Process of Low Carbon Hydrogen Cost-Benefit Analysis.



5. Future Perspectives

Even though several new hydrogen-producing, storage, and safety technologies have recently emerged, it is still vital for a complete transition to low-carbon hydrogen energy to make it more affordable and efficient. It is also exigent to produce affordable and efficient low-carbon hydrogen and safer hydrogen storage technologies for future research. The demand for hydrogen is growing exponentially compared to other renewable energy sources, and to counter such demand, it is necessary to bring more advancements to the low-carbon hydrogen economy. Even though technological advances should be made rapidly, it is also essential to implement policies to commercialise the applications of affordable and efficient low-carbon hydrogen. In recent times, national strategies have been absent, as well as robust policy frameworks; hence, for a strong hydrogen economy in the future, regulatory bodies must adapt to harmonised policy instruments to commercialise and strengthen the international hydrogen market.

6. Conclusions

The hydrogen economy is the potential future of humankind and the next phase; arguably, the last phase towards energy transition is low carbon/ carbon-less hydrogen energy. Several novelties, challenges, solutions, gaps, and policies were stated in the study, which had conclusive solid points as follows:

1) With less expensive electrolysers and renewable power, the cost of electrolytic hydrogen will surely decrease. However, in areas with inexpensive fossil fuels and CO_2 storage supplies, CCUS-equipped hydrogen will remain a viable choice.
2) A significant life cycle assessment analysis of green and blue hydrogen is necessary, and as shown in the study, green and blue hydrogen should be further differentiated into shades based on their actual emissions caused by respective overall system technologies.
3) There is a significant projection for both CPP and PPP towards the demand for hydrogen in 2030 for transport, buildings, power generation, hydrogen-derived fuels and hydrogen blending.
4) When the solutions to the current research gaps in the low carbon hydrogen economy were analysed, it was adamant to see the exigency to work towards scaling up, increasing the TRL, safety concerns and ignorance shown by the public.
5) Economic analysis from the hydrogen storage perspective showcased the efficiency and affordability of steam reforming, partial oxidation, and auto-thermal reforming. Still, many research gaps exist in decreasing the cost and increasing the efficiency towards electrolysis low-carbon hydrogen production systems.
6) Current policies needed proper district, state and national cooperation. For the start of an economy, looking at the grassroots level first and then moving towards the global level is necessary and highly recommended.
7) The significant research gaps in the current stance of low carbon hydrogen economy were in the economics and cost management, transport and storage infrastructure, hydrogen safety, waste management, and critical technologies. The research found that the most efficient and affordable low-carbon hydrogen production technology was Partial Oxidation (68% efficiency, 10$/kg), and Autothermal Reforming (66% efficiency, 10$/kg).

Since we are undergoing an energy transition, much research, development, industrialisation, and commercialisation are left to implement an LCH economy fully. Based on the current scenario, to reach carbon neutrality as an end goal, it is highly important to address the concerns about the current challenges and gaps faced not only in the LCH economy but also in other renewable source technologies and energy transition alternatives.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflict of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

The data used to have the findings of this study are submitted as a supplementary file.

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