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The prospects of hydrogen in achieving net zero emissions by 2050: A critical review

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ABSTRACT

Hydrogen (H_2) usage was 90 tnes (Mt) in 2020, almost entirely for industrial and refining uses and generated almost completely from fossil fuels, leading to nearly 900 Mt of carbon dioxide emissions. However, there has been significant growth of H_2 in recent years. Electrolysers' total capacity, which are required to generate H_2 from electricity, has multiplied in the past years, reaching more than 300 MW through 2021. Approximately 350 projects reportedly under construction could push total capacity to 54 GW by the year 2030. Some other 40 projects totalling output of more than 35 GW are in the planning phase. If each of these projects is completed, global H_2 production from electrolysers could exceed 8 Mt by 2030. It's an opportunity to take advantage of H_2S prospects to be a crucial component of a clean, safe, and cost-effective sustainable future. This paper assesses the situation regarding H_2 at the moment and provides recommendations for its potential future advancement. The study reveals that clean H_2 is experiencing significant, unparalleled commercial and political force, with the amount of laws and projects all over the globe growing quickly. The paper concludes that in order to make H_2 more widely employed, it is crucial to significantly increase innovations and reduce costs. The practical and implementable suggestions provided to industries and governments will allow them to fully capitalise on this growing momentum.

1. Introduction

The prospects of hydrogen as a sustainable fuel have garnered increasing interest as countries strive to achieve net zero emissions by 2050. Hydrogen has been identified as a potential solution for decarbonizing hard-to-abate sectors, such as heavy industry, transport, and heating.

To attain net zero emissions (NZEs) by 2050, a diverse variety of technology solutions will be required to completely change the energy infrastructure. Energy efficiency, behaviour modification, electricity generation, renewable sources, hydrogen (H_2) and H_2-based fuels, and carbon capture, utilization, and storage (CCUS) are the vital components of decarbonizing the world energy system [35]. The increasing relevance of H_2 in the NZEs Scheme is observed in its impressive growth in total final energy consumption (TFC): in the year 2020, H_2 and H_2-based fuels recorded below 0.1% of TFC; by the year 2030, they will account for two percent of TFC, and 10% by 2050 [14,33].

Nonetheless, this rise in demand is insufficient to make H_2 a vital factor in decarbonization. Hydrogen production should also become significantly more efficient and zero or low carbon emitting than it is now. For example, approximately 80% of the 90 Mt H_2 utilised mostly in 2020 was generated from fossil energy, mainly unabated. The remainder was almost entirely derived from residual gases generated in the petrochemical and refinery industries. This contributed to nearly 900 Mt carbon dioxide (CO_2) emitted during H_2 production, which is comparable to the United Kingdom and Indonesia's combined CO_2 emissions [47,56].

The NZEs scenario transforms H_2 production in an unprecedented way. By 2030, when global output exceeds 200 Mt H_2, 70% will be produced utilising less carbon dioxide (CO_2) systems (electrolysis or CCUS). The H_2 production will then increase to over 500 Mt H_2 by the year 2050, with nearly all of it depending on less-carbon advanced technology. To meet these targets, deployed capacity of electrolysis should increase starting from 0.3 GW currently to nearly 850 GW by the year 2030 and nearly 3600 GW by the year 2050, while CO_2 obtained in H_2 production should rise from 135 Mt presently to 680 Mt in the year

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Abbreviations and acronyms

Net zero emissions	NZEs
Announced pledges scenario	APS
Anion exchange membranes	AEMs
Carbon capture and storage	CCS
Carbon capture, utilization, and storage	CCUS
Carbon dioxide	CO_2
Direct air capture	DAC
Direct reduced iron	DRI
Electrified steam methane reforming	ESMR
European union	EU
European Commission	EUC
Final investment decision	FID
Fuel cell electric vehicles	FCEVs
Hydrogen	H_2
Liquefied Natural gas	LNG
Research and development	R&D
Fuel cells and hydrogen joint undertaking	FCH JU
Final energy consumption	FEC
Greenhouse gases	GHG
International organization for standardization	ISO
International energy agency	IEA
US department of energy	DOE
Mission Innovation	MI
Power-to-liquid	PtL
Memorandum of understanding	MOU
Solid oxide electrolyser cells	SOECs

2030 and 1800 Mt in 2050 [63]. In the NZEs Scenario, strong H_2 market growth and the deployment of environmentally friendly techniques for its processing allow H_2 and H_2-based fuels to mitigate up to 60 Gt of CO_2 emissions in the year 2021–2050, or 6.5% of all accumulated emissions reductions. Use of H_2 fuel is mostly vital for cutting emissions in difficult-to-decarbonize sectors, such as heavyweight industry (especially steel production and chemical manufacturing), aviation, heavy-duty road transport, and shipping, where direct electricity generation is challenging to enforce. Hydrogen can also add flexibility to the power industry by enabling seasonal grid storage and balancing growing renewable energy generation shares [21,52].

Even though the majority of the technological advances that can make a significant contribution are still in their early stages, H_2 is a crucial component of decarbonization for industry. Significant action is being taken. In 2021, the first pilot scheme in the world to manufacture carbon-free steel utilising low-carbon H_2 went into operation in Sweden. A new initiative for the manufacture of ammonia in Spain started at the end of 2021. It will use variable H_2 derived from renewable sources. Over the next two to three years, a number of projects with a capacity of tens of kilotonnes of H_2 are anticipated to start operating. Hydrogen projects for commercial uses like the production of glass, cement, and ceramics are also planned [26]. At least USD 37 billion has been pledged by nations that have implemented H_2 techniques; the private industry has also dedicated an extra USD 300 billion. However, to get the H_2 industry on a path to NZE by 2050, investments in less carbon dioxide (CO_2) H_2 supply and usage via 2030 total $1.200 billion [56]. The majority of government policy initiatives are centred on less CO_2 H_2 production. Less focus is being given to strategies to raise demand. Targets for the deployment of fuel cell electric vehicles (FCEVs) have been adopted by Japan, Korea, France, and the Netherlands. However, a radical shift in demand generation is necessary to increase the contribution of less CO_2 H_2 to clean renewable energy transitions [10]. A broad range of policy measures, such as auctions, carbon prices, mandates, quotas, and prerequisites for public procurement, are beginning to be announced by governments. The majority of these initiatives have not yet proven effective. If they are adopted quickly and broadly enough, more initiatives to increase H_2 demand may become possible [49].

The cost differential between H_2 derived from fossil fuels and less-carbon H_2 is a major impediment. The most affordable option available globally right now is to produce H_2 using fossil fuels. The levelized cost (LC) of H_2 production from natural gas varies between 0.5 USD and USD 1.7 per kilogram, based on regional gas prices (kg). The LC of production is increased to between 1$ (US) and 2 $ (US) per kg by using CCUS techniques to decrease CO_2 emissions from H_2 production. Hydrogen is produced for between USD 3 and USD 8 per kg using renewable electricity [33].

Through advanced technologies and expanded implementation, there is a substantial opportunity to reduce production costs. The possibility is demonstrated via the IEA's NZEs by the year 2050 Scenario, which projects that the price of H_2 produced from renewable sources could reach 1.3 USD per kg by the year 2030 in areas with abundant resource availability (range: from 1.3 to 3.5 USD per kg), making it competitive with the price of H_2 produced from natural gas using CCUS. In the long run, solar PV becomes less expensive with natural gas H_2 albeit without CCUS in a number of locations, with H_2 price via renewable electricity falling below 1 USD per kg (span from 1.0 to 3.0 USD/kg) in the NZE Scheme [12].

Although the deployment of H_2 as a clean energy source is growing, it is still insufficient to contribute to the global effort to achieve NZEs by the year 2050. By 2030, if every technological plan that has been announced materializes, compared to the net zero energy scenario's more than 200 Mt total H_2 demand, actual growth could reach 105 Mt. The electrolysis capacity could increase to 90 GW, which is significantly lower than the roughly 850 GW in the NZE Scheme, and less-carbon H_2 production could attain greater than 17 Mt, which is 1/8th of the production required amount in the NZE Scheme [5]. There could be a distribution of up to 6 million FCEVs, which is 40% more than in the NZE Scheme of 15 million FCEVs [62].

To place the world on the path to an environmentally friendly energy system by 2050, low-carbon H_2 needs to be adopted much more quickly. By establishing a worldwide economy for H_2, nations with limited local supply opportunities can benefit, and nations with significant potential for renewable energy or CO_2 storage can benefit from export markets. Efforts at technological advancement need to be accelerated as well. Today, a number of important H_2 technologies are still in the construction stage [12,41]. We project that as soon as possible, 90 billion USD in public funding must be directed toward clean energy innovation globally, with roughly half of it going toward technologies related to H_2.

Several research projects are currently underway as the use of H_2 has gained popularity in the effort to achieve NZEs by the year 2050. The paper from [17] examines the effects of this transformation on the economy in general, the potential contribution of H_2 to the decarbonization of the domestic energy infrastructure, the potential for H_2 as an export good, as well as the factors that encourage and inhibit large-scale H_2 production in Norway. In [10], the paper reviewed the most recent advancements in the H_2 economy (based on the key pros and cons), but it also focused on identifying the potential effects that this H_2 may have in a variety of industries in aspects of the utilisation of renewable sources and emissions reduction. The [25] review provided an analysis of H_2 development in low-carbon paths from various integrated energy infrastructure designs. The goal was to understand the factors and potential legislative frameworks that favoured H_2 over all other low-carbon technologies on the market. Other reviews on H_2 can be found in [2,6,7,38,39,42–46,48,55,61,63–65].

This paper examines the current state of hydrogen (H_2) and its potential for the future in combating global warming. It assesses the progress made by government, business, and other sectors in achieving emission reduction goals, as well as the initiatives launched in the Global Action Agenda. The focus of the review is to determine how useful H_2 can be in achieving these goals and to provide decision-makers with guidance on how to fine-tune initiatives to attract funding, promote the implementation of H_2 technology solutions, and increase demand for H_2 and H_2-based fuels. The paper also highlights the importance of creating standards and certification to accurately recognize the carbon output of different H_2 production methods, as there is currently a lack of internationally endorsed and accepted standards in this area.

The analysis of this paper is divided into five sections. First, the introduction discusses various advances in hydrogen and the novelty of the paper. The policy trends in section two present the advances made by countries in the adoption of H_2-related policy initiatives. Section three, on global H_2 demand and supply, offers deep analysis of current developments in various fields and technological advances and considers how trends might change over the long and medium-term. The importance of developing facilities and the H_2 trade while boosting demand and supply is emphasised in a section on these topics. Along with the latest developments and the prospects for the H_2 trade, it also describes the state of and prospects for implementing H_2 facilities. To reflect how they collectively support trends in the advancement and adoption of H_2 technology, investment opportunities and technology are combined in section four. Section 4b offers policy suggestions to hasten their deployment in the coming ten years. And finally, section five draws the conclusion of the paper.

2. The policy outlook for major hydrogen implementation sectors

Incorporating H_2 as a novel vector within energy sectors is a challenging task that will not be achieved at the rate needed to achieve climate goals without government involvement. As a result, many policymakers are actively cooperating with a diverse set of decision makers to resolve specific problems and define intelligent policies that can support in this transition. Policies and initiatives must be centred on pertinent key objectives and limitations, such as available resources and infrastructure facilities, because needs differ by industry and country.

Policymakers should focus on the following critical sectors when developing detailed policy systems to encourage hydrogen implementation all over the energy system:

2.1. Encourage and support research and development (R&D), large-scale public awareness campaigns, and information sharing

Technology will be essential to the continued success of H_2. As a result of its higher price compared to unrestricted H_2 produced from fossil fuels currently, low-carbon H_2's adoption is hindered. Early-stage multi-end-use technological advances cannot thrive in free marketplace, in part because they are yet to discovered the scale economies that come with full growth. In order to encourage private industry to innovate and commercialise innovations, authorities play a critical task in establishing the research programme and enacting the necessary policy frameworks [60]. Some selected H_2 R&D projects are presented in Table 1.

Hydrogen technology initiatives are currently not thriving, though some encouraging signs are starting to emerge, and many policymakers have introduced H_2-specific initiatives to finance investments in research and development in technological advances across the whole H_2 supply chain. Even so, existing public R&D spending on H_2 is lower than it was earlier 2000s, when the last wave of funding for H_2 innovations was in place. To avoid bottlenecks along the supply chain, more unified actions will be needed [41]. For effective development initiatives to be implemented, collaborative efforts between the government and business are essential. The FCH JU (Fuel Cells and H_2 Joint Undertaking), which has received more than 1 billion EUR in investment since 2008, is an excellent example of a government-private alliance to support research and development and innovation demonstration. On the strength of its accomplishments, the EC (European Commission) established ''Clean H_2'' for European (Joint Undertaking) towards the end of the year 2021, with a corresponding budget of 1 billion Euro from government financing and business investment till 2027.

The EC also established the Europe Clean H_2 Partnership in July of the year 2021 to pull together businesses, local, state, and federal governments, as well as civil society and other interested parties, in order to develop a H_2 financing initiative. Furthermore, in 2021, the Energy Sustainability sector Chilean launched the Green H_2 Incubator to coordinate key players and offer consultancy services to aid in the development of innovation projects and programs. In order to support the developing renewable H_2 industry in Morocco, decision makers from the private industry, and government developed the Green H_2 Cluster. The First Energy Earth shot for H_2 was started by the US Department of Energy (DOE), putting together interested parties that have the goal of reducing the price of clean H_2 by 80 percent (to 1.00 US dollars per kg H_2) by 2030 [41].

It is possible to link a larger group of interested parties through the use of intergovernmental projects and initiatives that foster knowledge exchange and the creation of best practises. For example, via the H_2 Valley System (A " H_2 Valley" is a location, such as a region, a city, an industrial cluster, or an island, where a number of H_2 systems are brought together to create a unified H_2 environment. This ecosystem uses a sizable quantity of H_2, which improves the project's economic growth. Idealistically, it ought to include the whole H_2 value chain, including storage, production, and end use. As a result, " H_2 Valleys" provide a way to scale this technology up and make it a workable solution.), the FCH JU and Mission Innovation (MI), a company that works to spur R&D investment and initiative, have collaborated to make it simple and easy for people to work together and share knowledge all over the world's more than 30 H_2 valleys. By announcing the H_2 (Clean) mandate in June in the year 2021, MI took a further step toward accelerating R&D in H_2 systems with the aim of bringing down the price of clean H_2 to USD 2.00/kg by 2030. The H_2 Valley Platform will showcase at least 100 H_2 valleys that MI hopes to create [21].

Policymakers and the private industry have developed international co-operation contracts in addition to the plethora of bilateral treaties that have been signed between them recently. Everyone shares the interim to medium-term goal of working together to exchange information, best practises, and technological advancement to lower price. They both have the lengthy-term objective of establishing the groundwork for future global H_2 supply chains to make sure the growth of trade in H_2 and fuels derived from H_2. The energy ministers from the countries that make up the Pentalateral union, Switzerland, France, the Netherlands, and Germany signed a combined political pledge in June 2020 reiterating their obligation to bolster collaboration on H_2 [36]. Table 2 lists a few bilateral treaties between governments to work together on developing H_2.

2.2. Standardisation and barrier-removal

Regarding rules, laws, and benchmarks for the use of H_2, there are two significant concerns that have arisen. The first is the requirement to audit national laws that specify what utilities and energy providers are responsible for. These enterprises should be kept apart by regulatory systems at the moment because of certain factors in the market structure. But if H_2 adoption is viable, it can also contribute to the gas network's adaptability and dependability while also becoming a crucial component of the electrical grid. A new role needing special regulation will be created as a result of H_2 facilitating sector coupling between gas and electricity utilities. The second concern is the requirement for a standardised structure that is based on international or national norms and is adequately relevant to the usage of H_2 and its carriers. Many international groups are involved in this iterative effort. To remove obstacles in the near future, regulations must be modified [41]. The Regulatory Gaps Compendium survey was carried out by Regulations, Codes, Standards, and Safety of the IPHE's Working Group amongst some of the participating nations to ascertain the regulatory requirements in key areas for the implementation of H_2 and fuel cells. Participants offered their opinions

Table 1
A few current H_2 research and development projects.

R&D Programme	Investment and project timeline	Description	Country	Reference
Arena-funded H_2 R&D projects	$22.1 million (AUD). 5 years project.	Arena is a government agency in Australia that invests in renewable energy technologies and projects. Some of the recent projects are the H_2GO, HyP SA and Mingenew Irwin Group Hydrogen Hub project.	Australia	[4]
Clean H_2 partnership	1 billion (EUR). 10 years project	The Clean Hydrogen Alliance (CHA) is a European Partnership launched in July 2020 with the aim of accelerating the deployment of hydrogen technologies across Europe. The initiative is part of the European Commission's broader strategy to achieve climate neutrality by 2050.	European Union (EU)	[18]
PEPR Hydrogène	80 million (EUR). 8 years project	PEPR Hydrogène is a French government program launched in January 2021 by Bruno Le Maire, the Minister of the Economy, Finance, and Recovery. The program aims to support the development of the hydrogen industry in France and accelerate the country's transition to a low-carbon economy.	France	[8]
Innovation Programme for H_2 and Fuel Cell Technology (NIP)	250 million (EUR). 10 years project	The Innovation Programme for H_2 and Fuel Cell Technology (NIP) is a German government initiative launched in 2006 to promote the development and market penetration of hydrogen and fuel cell technologies. The NIP aims to support research and development in these areas, as well as to facilitate the deployment of hydrogen and fuel cell systems in various sectors, such as transportation, industry, and energy generation.	Germany	[16]
Hydrogen flagship projects	700 million (EUR). N/A	The German Federal Ministry of Education and Research has launched a set of "Hydrogen Flagship Projects" aimed at promoting the use of hydrogen as a key technology in achieving climate neutrality. These projects are focused on developing and implementing hydrogen technologies in various sectors of the economy, such as transport, energy, and industry.	Germany	[20]
Low Carbon H_2 Supply	93 million (GBP). The project duration not stated.	The UK government has recognized the importance of low-carbon hydrogen as a key component of its efforts to achieve net-zero emissions by 2050. The government's "Low Carbon Hydrogen Strategy," published in 2021, sets out a plan to scale up the production and use of low-carbon hydrogen across the UK.	United Kingdom	[23]
Million Mile Fuel Cell Truck (M^2FCT) and the H_2New consortia	100 million (USD). 5 years project	The Million Mile Fuel Cell Truck (M2FCT) project aims to develop a hydrogen fuel cell system that can power a heavy-duty truck for 1 million miles of operation. The project is being led by the center for Transportation and the Environment, a non-profit organization based in Atlanta, Georgia, and is supported by funding from the U.S. Department of Energy	United States	[59]

Table 2
A few international treaties between governments to work together on developing hydrogen.

S/N	Objectives	Countries
1	Create unique initiatives, such as a H_2 distribution chain between the two nations, to facilitate the growth of the hydrogen sector. Concentrate on identifying opportunities and conducting scientific research.	Germany/ Australia
2	Establish a collaboration to combine cooperation, technological advancement, and renewable energy sources with a focus on H_2.	Germany/Canada
3	Intensify collaboration on renewable H_2 and define projects that are feasible	Germany/Chile
4	Establish clean H_2 production and make investment and research efforts available to the whole value-chain.	Germany/ Morocco
5	Collaborate to create, refine, and transport H_2 using renewable sources of energy.	Saudi-Arabia/ Germany
6	Analyse the possibilities and steps necessary to produce H_2 using sources of renewable energy.	Portugal/Morocco
7	Create a formal negotiation about the creation of green H_2 import-export routes, coordinating investment priorities and promoting private sector cooperation.	Netherlands/Chile
8	Work together to link the two countries' H_2 plans by advancing the strategic supply chain for generating and shipping H_2 derived from renewable sources.	Portugal/Netherlands
9	Establish a global H_2 distribution network by working together on standards, regulations, and technology.	Arab Emirate/Japan
10	Release a joint declaration emphasising the agreement already reached between the two nations and stressing the relevance of collaboration on a global H_2 distribution chain.	Argentina /Japan
11	Increase bilateral R&D, networks, and alliances, as well as cooperation on creating distribution networks for low-carbon H_2 and its derivatives.	NewZealand/ Singapore
12	Encourage collaboration on initiatives and projects to speed up the implementation of H_2 through knowledge sharing, the creation of distribution networks, and joint ventures.	Chile/Singapore
13	Create collaborative H_2 projects with detailed action plans.	Korea /Australia

on key areas of two topics: H_2 facilities and H_2 for transportation and mobility [32].

According to the survey's findings, there is a broad need for regulation, especially as business activity in the sector picks up and moves beyond just road transportation. Infrastructural projects require the development of a lawful structure for introducing H_2 into natural gas networks (at both the transmission and distribution stages), as well as specifications for the scaling-up and widespread application of liquid H_2 in refuelling facilities.

The most urgent need in the area of transportation and mobility is to make it possible for H_2 to be used in modes of transportation other than the automobile, such as shipping, rail, aviation, and shipping. The survey found that safety is a primary concern and that initiatives to meet the other needs should include advancements in this area as well (including maintenance needs, approval processes, and audits) [32]. Some countries have started to adjust their regulations in order to eliminate constraints to hydrogen deployment. For example, the Chinese National Energy Administration in the year 2020 announced a draught of the novel Energy policy, in which H_2 is listed as an energy resource for the first time. This implies that H_2 will be a freely marketable energy asset, with less strictly enforced transportation needs than hazardous substances.

Other nations, such as France, Colombia, Chile, and Korea, have changed their energy laws to make it easier for H_2 to be used as an energy source. Many nations are looking into ways to lessen the impact of tax regulations, which can also significantly hinder the adoption of advanced hydrogen technologies. Germany declared that H_2 generated via renewable electricity will not be subordinated to the tax levied employed to finance clean power, and the EUC currently suggested revision to the Energy Taxation Directive (ETD) to prevent multiple taxing of energy products, as well as H_2 [11].

Carbon accounting standards are needed for a market for low-carbon H_2. In order to export less-carbon H_2 from areas with easy means to renewable energy sources or to produce H_2 from fossil fuels at a low cost using CCUS, international H_2 trade may one day serve as a cornerstone of the transition to clean energy. To remove and/or reduce regulatory barriers, appropriate standardisation agencies have to create global standards based-on a shared description of less-carbon H_2 in order to promote trade. A market for low-carbon H_2 was recognised by nations at the 32nd IPHE Steering Committee as being dependant on the development of globally accepted accounting standards for various H_2 sources along the value chain. A H_2 Task Force was created to review and agree on a system in order to achieve this [43].

The use of such a universally accepted international context will prevent environmental effects from being mislabelled or double counted and should lead to agreement on how to handle "certificates of origin." The postulate is founded on the following guiding principles: inclusivity (the system of method must not eliminate any possible principal energy), flexibility (strategies should permit for special situations and therefore flexibility), transparency (technologies should be transparent in strategy and moulds to boost assurance), comparability (the strategy must be similar with those employed for other energy paths), and practicality (the system of methods should be feasible, enabling uptake by industry).

2.3. Set objectives and long-term policies

Governments should decide on the most effective way to use H_2 to promote decarbonization efforts in their long-term energy initiatives. Then, in order to increase stakeholder confidence in the advancement of a market for H_2 and associated systems, they should create strategies that send lengthy-term indications about the role. Incorporated actions can set goals for the future, attract investment, and promote collaboration between nations and businesses.

There are many different ideas about how H_2 production should be done amongst the nations that have endorsed H_2 techniques. All strategies involve the generation of H_2 from electricity; in certain cases, this is the best long-term option. Even though others are not as much of precise about the source of the electricity (the approach of France references renewable and lower-carbon electricity), some countries (Chile, Portugal, Germany, and Spain) promote renewable power [11]. While a number of governments have assigned a substantial role to H_2 production via fossil fuels with CCUS, other governments (as well as the EU) only take this choice into consideration for the interim-and medium-term to limit global warming from current assets while encouraging the concurrent adoption of renewable H_2 [41]. Canada has adopted a distinct strategy; rather than promoting any one production path, they are concentrating on the carbon intensity of H_2 production and setting long-term goals to reduce it to zero. A few nations, including Korea and Canada, have raised the possibility of using by-product H_2 (from petrochemical/chlor-alkali industry sectors) to fill minor portions of the demand. The majority of techniques also mention the advantages of cutting-edge technologies like biomass-based transportation and methane pyrolysis. The future of these technologies is regarded as uncertain because they are still in the preliminary stages of development [58]. Table 3 lists the governments that have endorsed national hydrogen techniques, declared targets, prioritised the use of H_2, and dedicated funding.

2.4. Assist in demand generation

For low-carbon H_2 to be widely used, demand must be generated. Making projects marketable and overcoming deployment challenges will require policy support to "drive" incentives to invest across the supply chain. Policy support to fill the price gap with existing players for techniques that employ H_2 and are prepared for commercialization can encourage quicker implementation and speed up cost savings that come from scaling up and learning-by-doing. Although there has been some progress, not quite adequate policies have been put in place to support longer-term goals and spur interest in low-carbon H_2 [60].

The use of H_2 in transportation is highly valued by national H_2 initiatives. Several nations have policies that support the adoption of FCEVs, which are widely viable for passenger vehicles, buses, and light-duty automobiles. More than 20 nations provide particular purchase subsidies for FCEVs, with prices spanning from more than $30,000 in Korea to 1500 Euro (approximately $1700) per vehicle in Finland. In Korea, fuel cell bus buyers actually receive KRW 300 million (approximately USD 250,000). At least 20 nations have tax incentives in place, and of those, at least 17 offer particular corporate tax breaks to encourage the adoption of FCEVs in commercial fleets [58].

A lack of goals and initiatives for generating demand may prevent the growth of low-carbon supply. Low-carbon H_2 production has exceeded demand expansion as a result of the majority of government goals and regulations being solely focused on increasing H_2 supplies up until this point [25]. Tactical action is required in order to prevent supply chain disparities that could lead to ineffective policy support. Insufficient H_2 demand stimulation could prevent producers from finding buyers and delay the creation of lower-carbon H_2 source capacity. This could lead to lower-carbon H_2 capacity only substituting a portion of existing industrial production, which would slow down scale-up, prevent cost savings, and subsequently delay the deployment of H_2 as a source of clean energy [43].

2.5. Reduce the risks associated with investments

Risks associated with unreliable demand, a lack of information, and the sophistication of the supply chain are present in many ongoing projects. Measures to reduce financial cum operational risk can drive the scales in favour of private sector venture in these initial developments.

The implementation of policies to reduce the risks posed by project developers for H_2 has received special attention from European lawmakers. The Netherlands suggested integrating H_2 into the SDE++ programme, which provides incentives for the development of emissions reduction techniques and renewable energy sources in its Climate Agreement (initiated June 2020). The government of Dutch has pledged 2 billion Euro to the Porthos project in May 2021 to close the funding gap between the existing rates for carbon dioxide emission allowances and the costs associated with capturing, hauling, and storing carbon dioxide underground. This system recently brought about the intended effects it was intended to have. This will make it easier to develop CCUS-based programs for the production of H_2 from fossil fuels [13].

Nevertheless, regardless of the policy measures that various governments opt for, their signals will be much better if their thresholds of ambition and timeframe are widely associated in all areas of government and worldwide. In order to scale up, H_2 manufacturers and supply-chains needs to be able to obtain funding based on a global viewpoint and the biggest markets available. Irrespective of the value

Table 3
Governments that have enacted national H_2 techniques, set goals, prioritised the use of H_2, and committed financial support.

Production	Committed public finance	Applications	Targeted deployment 2030	Document	Year	Country
Coal with CCUS, Natural Gas with CCUS, Electrolysis (renewable)	AUD 1.3 billion	Building, electricity, exports, industry, shipping and transport	Not recorded	National H_2 strategy	2019	Australia
H_2 (By-product), Biomass, Electrolysis, Oil with CCUS, Natural gas with CCUS	25 million CAD through 2026 (1)	Building, refining, mining, electricity, exports, industry, shipping and transport	Used: 4 Mt H_2/year 6.2% TFEC	Canadian H_2 strategy	2020	Canada
Renewable Electrolysis	USD 50 million in 2021	Building, mining, refining, exports, industry, and transport	Electrolysis of 25 GW (2)	National Green H_2 Strategy	2020	Chile
Electrolysis	N/A	Industry (chemicals) and transport	Carbon-free demand: 97 kt H_2/year	H_2 Strategy	2021	Czech Republic
Electrolysis (renewable) Natural gas's role in CCU's transition	3.77 billion EUR by 2030	Industry, refining and transport	Electrolysis of 40 GW	EU H_2 Strategy	2020	European Union
Electrolysis	7.2 billion euros by 2030	Industry, refining and transport	Electrolysis of 6.5 GW 20–40% industrial hydrogen decarbonised (3) 20,000 to 50,000 FC LDVs (3) 800 to 2000 FC HDVs (3) 400 to 1000 HRSs (3)	H_2 deployment plan, and national strategy for decarbonised H_2 development	2018, 2020	France
Electrolysis (renewable)	9 billion euros by 2030	Aviation, electricity, refining, industry, shipping and transport	Electrolysis of 5 GW	National H_2 strategy	2020	Germany
Fossil fuels with CCUS Electrolysis	N/A	Electricity, industry, and transport	Production: 240 MW electrolysis, 20 kt per year of less-carbon H_2, and 16 kt per year of H_2 that is carbon neutral. Use: 20 HRSs, 4 800 FCEVs, and 34 kt/year of low-carbon H_2.	National H_2 strategy	2021	Hungary
Fossil fuels with CCUS Electrolysis	699.6 billion yen by 2030	Building, electricity, steel industry, refining, shipping and transport	Total consumption: 3 Mt H_2/yr. Supply: 420 kt low-carbon H_2, 800,000 FCEVs, 1200 FC buses, 10,000 FC forklifts, 900 HRSs. Demand: 3 Mt NH_3 fuel (4)	Strategic roadmap for H_2 & fuel cells. Green growth strategy	2019, 2020, 2021	Japan
Electrolysis, H_2 by-product and Natural gas with CCUS	2020: KRW 2.6 trillion	Electricity, building and transport	Used (total): 1.94 Mt H2/year. FC cars: 2.9 million (and 3.3 (million) exported) (5) HRSs:1200 (5) FC taxis: 80,000 (5) FC buses: 40,000 (5) FC trucks: 30,000 (5) GW stationary FCs: 8 (and 7 GW exported) (5) GW of micro-cogeneration FCs: 2.1 (5)	H_2 economy roadmap	2019	Korea
Electrolysis (renewable)	900 million euros by 2030	Electricity, industry and transport	TFEC: 1.5–2%, TFEC in road transport: 1 to 5 percent, TFEC in industry: 2–5%, H_2 in gas grid: 10–15 vol%, TFEC in maritime transport: 3–5%, HRS: 50–100	National H_2 strategy	2020	Portugal
Electrolysis and Natural gas with CCUS	£1 billion	Aviation, building, refining, Electricity, industry, shipping, and transport	5 GW of low-carbon energy production capacity	UK H_2 strategy	2021	UK

Recall that TFEC stands for total final energy consumption. (1) Canada has pledged more than CAD 10 billion in support for low-carbon technologies, including H_2, in addition to CAD 25 million. (2) Rather than capacity installed by 2030, this goal refers to projects for which at least some funding has been committed. (3) The goal year is 2028. (4) Taken from the ammonia provisoframework. (5) The target date of 2040.

chains sought, the five major policy classifications and scenarios of cross-cutting policy needs (Table 4)

3. The demand for hydrogen and supply

Hydrogen energy is often touted as a promising clean energy source for the future, as it produces only water as a byproduct when used in fuel cells. However, there are several difficulties posed by hydrogen energy that make it challenging to implement on a large scale [54].

- Production and transportation: Hydrogen is not found in its pure form in nature, so it must be produced through processes such as steam methane reforming or electrolysis of water. Both methods require significant energy inputs, which can make the production of hydrogen expensive and environmentally challenging. Moreover, transporting hydrogen requires specialized infrastructure that is not yet widely available, and it can be expensive and challenging [64].
- Storage: Hydrogen has a low volumetric energy density, which means it takes up a lot of space compared to other energy storage

Table 4
The five essential policy classifications and scenarios of strategic policy requirements for H_2 advancement, irrespective of the supply chain sought [19].

Category of policy	Requirements	Goal	Examples
Reduce the risks associated with investments	Initiate initiatives that shift the balance in line with the interests of private sector investment in distinct amenities during the initial phases of scale-up, when uncertainties are primarily caused by a lack of demand, inexperience, and value chain sophistication	Deal with the numerous hydrogen systems that are approaching the "death zone," where demand formation strategy is inadequate on its own to create projects marketable or get around systemic problems in coordination. Policies are required to handle risks related to both operational and capital costs. It consists of loans, export credits, risk insurance, and financial accounting that permits trading in "assurances of origin," controlled returns, water management planning, tax breaks, and CCUS.	Australian Clean Energy Finance Corporation, Chinese policy bank loans, EIB Energy Lending Policy, EU projects of common interest to Europe, multilateral bank financing, Southern California Gas Company certification for renewable natural gas, and EU Connecting Europe Facility are just a few examples of available financing.
Encourage and support research and development (R&D), large-scale public awareness campaigns, and information sharing.	Governments must keep focus in establishing the research programme for projects that are in the early stages and involve high levels of risk, taking those risks themselves, and encouraging private area investment. A variety of rule instruments can stimulate the private industry to take an active role in pro1moting innovation based on market requirements and competition for innovations that are nearing the peak of market scale-up and low-risk projects.	Meet the demand for more cost-effective to generate and deploy, higher-performing, lower-cost systems that function in an integrative way. Included are direct project financing and tax incentives; co-funding; low-interest loans; intricate pilot scale coordination; fairness in start-ups; multilateral collaborative effort initiatives; targeted advertising initiatives; and prizes. Aspects of need that cut across sectors: •Electrolyzers: effectiveness, lifespan, production and implementation expense, energy recovery, oxygen production • Fuel cells: precious metal substance, effectiveness, recycleability, production costs, and storage tank costs. • Safety of H_2, NH_3, and toluene: comprehension of consequences of novel applications; management strategies. • CCUS and CH_4 pyrolysis: Acquisition rates greater than 90%; incorporated demonstrations of pre-commercial methods. • Fuels and feedstocks depending on H_2: Fischer-Tropsch, methanation, and Haber-Bosch, all of which are flexible and effective. Solid-state, portable tanks, and porous media are all used for storage. • DAC: incorporation with exothermal systems, capital costs, effectiveness, and sorbent costs (for example, Fischer-Tropsch). • Gasification costs and effectiveness for biomass.	Japanese NEDO Roadmap for fuel cells and H_2; French H_2 Plan; Clean Energy Ministerial Initiatives; Mission Innovation challenge; Germany National Innovation Project for H_2 and Fuel Cell Techniques.
Set objectives and long-term policies	Commitments from the private and public sectors to an initiative for the use of H_2 in 2030 and 2050, integrated into a comprehensive energy, environmental, and commercial regulatory structure with delivery measures.	Giving all parties concerned more assurance that there will be a demand for low-carbon H_2 and associated systems in the long term will encourage investment and international cooperation between businesses. This includes: national H_2 frameworks and objectives for H_2 usage; global industrial techniques; and global obligations and treaties.	The Netherlands Climate Law and Agreement; EUC climate-neutral strategy for 2050; make policies for carbon free in 2050 in Germany/Frances; Nationally determined contributions under the Paris Agreement; UK Climate Change Act; Basic Japan H_2 Strategy; Ecological (China) Civilization commitment; Make in India;
Assist in demand generation	Initiatives that put a financial benefit on H_2 to be utilized in modern innovations or from new sources, increasing H_2 demand all over various applications in a coordinated manner, global collaboration that assist in synchronisation scale-up of H_2 market, limiting risks involved with market pressures for trade-exposed industries, and boosting investment in industrial capacity are some examples of policies that could be implemented.	Utilizing demand-side regulations that "draw" capital up the value chain, increasing commercial deployment while ensuring that your projects are marketable. Hydrogen techniques are prepared to move past pilot projects in a variety of applications and into self-sustaining businesses that financiers can understand with policy support to close the price gap. Included are reverse auctions, tax credits, mandates and bans, quality standards, rules for public procurement, rules for the electricity and gas markets (including those for supporting services markets and markets with locational and temporal pricing), and pricing for CO_2 and pollution. Everyone should be open to H_2 on equal terms, but policies that are overly innovation-normative should be avoided. For instance, auctions for less-carbon electricity that is incorporated with power storage could be held.	Zero Emissions Vehicle (ZEV), California Less Carbon Fuel Standard (LCFS) mandate; EU Emissions Trading System, Clean Vehicles Directive and emissions standards for cars and trucks; US 45Q tax credit for CCUS; UK Renewable Transport Fuel Obligation (RTFO); Canadian Clean Fuel Standard; .

(*continued on next page*)

Table 4 (*continued*)

Category of policy	Requirements	Goal	Examples
Standardisation and barrier-removal	Reduce or eliminate unessential regulatory obstacles and establish uniform standards that promote trade and guarantee the security of every link in the value chain. Encourage the community to ensure that they are aware of the risks and effects of new H_2 initiatives so they can make wise decisions.	Remove obstacles that obstruct deployment or raise risks to help the market accept H_2 techniques. You should also address any prospective people's concerns. Cross-cutting concerns include supply chain purity and pressure, preventing double taxation of energy, and safety rules. The licencing of CO_2 intensity and H_2 supply provenance, as well as standards for the existing processes they replace, are important issues. A thriving structure that envelops CO_2 inputs to H_2-based fuels and products (feedstocks) and prevents confusing effects on the environment (known as "assurance of origin") is required.	International Partnership for H_2 and Fuel Cells in the Economy (IPHE); H_2 Technology Collaboration Programme; EU CertifHy; Organization for Standardization (ISO) TC 197.

methods. Hydrogen also has a low gravimetric energy density, which means that it has a low energy content by weight. As a result, storing and transporting hydrogen can be challenging [1].

- Safety concerns: Hydrogen is highly flammable and requires careful handling to ensure safety. It can also embrittle certain metals and alloys, which can create concerns for infrastructure and equipment.

On the other hand, lithium-ion batteries (Li-ion) have become increasingly popular in recent years, especially for portable devices and electric vehicles. Here are some of the advantages of Li-ion batteries compared to hydrogen [56]:

- Energy density: Li-ion batteries have a much higher energy density than hydrogen. This means that they can store more energy per unit of weight and volume, making them more suitable for portable devices and electric vehicles.
- Cost: Li-ion batteries have become cheaper in recent years, making them more cost-competitive than hydrogen.
- Infrastructure: The infrastructure for Li-ion batteries is much more developed and widely available than that of hydrogen.
- Safety: Li-ion batteries are considered safer than hydrogen because they are not flammable and do not require high-pressure storage.

In summary, while hydrogen has the potential to be a valuable source of clean energy, it poses several difficulties related to production, transportation, and storage, as well as safety concerns. Li-ion batteries, on the other hand, have advantages related to energy density, cost, infrastructure, and safety. The choice of energy source will depend on the specific application and the trade-offs that must be made.

3.1. The demand for hydrogen

The demand for H_2 on a global level reached 90 Mt H_2 in 2020, up 50% from the year 2000. Nearly all of this demand is for manufacturing and refining purposes. Roughly 40 Mt of H_2 is used by refineries every year as raw material, reagents, or as an energy source. The industry sector has a slightly higher demand (greater than 50 Mt H_2), primarily for feedstock. Roughly 45 Mt H_2 is required for chemical production, with approximately 75% going to ammonia production and 25% going to methanol production. The direct reduced iron (DRI) method of producing steel uses the final 5 Mt of H_2. dummy citation Table 5

With the exception of a slight rise in demand for DRI production, this distribution has hardly shifted since 2000. A small rise in demand for DRI manufacturing is the only significant change to this distribution since the year 2000. Since the beginning of FCEV creation and the start of pilot projects to introduce H_2 in gas grids and employ it for electricity generation, the deployment of H_2 for novel applications has been slow. Uptake has largely been restricted to the last ten years. The success of these experiments led to the advancement of some H_2 technology solutions to the point of commercialization [52].

In parallel to this, policymakers and businesses are pledging strongly to reduce carbon emissions in response to growing climate change concerns. Although this has sped up the use of H_2 in potential approaches, there is still very little demand in this field. For instance, the annual demand for H_2 in transportation is just 0.02% of the total demand, or even less than 20 kt H_2. According to the IEA's Net Zero by 2050 guidelines, accelerating the adoption of H_2 systems in many areas of the energy sector is necessary to meet government decarbonization goals [31]. Government commitments point to increased hydrogen usages, but not practically enough in achiving net zero emissions from energy systems by 2050 (see Fig. 1).

The chemical industry, for example, needs to use H_2 much more widely. Additionally, aviation, shipping, heavy industry, and heavy-duty road transport need to significantly increase their usage H_2 and H_2-based fuels. These changes are necessary to reach net zero emissions by the year 2050. By 2050, the H_2 demand in the NZEs Scenario nearly doubles to 530 Mt H_2, with industry and transportation accounting for half of this demand. In fact, industry demand increases by almost three-fold from about 50 Mt H_2 in the year 2020 to about 140 Mt H_2 in the year 2050. The transport demand surges from lower than 20 kt H_2 to greater than 100 Mt H_2 in the year 2050 as a result of the volumes that limited shares of H_2 can accomplish in some sectors [24].

The utilisation of H_2 in gas-fired energy plants and fuel cells (stationary) aids in balancing rising renewable energy production; incorporating greater portions of wind energy and solar PV; and providing seasonal energy storage, all of which assist in increasing power industry penetration. The adoption of H_2 in buildings is also rising, though its uptake is still very constrained to specific circumstances where other eco-friendly and effective techniques cannot be accepted or where it is required to increase the flexibility of the electricity grid. By 2050, the production of H_2-based fuels like NH_3, synthetic kerosene, and synthetic methane will account for about one-third of the H_2 demand in the NZE Scenario. Ammonia use is expanding beyond its current uses, which are mainly nitrogen fertilisers, and is now being used as fuel [31].

Ammonia fills about 45% of the demand for shipping fuel globally in the NZEs Scheme because it has benefits over using H_2 directly for long-distance shipping. NH_3 is also being co-fired in established coal plants more frequently to lower CO_2 emissions during the power generation process. Some former coal-fired components have even undergone full retrofits utilise 100% NH_3 to produce low-carbon dispatchable power. The NZEs Scheme also uses synfuels made from H_2 and CO_2 generated from biomass systems such as biofuel production and bioenergy fired power or from the atmosphere like direct air capture (DAC). One-third of the world's demand for aviation fuel is specifically satisfied by synthetic kerosene, and 10 percent of the demand for grid gas deploy in transportation, buildings, and industry is satisfied by synthetic methane. In total, ten percent of the world's final energy demand will be satisfied by H_2 and H_2-based fuels in 2050. Only refining experiences, a drop-in H_2 demand in the NZEs Scenario, from nearly 40 Mt H_2 in 2020 to 10 Mt H_2 in 2050. This is due to the replacement of oil-derived products by clean technologies and fuels, which reduces the need for oil refineries [15].

The adoption of H_2-based fuels throughout the energy system is gaining momentum due to recent government net zero pledges, but the volumes necessary to accomplish net zero emissions by 2050 are grossly inadequate. Despite the fact that the Announced Pledges Scenario (The "APs Scenario" outlines a route for the timely and complete implemen-

Table 5
An overview of H_2's use in industry and its prospects in the future [29].

Industry	Existing H_2 role	H_2 demand by 2030	H_2 long-term demand	Low-carbon H_2 supply Prospects	Challenges
Refining	It is mainly used to remove contaminants such as sulphur from crude and enhance heavier crude. Smaller quantities are utilised for biofuels and oil sands.	Current policies would result in a 7% increment. Stricter pollution controls aided growth, but reduced oil market growth tamed it.	Strong considering oil demand in the future, although will most probably continue to be a major demand driver in the year 2050, even if the Paris Agreement is followed.	Remodel H_2 powered by natural gas or coal with CCUS. Substitute H_2 produced from low-carbon electricity for merchant H_2 purchases.	Due to the close integration of H_2 production and use within refining operations, modifying existing capacity would be financially challenging. H_2 costs significantly impact margins for refining.
Industry (Chemical) production	Along with a number of other relatively small industrial processes, it is employed to produce CH_3OH and NH_3.	CH_3OH and NH_3 prices will rise by 31% under current regulations as a result of population and economic expansion.	Notwithstanding material efficiency (which includes energy recovery), it is anticipated that there will be a rise in the demand for H_2 for current uses. Additionally, there may be a rise in the demand for CH_3OH and NH_3 for clean uses as H_2-based fuels.	Utilising CCUS to remodel or construct H_2. CH_3OH and NH_3 production can be done with low-carbon H_2 (methanol and urea will still need a carbon source).	The price of gas and electricity defines how competitive low-carbon H_2 sources are. Retrofitting with CCUS is not always an alternative.
Production of iron and steel	Direct reduction of iron (DRI), which needs H_2, is the method used in 7% of basic steel production. The blast furnace route yields H_2 as a byproduct in the form of a combination of gases, which is frequently employed on site.	The DRI pathway is utilised more often than the predominant blast furnace pathway, making it a double under current policies.	Even after considering improved material efficiency, demand for steel grows exponentially. The desire for low-carbon H_2 may rise significantly over time if production is totally dependant on H_2.	Installation of CCUS in the DRI Infrastructure The existing DRI route allows for the replacement of about 30% of natural gas with electrolytic H_2. The conversion steel mills completely use H_2 as the primary reduction agent.	The cost of production must be increased for each option, and/or procedures must be modified. Even though costs for direct CCUS uses are highly speculative, they are typically anticipated to be lower due to direct electrification's lengthy competition
Heat at a high temp. (excluding steel, iron chemicals, and sand)	Production of H_2 for heat production is almost exclusively focused on this. Off-gases from the steel and chemical sectors that contain H_2 are only used in certain circumstances.	Demand for high-temperature heat will rise by 9% under current regulations. No more H_2 use without strong policy backing.	In the prevailing political climate, H_2 has the possibility of competing on price as the demand for heat is predicted to increase further.	H_2 from any origin, such as industrial hubs or close-by H_2 transmission lines, could take the place of natural gas. Natural gas is used in blends, which are easier to make but less advantageous for the environment.	H_2 may be competitive with direct electricity generation but is predicted to perform poorly against biomass and direct CCUS in general. Full fuel transitions, also known as CCUS, typically require a sizable investment.

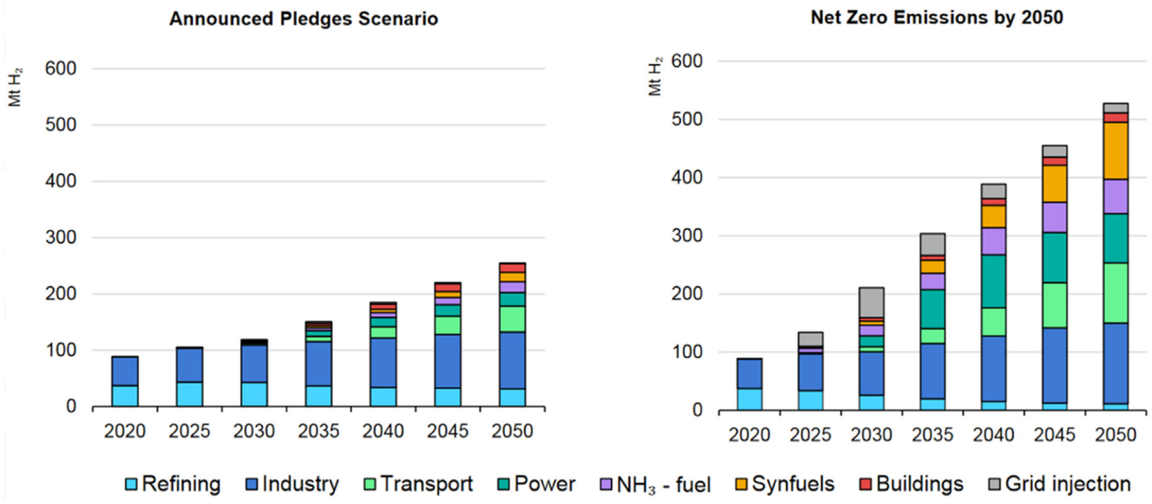

Fig. 1. Sector-specific H_2 demand under the Announced Pledges and NZEs Schemes, 2020–2050 [29]. Recall: "NH_3-fuel" describes the process of converting H_2 into NH_3, which is then used as fuel. Industry demand considers the chemical industry's use of H_2 as a raw material to create NH_3.

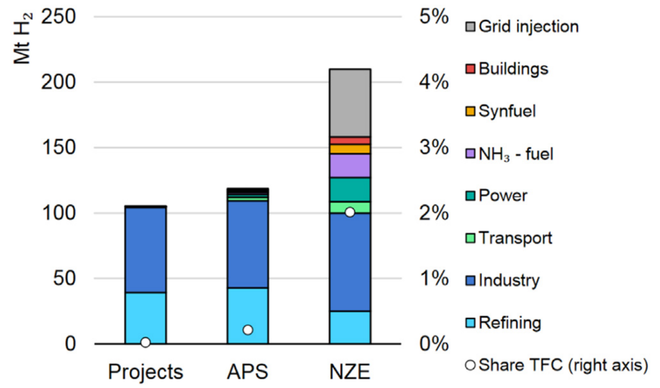

Fig. 2. 2030 schemes for the project case, announced commitments, and net zero emissions [30].

tation of the NZEs commitments made by governments up to this point) predicts that by 2050, the world's demand for H_2 will have nearly tripled to over 250 Mt, the NZEs Scenario's predicted demand is only about half of this.

With the exception of refining, where demand is lower due to a slower rate of replacement of fuels dependant on oil, almost all industries experience decreased demand under the APs Scenario. As a result, there is a significant reduction in the usage of H_2 and H_2-based fuel in transportation usages. The H_2 application in transportation is 55 percent lesser in the APs than in the NZEs Scheme. The main distinction in the demand for H_2 to generate H_2-based fuels is the 80% reduction in synfuel demand and the approximate 70% reduction in NH_3 production in the reported pledges compared to the NZEs scenario. The AP Scenario's H_2 demand for generating electricity is roughly one-quarter that of the NZEs Scenario because electricity processes there need smaller balancing of production and seasonal storage than they do in the NZEs Scheme. Demand growth is strong in both scenarios for the industry, even though it is 30% less in the AP than in the NZE because feedstock is the industry's main use of H_2 [41]. Growing the use of H_2 as a clean energy source will take time, as it often takes decades for a fuel to have a significant impact on the energy mix. Consequently, prompt action is needed to speed up transformation and establish the necessary conditions by 2030 for H_2 techniques to be widely adopted in order to ensure their lengthy viability in the clean energy transition (see Fig. 2).

3.1.1. Refining

In 2020, H_2 was primarily consumed for oil refining (roughly 40 Mt H_2). Hydrogen is used in refineries to enhance heavy oil fractions into lighter products and to purge contaminants (particularly sulphur). Hydrogen for refining is most widely used in China, followed by the Middle East (nearly 4 Mt H_2/year) and the United States (nearly 7 Mt H_2/year). These, when combined, over half of the world's demand comes from three regions. Approximately half of the demand for refining is satisfied by H_2 (by-product) from other systems in the refinery (such as catalytic naphtha reforming) and via petrochemical methods incorporated into some refineries like steam crackers [24]. The remaining needs are satisfied by specialised on-site production or commercial H_2 obtained from outside sources. The significant proportion of on-site manufacturing is derived from natural gas reforming, with a few exclusions like the use of coal gasification, which accounts for just under 20% of committed production of H_2 at processing facilities in China.

In the announced pledges (APs) and NZEs strategies, the demand for H_2 is only falling steadily in the oil refining industry. As climate goals are raised, oil refining activity decreases more quickly as oil demand falls, particularly after 2030. The H_2 demand rises to more than 40 Mt H_2 in the APs case before declining to about 30 Mt H_2 in 2050. 25 Mt H_2 and 10 Mt H_2 are projected in the NZEs for 2030 and 2050, respectively. Refinery owners will be faced with a dilemma as a result of declining oil demand because it may be challenging to justify investing in decarbonizing current H_2 production if there is a risk of lower profitability [41].

The possibility to supply growing H_2 industries and meet demand in emerging industries (such as transportation, other commercial uses, and electricity production), like those highlighted in the APs and the NZEs scenarios, could strengthen the strategic plan for such investments. In order to help the oil and gas industry achieve their net zero goals, decarbonizing high-temperature heat operations in refineries may be an alternative. Another important opportunity is the production of synthetic hydrocarbon fuels (synfuels) with low carbon content. Synfuels are "drop-in" fuels, which means they can substitute oil-derived fuels without needing to be modified and use established distribution systems and end-use techniques. Table 6 presents projects to decarbonize H_2 production in refining that are currently being developed.

3.1.2. Industry

Industry, the leading end-use sector and source of 26% of the CO_2 emissions from the global energy system, accounts for 38% of the expected total energy demand. Hydrogen production accounts for 6% of all industrial energy use, and it primarily serves as a raw material for chemical synthesis and as a reducing agent in the production of iron and steel. The yearly market growth for H_2 is 51 Mt. Regardless of how H_2 is generated, economic growth and increase in population will necessitate more output from the major industrial areas that employ it today. The quest for net zero objectives for energy technologies will influence current assets by causing changes in supply for both new and established uses. The APs Scenario predicts a 30% increase in industrial H_2 demand from current levels to 65 Mt by 2030, with 5% of that increase coming from new uses. The percentage of new uses increases to 26% by 2050, when demand keeps increasing from today [24].

A greater use of H_2 is necessary to achieve NZEs by 2050. According to NZEs, overall industrial H_2 demand will be almost three times as much in 2050 as it is in 2030, or 11% higher than it is now. These increases are shown to be relative to the APs Scenario. By 2030, 21 Mt H_2 of low-carbon H_2 will play a more significant role (more than 3 times greater than in the APs Scenario). As slightly earlier as 2030, electrolytic H_2 utilisation is much more than five times greater than that of CCUS-equipped production, which is only about a third of what it is in the APs Scenario. Fig. 3 shows the use of low-carbon H_2 in 2030, total industrial H_2 demand, announced commitments, and net-zero-emissions scenarios, 2020–2030 [35]. A few chosen schemes that can enhance the application of lower-carbon H_2 are presented Table 7

3.2. The supply of hydrogen

3.2.1. Hydrogen production

According to ongoing or upcoming projects, the amount of low-carbon H_2 produced up until 2030 may increase quickly. A total of 350 initiatives could increase electrolytic H_2 production to 5 Mt H_2, while 47 initiatives using CCUS and fossil fuels could increase it to 9 Mt H_2 (which includes the 16 established plants). By 2030, electrolytic production of H_2 could attain 8 Mt H_2 by considering an additional 40 projects that are in the early stages of development [27].

The 12 Mt H_2 required in the APs Scenario for 2030 cannot be produced by electrolysers. However, the nine (9) Mt H_2 from natural gas with CCUS can be produced. However, only two-thirds of the required output is anticipated from all planned projects combined. In the NZEs Scenario, which calls for the production of 80 Mt H_2 of electrolytic hydrogen and sixty (60) Mt H_2 from natural gas with CCUS in 2030, this gap widens considerably. In spite of this, a lot of programs are probably going to be developed in the coming years, which will improve the project channel as it stands [34].

The APs scheme predicts that by 2050, the world will produce 250 Mt H_2 of H_2, with 51% coming from electrolysis, and 15% from fossil fuels

Table 6
A few upcoming projects to decarbonize H_2 production in the refining industry [29].

Technology	Capacity	Project owner	Country	Current status	Start-up date
CCUS & Natural gas	500 kt CO_2/year	Preem CCS	Sweden	Feasibility analysis	2025
CCUS & Natural gas	90 kt H_2/year	Stanlow refinery	UK	Feasibility analysis	2025
Electrolysis (PEM)	20 MW	Gela biorefinery	Italy	Feasibility analysis	2023
Electrolysis (Alkaline)	100 MW	H24All	Spain	Phase 1- FID & Phase- 2 still in Feasibility analysis	2025
Electrolysis (Alkaline)	30 MW/300 MW	Westkuste 100 two-phases	Germany	Phase 1- FID & Phase- 2 still in early stage analysis	2023–2028
Heavy residue gasification with CCUS	1000 kt CO_2/year – 1000 kt H_2/year	Pernis-refinery (gasification)	Netherlands	Feasibility analysis	2024
Electrolysis (PEM)	100 MW	Refhyne two-phases	Germany	Feasibility analysis	2025
Electrolysis (PEM)	300 MW/1000 MW	HySynergy three-phases	Demark	Feasibility analysis	2025 –2030
Electrolysis (SOEC)	2.6 MW	Muitiphly	Netherlands	Under construction	2022
Electrolysis (PEM)	10 MW	OMV Schwechat Refinery	Austria	FID	2023

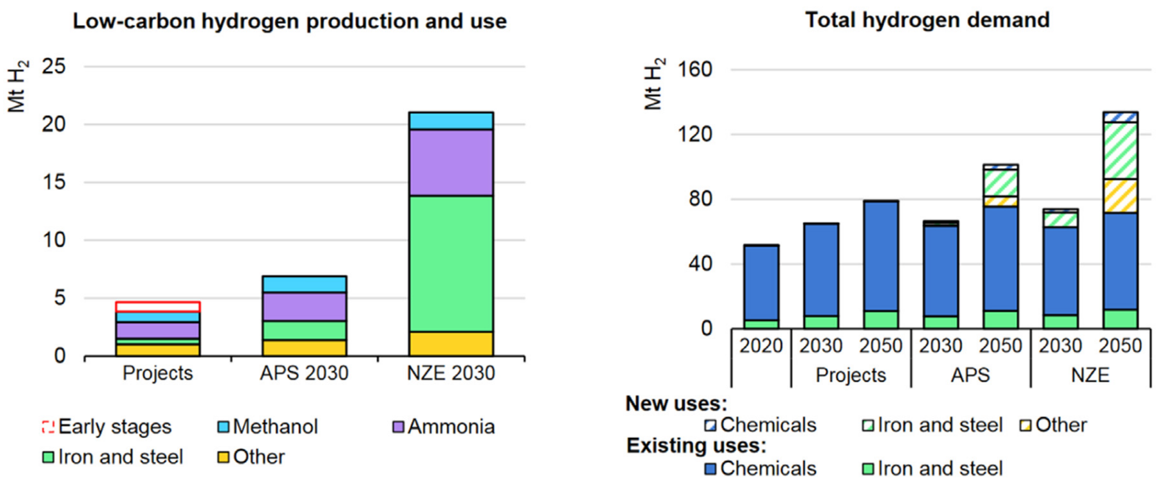

Fig. 3. Overall industrial H_2 demand for Projects, APs, and NZEs, as well as low-carbon H_2 applications, 2020–2030 [29].

Table 7
A few initiatives to expand industry's use of low-carbon H_2 [29].

Technology	Capacity	Project owner	Country	Current status	Start-up date
NH_3					
Electrolytic NH_3 generation from renewables	10 MW	Western Jutland Green Ammonia	Denmark	FID	2023
Electrolytic NH_3 generation from grid electricity	20 MW	CF Industries	USA	FID	2023
Electrolytic NH_3 generation from solar PV	50 MW	HyEx	Chile	Early stage analysis	2024
Electrolytic NH_3 generation from offshore wind	1 GW	Esbjerg green ammonia	Denmark	Early stage analysis	2027
Capture and stored CO_2 from NH_3 gas-based generation	1 Mt NH_3 per year	Barents blue ammonia	Norway	Early stage analysis	2025
Electrolytic NH_3 generation from renewables	100 MW	Yara Sluiskil	Netherlands	Early stage analysis	2025
CH_3OH					
Production of electrolytic CH_3OH from targeted renewable sources	63 MW – phase 1 & 300 MW – phase 2	North-C-Methanol	Belgium	Feasibility analysis – Phase 1 & Early stages – Phase 2	2024 –2028
H_2 and CH_3OH production CCUS with petcoke gasification	4.2 Mt CO_2/year	Lake Charles Methanol	USA	Feasibility analysis	2025
Production of electrolytic CH_3OH from targeted renewable sources	10 MW – 100 MW	Power to Methanol	Belgium	Feasibility analysis – Phase 1 & Early stages – Phase 2	2023
Steel & Iron					
Injection of H_2 into blast furnaces	100 MW 400 MW	Thyssenkrupp steel plant	Germany	Initial stages	2022 2025
Using specific renewables in making 100% H_2-based steel production	1.5 GW	H2 Green Steel	Sweden	Initial stages	2030
Other notable applications					
Natural gas replacement in zinc refining process	1 MW	Sun Metals Zinc Refinery	Australia	FID	2022
Nickel refining using electrolytic H_2	10 MW	BHP Nickel West Green H_2	Australia	Early stages	2023
Ceramic creation using green H_2	100 MW	ORANGE.BAT Castellon	Spain	Early stages	2024

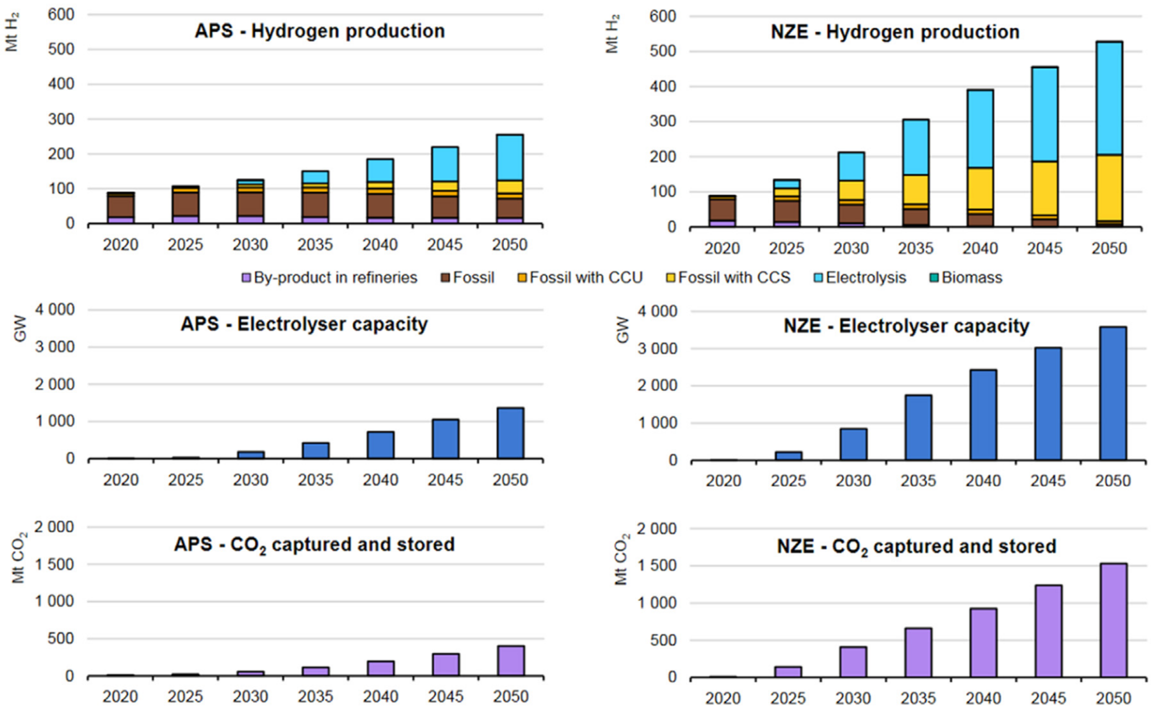

Fig. 4. Worldwide electrolysis potential, CO_2 storage and capture, and production of H_2 all fall under the APs and NZEs initiatives [28].

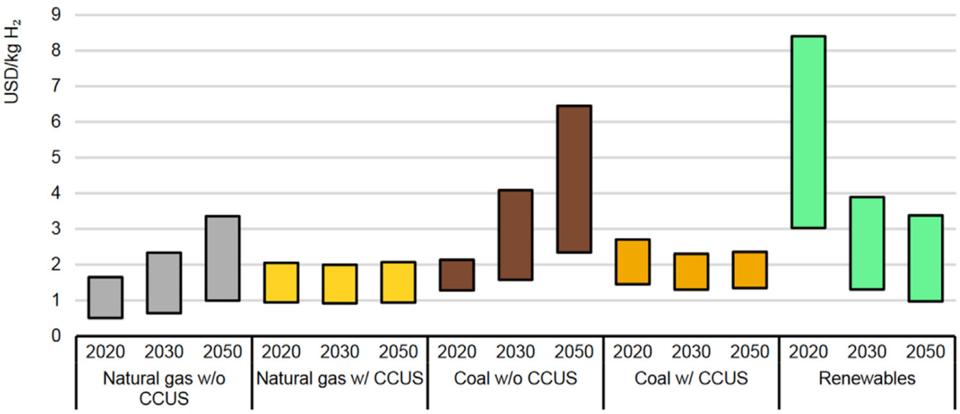

Fig. 5. By technology, the levelized cost of producing H_2 in 2020, the NZEs Scenario, 2030, and 2050 [29].

(with CCUS), and the rest from fossil fuels without CCUS. This translates to a 1350 GW worldwide electrolyser potential and a CO_2 capture rate of 0.4 Gt/year. The installed electrolyser potential achieves 3600 GW, the capture rate increases to 1.5 Gt CO_2/year, and the worldwide production multiplies compared to the APs initiative, with electrolysis accounting for 60% and fossil fuels accounting for 36% with CCUS. Specifically, this equates to 925 bcm of natural gas (accounting for 50% of the world's demand for natural gas) and roughly 15,000 TWh of electricity usage (20% of worldwide production) [27]. Electrolysis and the implementation of CCUS are required for decarbonizing H_2 production (Fig. 4) [3].

The least expensive alternative presently available is to produce H_2 using fossil fuels in the majority of the world. The levelized cost of H_2 generated from natural gas ranges from $0.50 to $1.70 per kilogramme of H_2, based on local gas prices (see Fig. 5). For most places, using renewable energy is much more expensive, costing USD 3–8/kg H_2. In fact, based on electricity prices and the number of maximum hours of renewable energy supply, renewable electricity can account for 50 to 90% of the total production costs [52]. Even so, the cost difference between production processes is anticipated to close quickly as the cost of electrolysers and renewable electricity declines. Pricing CO_2 emissions could reduce the gap even more by increasing the price of H_2 made from fossil fuels (for example, via carbon prices). For instance, a rise in the cost of 0.90 USD per kg H_2 for natural gas-based generation without CCUS or 2.00 USD per kg H_2 for coal gasification (without CCUS) results from a carbon price of USD 100/t CO_2. The effect of CO_2 prices on the cost of generating H_2 from fossil fuels with CCUS can be significantly decreased with high capture rates (90–95%). Natural gas (with CCUS) has a production price of 1.00–2.00 USD per kg H_2 that is roughly 0.50 USD per kg H_2 greater than without CCUS, relying on gas prices. To fill this cost gap, a CO_2 price of USD 70/t CO_2 would be necessary [57].

In the meantime, lowering the price of less-carbon electricity would be essential to lowering the cost of electrolysis-based H_2 production. The US H_2 Earthshot project's 2030 target of producing hydrogen at a cost of $1.00/kg H_2 translates into electricity costs of $20 per MWh, free of CAPEX and fixed OPEX (at 70% performance, lower heating value). Electricity cost should be satisfactorily under 20 USD per MWh to cover additional OPEX and CAPEX costs in order to achieve the desired H_2 production cost. Solar PV may be less expensive in areas with abundant solar resources and consequently high electrolyser full-load hours. Actually, bids of USD 14–17/MWh were received in the Middle East during the 2019 and 2020 utility-scale solar PV tenders [21].

Additionally, technological advancements to increase electrolyser efficiency balance the impact of rising electricity prices on the expense of producing H_2. Enhancing efficiency extends beyond the electrolyser; if variable renewable energy sources are the primary source of electricity, it is essential to optimise inverters for expected operation at part load. Thus, the estimated cost of producing H_2 after 2030 is quite uncertain and will be influenced by other new technologies, the effects of scaling up, and learning from experience.

3.2.2. Cutting-edge technologies

3.2.2.1. Solid oxide electrolyser cells (SOECs). A significant change from alkaline and PEM electrolysers is that SOECs produce H_2 using steam rather than H_2O. SOECs also have relatively low costs because they use ceramics as the electrolyte. They need a heat source in order to produce steam, despite operating at high electrical and temperatures efficacies of 79 to 84 percent (LHV). So, if SOEC H_2 were to be deployed to create synthetic hydrocarbons power-to-gas/power-to-gas, it would be feasible to recover waste heat from these synthesis methods (such as Fischer-Tropsch synthesis and methanation) to create steam for additional SOEC electrolysis [9]. Other possible heating elements for SOECs include solar thermal, nuclear energy, geothermal, and industrial waste heat systems. Another feature that sets SOEC electrolysers apart from PEM and alkaline electrolysers is their ability to be used in reverse mode as fuel cells to convert H_2 back into electricity. In conjunction with H_2 storage systems, they could offer balancing facilities to the power grid, boosting the total system utilisation rate. Additionally, CO_2 and steam can be electrolyzed together in SOEC electrolysers to generate syngas (a combination of H_2 and CO), which can then be used to make synthetic fuel [37].

Large-scale SOEC systems are currently in the demonstration phase (TRL 6–7). Existing operational processes with a capacity of less than 1 MW are frequently associated with the production of synthetic hydrocarbon fuels. The largest system currently in use, with a capacity of 720 kW, generates H_2 for a DRI steel plant using renewable electricity and waste heat. Nevertheless, a 2.6-MW SOEC facility is being built in Rotterdam, and numerous industries, primarily in Europe (such as Bloom and Sunfire), are producing SOEC processes. By 2023, the Danish government intends to open a manufacturing facility with a 500 MW annual capacity.

3.2.2.2. Methane pyrolysis. The method of converting CH_4 into gaseous H_2 and solid carbon (such as graphite and carbon black) without producing any direct CO_2 emissions is known as CH_4 pyrolysis, also referred to as CH_4 splitting, or cracking. The reaction involves comparatively high temperatures (greater than 800 °C), that can be reached using both plasma and more traditional methods (such as electrical heaters). The CH_4 pyrolysis uses 3 to 5 times less electricity per unit of H_2 produced than electrolysis, but more natural gas is needed [51]. Methane and electricity integrated into H_2 have a cumulative energy conversion efficiency of 40 to 45%. Noticeably, the method might generate extra income from the sale of carbon black for utilisation in tyres, rubber, plastics, and printers, though the market opportunity is probably limited given that the world's carbon demand in 2020 will be 16 Mt of carbon black, that equates to the H_2 production from the pyrolysis of 5 Mt of H_2. Other uses for carbon from pyrolysis include building materials and the replacement of coke in the production of steel compared to steam methane reforming [45].

TRLs of 3 to 6 have been observed across several CH_4 pyrolysis system designs that are in development. To generate the high temperatures needed, the United States Monolith Materials uses plasma. The business in Nebraska started an industrial plant in 2020 after running a pilot plant for four years. It is currently developing a plant that will produce NH_3 on a commercial scale. Australia (Hazer) Group is building a trial plant for its catalytic-supported fluidized bed reactor system, which will convert biogas into H_2 and graphite. The companies and RWE reported a project in 2021 to employ offshore wind energy to power a CH_4 pyrolysis plant and a H_2 electrolysis plant, respectively. The Russian company Gazprom is creating a plasma-based method for CH_4 pyrolysis. An electrically heated molten metal reactor is being developed by the American startup C-Zero for the pyrolysis of CH_4 [40].

3.2.2.3. An anion exchange membranes (AEMs). The advantages of PEM and alkaline electrolysis are combined in AEM electrolysis. It does not need platinum because Cerium dioxide-La_2O is a transition metal catalyst (unlike PEM electrolysis). One main benefit is the absence of the corrosive electrolytes used in AEL because the AEMs acts as a solid electrolyte. Even though the AEM system is still in its early life, Germany (Enapter) is working on kW-scale AEM electrolyser processes that can be connected to create MW-scale facilities [53].

3.2.2.4. Electrified steam methane reforming (ESMR). A common method for creating H_2 from natural gas is SMR, which can be employed in conjunction with CCUS to cut CO_2 emissions. The gas stream (Synthesis) following the steam CH_4 reformer, which is categorised by high CO_2 concentrations, and a flue gas (diluted) stream brought on by the production of steam from natural gas, must both be used for CO_2 capture in order to accomplish capture rates of 90% or higher. The latter needs more energy for capture since it contains less CO_2 in it [49].

The production of steam using a different heat source is an option available to capture CO_2 from flue gas, that is responsible for 40 percent of the emissions of CO_2 from natural gas SMR. Haldor Topsoe (Denmark) utilises 8 kWh/kg H_2 of low-carbon electricity (thus, SMR becomes ESMR). Up until now, the technique has only been tested at the TRL 4 (laboratory scale), nevertheless a test plant is currently being built to utilise biogas as a raw material in ESMR to create H_2 and CO, that can be used to create CH_3OH [21].

4. Investments and policy recommendations

4.1. Investments

Though current hydrogen investment opportunities are promising, substantial increase across the whole operation, consumers, and technology value chains are necessary to meet government climate goals. The APs Scenario simulates investments up to 250 USD billion for the year 2020 to 2030, with an aggregate investment of 3.2 USD trillion in the year 2050. Despite being higher than those for which financial support has already been committed, this is less than the business stakeholder investments that have been announced through 2030. Future investments might have a significant impact on how things turn out in the long run. For electrolysers, annual investments of USD 7 billion and 4 billion USD for FCEV installations are required until 2030 (14 times record investments). Global accumulated investments should rise to 1.2 trillion USD by 2030 and 10 trillion USD by 2050 in order to reach NZEs by that date [50].

In the APs Scenario and the NZEs Scenario, the accumulated global investments up to 2050 are 25% and 27%, respectively, for increasing low-carbon H_2 generation capacity. The portion of investments in H_2 production must be greater before the year 2030 than after because it is necessary to employ capacity for both novel production and the decarbonization of established applications (that only needs modest investments in end-uses and structure). Even though production capability investments are expected to increase until 2050, their share is decreasing as more capital is invested in new end-uses and infrastructure improvement [24].

In both the APs and NZEs scenarios, end-use technologies represent approximately 60% of total global investments through 2050, with the investments steadily rising. Investments in end-use techniques are significant. They are projected at 8 billion USD per year in the APs Scenario

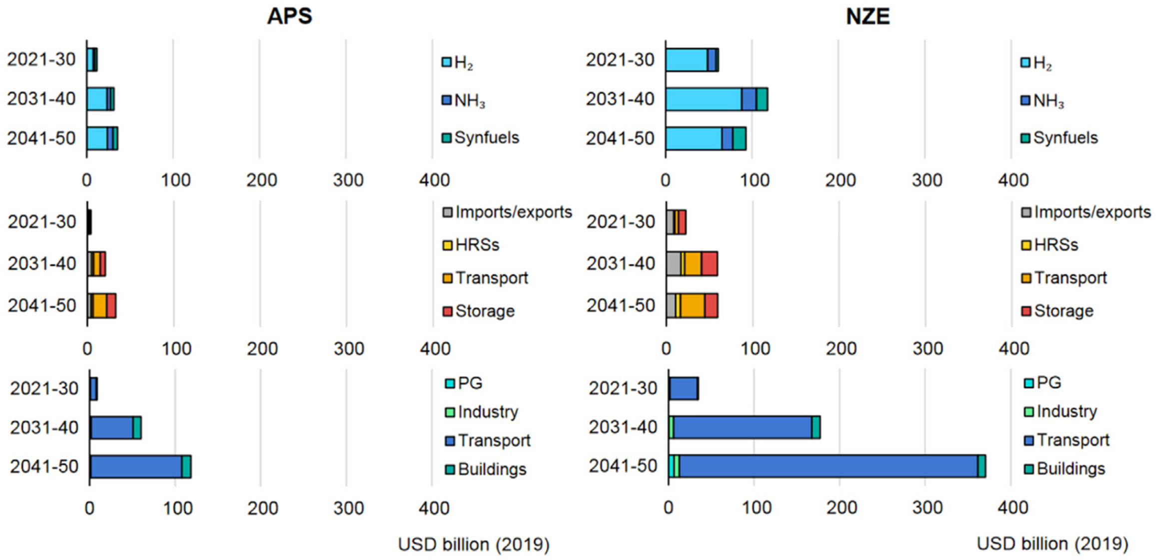

Fig. 6. Sector-specific annual investment requirements for H_2 globally under the APs and NZEs scenarios [29].

and 30 billion USD in the NZEs Scenario for 2020–2030. After 2030, a number of end-use technology solutions will move from the research and development stage to commercialization and wide-scale deployment, generating new demand for H_2, especially in the transportation industry. As a result, investments significantly increase, reaching USD 90 billion per year in the APs scenario and USD 270 billion per year in the NZEs scenario by 2050 [22].

Large investments are indeed needed to build the facilities (such as pipelines, refuelling stations, import/export terminals, and storage) that will allow H_2 to be distributed to end users. In fact, the APs Scenario (USD 575 billion) and the NZEs Scenario both place investments in infrastructure at 14% and 18% of total global investments through 2050, respectively (USD 1400 billion).

Even though simulation indicates that this share will more than double in the NZEs scenario and nearly double in the APs scenario by 2030, this does not mean that infrastructure projects can be put off for another ten years. Instead, increasing H_2 storage space can be essential to ensuring supply safety in the interim-term and providing a counterbalance for long-term renewable energy integration. Progress can also be made by reusing natural gas pipelines and blending H_2 into the gas grid. Contingent on regional conditions, increased investments in new pipeline networks may be needed as H_2 demand rises [57]. Additionally, the growth of global H_2 supply networks may encourage spending on import/export facilities and H_2 transport vessels. Significant opportunities to cut costs might be present by reusing existing facilities. Liquid synfuels could be imported and exported using oil-derived product facilities with only minor modifications, while some LPG and LNG facilities could be improved to facilitate the import and export of H_2 and NH_3. To place the world on a path to achieve NZEs by 2050, investment in H_2 must rise to USD 1.2 trillion by 2030. Fig. 6 shows the investment needs in achieving the 2050 NZEs.

4.2. Policy recommendations

The IEA's blueprint for achieving net zero by 2050 demonstrates that in order to do so, proactive measures are needed to make the year 2020s the era of clean energy advancement via widespread adoption of currently accessible low-carbon technology solutions and speeding up innovation of those still in progress. One interesting indicator is H_2 innovations, which must advance and be deployed at a significantly faster rate between now and 2030. The three main objectives are to substantially boost H_2 usage by introducing emerging technologies; to greatly enhance the cleanliness of H_2 production (i.e., move away from fossil fuel-based pathways that continue unabatedly); and to markedly lower the cost of innovations for H_2 production and applications [30]. Policymakers must take the initiative in promoting the clean energy transformation in order to reach the NZEs milestones by instituting national policies that encourage coordinated action.

Policies must be focused on the following:

- Creating plans and strategies for the use of H_2 in energy technologies should be the focal point of policies.
- The use of low-carbon H_2 to replace fossil fuels should be strongly encouraged.
- Encourage investment in industries and infrastructural facilities.
- To guarantee that vital technology solutions rapidly enter the commercial market, strongly support innovation.
- Create effective regulatory, certification, and standardisation regimes.

The application of one will have an influence on the possible results of the other because all of these policy initiatives are interrelated. Some are logical first stages, like describing the function of H_2 in a country's energy plans. Without adequate demand-generating and investment-mobilizing fiscal stimulus, it is highly improbable that this role can be fulfilled. This infrastructure is required to link H_2 producers and consumers during the early stages of adoption. Such infrastructure development involves collaboration amongst numerous stakeholders, with local governments playing a crucial role. If the duties of the various stakeholders are accurately and clearly described in H_2 techniques and roadmaps, collaboration efforts can be facilitated.

The degree toward which demand can be generated, in turn, will rely on effective engagement in 2 critical sections: support for advancement to make sure that techniques are established and become marketable; and the institution of guidelines and certification strategies to guarantee the interconnectivity of these technology solutions worldwide and give consumers assurance about the products they are purchasing on the market. The growth of the market will also rely on efficient regulation that ensures fairness and equality [57]. dummy citation Fig. 7

5. Conclusion

A rapid switch from non-renewable carbon-based sources of energy to clean and low-carbon sources of energy is required to accomplish ambitious carbon neutrality goals, such as bringing the average temperature worldwide down to 1.5 °C. Hydrogen's special qualities allow

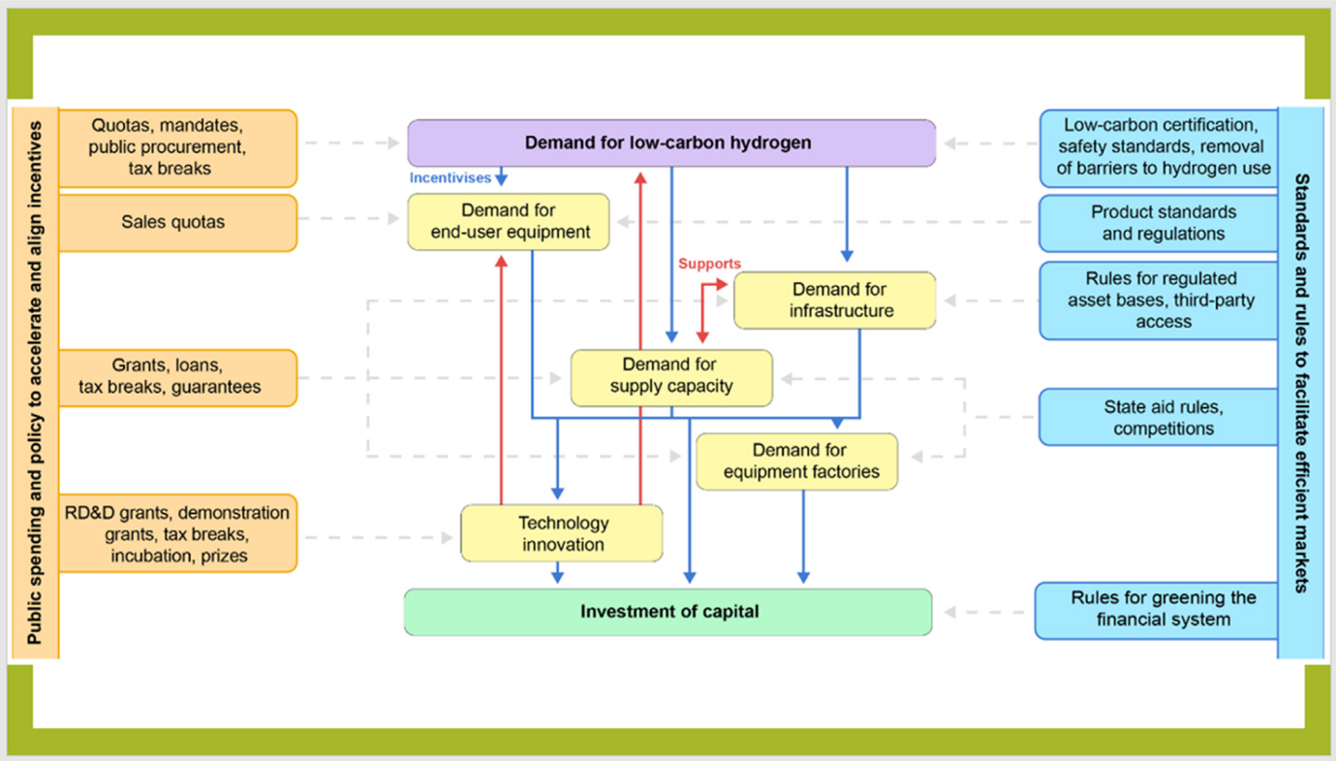

Fig. 7. How legislative and institutional changes can increase and facilitate reward systems throughout the H_2 supply chain [30].

for a quicker transition to energy and facilitate both the energy sector and end-use applications. Policymakers, financiers, research scientists, the private industry, society, and nations must all work together and promote H_2 storage systems for them to be deployed more quickly.

Government commitment to increasing H_2 supply and applications must be demonstrated by national H_2 techniques and guidelines with clearly outlined benchmarks and strategic targets for generating and H_2 usage. Ideally, they would be a component of larger government plans to meet climate goals, securing H_2's place in the energy landscape. Building investor trust in the rising market for less-carbon H_2 and associated technologies is therefore essential.

It is obvious that highlighting a "push" for less-carbon H_2 by raising production rate without sufficiently growing the market's "force" for the finished product can lead to disparities and even limitations in the H_2 value chain. Practical goals must be set for the deployment of new H_2 systems within this decade as well as the application of less-carbon H_2 in currently operating uses. This review's suggested goals for 2050 can be accomplished by actively supporting these goals at the regional level, which will enable unified international action.

Insufficient demand may prevent supply projects from taking off, making it harder to meet government goals for the low-carbon production of H_2. The prescriptive analytics in this paper state an increasing need for a greater desire to increase the amount of less-carbon H_2, to completely phaseout fossil fuel-based H_2 demand in industry and refining and establish a market for novel systems like energy storage, heavy-duty transport, aviation, new industrial uses, and shipping.

Finally, there is currently a transition taking place in the energy sector, and it is technologically possible and probably much less expensive than the current system to continue this transition to a scheme with net-zero greenhouse gases or even 100% renewable energy in the long term. Consistent technological advancement and infrastructure building, solid policy backing at all governmental levels, and facilitating the availability of private capital required for continuing to invest in this transition are the 3 primary factors that will help bring this transition about. Significant public approval will result from government and non-governmental assistance for these interrelated factors, which is necessary for the transition to take place.

6. Future outlook

Hydrogen is widely considered as a key element in the global transition to a net-zero economy by 2050, as it can be used as a clean energy carrier and fuel for a wide range of applications, from power generation to transportation and industrial processes. The prospects of hydrogen in achieving net-zero emissions by 2050 are promising, but there are several challenges and uncertainties that need to be addressed.

On the positive side, hydrogen has the potential to significantly reduce greenhouse gas emissions, especially in hard-to-abate sectors such as heavy-duty transport, steel, cement, and chemicals. Hydrogen can be produced from a variety of sources, including renewable electricity, natural gas with carbon capture and storage (CCS), and biomass, which can help to diversify energy supply and reduce dependence on fossil fuels.

However, the widespread adoption of hydrogen faces several challenges. One of the main challenges is the high cost of producing hydrogen, especially from renewable electricity. The production of hydrogen from renewable electricity requires large-scale deployment of electrolyzers, which are still expensive and not yet cost-competitive with fossil fuels.

Another challenge is the lack of infrastructure for hydrogen production, transport, and storage. To achieve the scale required for a net-zero economy, significant investments will be needed to develop hydrogen infrastructure, including pipelines, storage facilities, and refuelling stations.

Currently, grey hydrogen is the most common form of production due to its low cost, but it is not a sustainable solution in the long run. Blue and green hydrogen offer more promising prospects for achieving net-zero emissions, but their cost is currently higher than grey hydrogen.

In order to increase the use of blue and green hydrogen, significant investments are needed in research and development, as well as in infrastructure to support their production, storage, and transportation.

This includes building new pipelines, storage facilities, and distribution networks.

Another challenge is the need for policy support to create a level playing field for hydrogen with traditional fossil fuels. This includes carbon pricing mechanisms, renewable energy targets, and regulations to encourage the use of hydrogen in various sectors such as transportation, industry, and heating.

Furthermore, the environmental sustainability of hydrogen production and use depends on the source of hydrogen. For example, hydrogen produced from natural gas with CCS may not be completely carbon-neutral, and the use of biomass for hydrogen production may compete with food production and biodiversity conservation.

Overall, while the prospects of hydrogen in achieving net-zero emissions by 2050 are promising, significant challenges need to be overcome, including reducing the cost of hydrogen production, developing hydrogen infrastructure, and ensuring the environmental sustainability of hydrogen production and use.

Declaration of Competing Interest

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

Data availability

The authors do not have permission to share data.

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