Speed and Scale for Disruptive Climate Technologies:

Case for a Global Green Hydrogen Alliance

ARUNABHA GHOSH AND SANJANA CHHABRA[1]

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Cover photo: Knowledge sharing can lead to the proliferation of hydrogen fuel cell-powered trucks to decarbonise transport globally.
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Summary

Many major emitters have recognised that without significant industrial decarbonisation, pronouncements of net-zero would have little certainty. How would global industrial emissions be reduced at the pace needed for advanced economies and without deindustrialising fast-growing emerging economies? Green hydrogen could be a game-changer for heavy industries, such as steel, ammonia and petrochemicals, in addition to transport. Many countries have announced national and regional programmes but green hydrogen technology is still far from commercialisation at scale.

Three trends — expected shifts in sectoral uses, geographical spread to emerging economies, and the need for low-carbon production — will serve as the foundations of a new wave of hydrogen production and consumption in the coming decades. These shifts must unfold concurrently.

At least 32 countries plus the European Union have announced or are developing national-level policies and strategies for hydrogen. At least 24 countries and regions have targets and pilots for green hydrogen.

But the scale of transformation has not been fully internalised. Under IEA's net-zero scenario, low-carbon hydrogen use would have to be 19 times greater in 2030 compared to even its sustainable development scenario. The world needs more collaborative action.

There are more than a dozen bilateral partnerships and at least 10 multi-country or multi-firm platforms focused on hydrogen. But they seldom involve developing countries, are not oriented towards joint technology development, and do not focus on deploying technologies in countries that will have the greatest demand for cleaner fuels for industrial development.

Three challenges dominate. First, path dependency in national programmes could lead to sub-optimal outcomes related to technology choices (continued reliance on fossil fuels for hydrogen production), end uses (lesser focus on abating industrial emissions) and differential standards (for storage, transportation and safety).

Secondly, there is a gap between the geographical distribution of green hydrogen potential and the primary destination of investment and projects. Many countries in the tropics have optimal renewable resources and other low-carbon resources for producing hydrogen. But the bulk of the hydrogen programmes are concentrated in developed countries. Of the 33 countries and regions analysed, only seven are in Asia, two of which are developed countries and three are major oil and gas producers. Nearly all of the bilateral partnerships are among developed countries. Multi-party partnerships have primarily been promoted to support national programmes of the sponsoring country, rather than as genuine collaborative efforts.

The biggest obstacle is the absence of leadership. If green hydrogen has the potential to be a foundational fuel for industrial and transport decarbonisation, its development and deployment must be treated as a global public good. There is a need to avoid mercantilist instincts wherein technology development is restricted to a few countries, while trade dependence increases for a clean fuel.

A Global Green Hydrogen Alliance should be designed as a multi-country, multi-institutional network to assess, develop and design affordable green hydrogen technologies that can be deployed at scale, in both advanced economies as well as in developing countries. It would follow a six-step approach.

Step 1: Global inventory of hydrogen programmes and activities to increase transparency and help connect technology developers and firms across borders, creating conditions for collaboration.

Step 2: Periodic technology assessments (biennially) to help members be up-to-date about what gaps remain and about new opportunities for joint research.

Step 3: Bilateral/plurilateral partnerships, with the rule being that any initiative would need sponsors from at least two countries to promote collaboration and reduce costs.

Step 4: Pooled funds for enhanced joint R&D, with members allowed to contribute in cash or offer their human resources and laboratory and industry facilities in kind. A portion of this pooled fund could be set aside as a corpus to underwrite R&D projects via partial risk guarantees.

Step 5: Rules of intellectual property ownership and licensing, wherein participating institutions retain their original IP while any new technology developed by a work programme consortium is jointly owned.

Step 6: Alliance-wide standard-setting and inspections for safe storage and transportation via technical supervisory committees having the mandate to set standards and protocols, build capacity in developing countries, and undertake periodic inspections.

The Alliance's institutional design should prioritise scale, speed and risk. None of the six steps requires a large, bureaucratic secretariat. The Alliance could be designed on a networked governance model, with a governing council overseeing progress made by individual work programmes. Under the Alliance, pilot programmes could up and running in developing countries by 2025. Given pressing concerns about post-pandemic economic recovery, it is easier to see the value of pooling resources through a networked but global platform.

Finally, the Green Hydrogen Alliance must follow a risk-risk approach. These include failures in technological development or in end-use applications, second-order risks associated with the adverse impacts of faulty storage or transportation of green hydrogen, and tertiary risks involving trade or intellectual property disputes. Set against these risks should be the assessment of the failure to combat climate change by not deploying technologies for industrial decarbonisation rapidly and at scale.

The Global Green Hydrogen Alliance, by building on the existing initiatives and correcting for their governance failures, can be tactically and operationally more efficient, but it would be most critical as a governance innovation at a strategic level.

1. Introduction

By 23 April 2021, 44 countries and the European Union had declared net-zero commitments (IEA, 2021), promising to reduce their greenhouse gas (GHG) emissions to zero or offset whatever residual is difficult to completely eliminate. Whereas many of these countries have set 2050 as the target year, China is looking at 2060 and others are considering later years. Whereas the Intergovernmental Panel on Climate Change demands net-zero emissions for the world as a whole by 2050, the same principle need not apply to all countries. In fact, many of the developed countries that have set net-zero targets will enjoy long transition periods between when peaking emissions and bending the curve downwards to reach net-zero emissions[2] (Ghosh & Chaturvedi, 2021). The transition period is likely to be far shorter for developing countries giving them fewer additional years of carbon space within which to reach higher standards of living.

There also remain many questions about the credibility of the targets, given that they are not always backed up by adequate and concrete policies along a set timeline that would trigger near-term action and signal real intent. More recently, some countries have come forward to declare aggressive emission reduction goals for 2030 or 2035. For instance, the United States promised to reduce emissions by 50-52 per cent by 2030 against 2005 levels. The United Kingdom also raised ambition to reduce emissions 78 per cent by 2035 compared to 1990 levels. The EU pledged 55 per cent reduction (against 1990 levels) by 2030. These are, no doubt, encouraging signs of a clearer intention to reduce emissions to levels that give a chance for global average temperatures to stabilise. However, by some measures, high-income countries should be aiming for net-zero emissions latest by 2035, rather than wait for 2050 or later (Chaturvedi & Ghosh, 2021). Yet, the pressure on middle-income and low-income countries to reduce emissions disproportionately faster continues unabated.

The politics of emission reductions will continue but there is a technological and financial challenge: How would global industrial emissions be reduced at the pace needed for advanced economies and without deindustrialising fast-growing emerging economies? Industrial emissions accounted for approximately 25 per cent of GHGs worldwide in 2019 (IEA, 2021). For developing and emerging economies, which have not transitioned to possessing a dominant service sector, the share of industrial emissions could be higher. Likewise, the transportation sector accounts for another 24 per cent of emissions globally. While the share is lower (15.3 per cent) in emerging markets and developing economies, it is also expected to be a source of rapidly growing emissions (IEA, 2020). Additionally, even with rapid growth in renewable energy, the overall share of fossil fuels in final energy consumption at the global level remains as high as it was a decade ago. The decarbonisation of the power sector is clearly an imperative, but it will not on its own replace liquid fuels, especially in long-distance freight transport, or substitute for high-intensity heat in heavy industrial processes.

Hydrogen could potentially play this vital role, necessary if we are to make a green energy transition and achieve the Paris Agreement goals. As a substitute for coal in a blast furnace or as the energy source in a fuel cell powering a truck, hydrogen has remained one of the Holy Grails in energy innovation. Previous attempts to commercialise hydrogen at a large scale have not succeeded. Moreover, the production of hydrogen is very energy-intensive and relies on burning large amounts of coal or natural gas, resulting in more GHGs emitted. But the latest round of excitement around hydrogen promises a double transition: A fuel switch in end-use sectors as well as a cleaner way to produce hydrogen fuel from renewable energy¾ that is, the production of "green hydrogen." If successfully deployed, green hydrogen could be a game-changer for heavy industries, such as steel, ammonia and petrochemicals, in addition to transport.

Many countries have announced national and regional programmes for (green/clean) hydrogen. However, the technology and its applications in various industrial sectors are still significantly short of commercialisation at scale. Deployment so far is primarily via pilot projects. And, the centres for potential hydrogen demand, generally in emerging economies and particularly in Asia, remain mostly out of the loop of these developments. If industrial decarbonisation is to pick up speed, then research, demonstration and deployment of green hydrogen would also have to accelerate, at the global level, and connected to centres for potential hydrogen demand.

This paper proposes a new platform, a Global Green Hydrogen Alliance, as an action-focused multi-country, multi-institutional network to assess, develop and design affordable green hydrogen technologies that can be deployed at scale. The premise of creating a new platform rests on the gaps in current efforts to develop and scale hydrogen technologies, coupled with the urgent need to find core solutions to make the practical transition to a clean energy future, in line with the crucial Paris Agreement goals. The pace at which disruptive clean technologies and alternative foundational fuels are being developed does not match the speed with which emissions must reduce. Collaborative efforts and sharing of data on virus sequencing helped to develop vaccines against COVID-19 faster than had been the norm or what had been anticipated. A similar sense of urgency can drive cooperation on green hydrogen. The proposed alliance could benefit advanced economies, where research is underway, as well as emerging economies, where the scope for deployment is greater. A larger collaborative platform can achieve more sooner than if each country pursued the R&D individually.

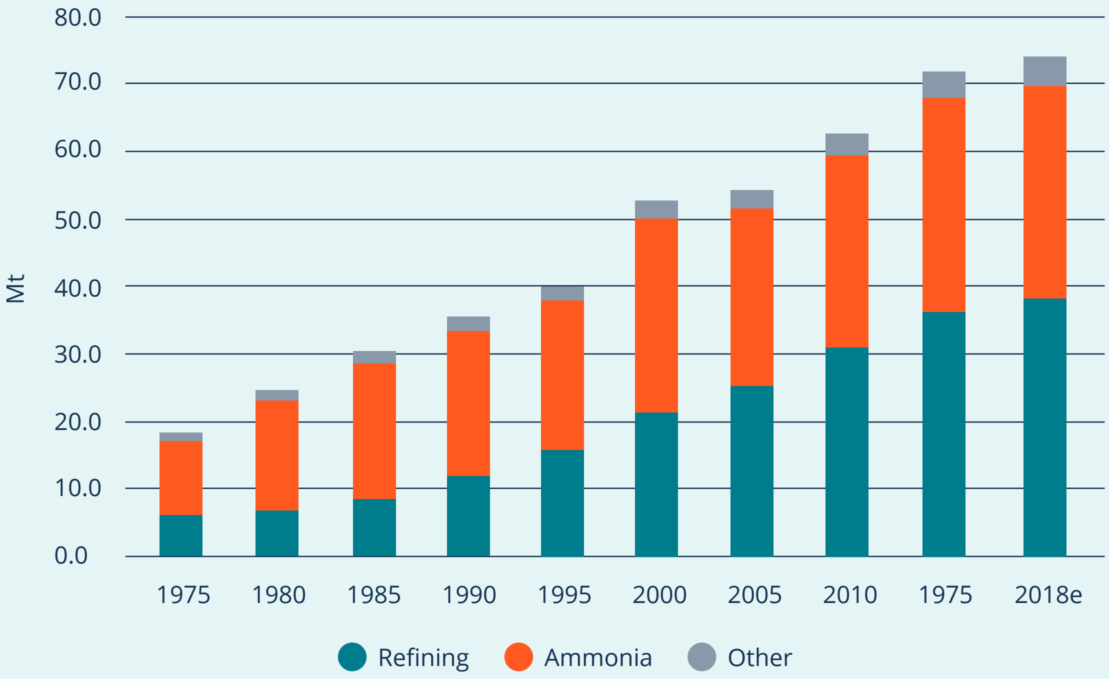
The paper first examines the current state of play in terms of hydrogen demand and expected growth. It identifies three shifts underway, namely, sectoral applications, geographical spread and the need to use cleaner energy sources to produce hydrogen. The following section explains green hydrogen as a technology and demonstrates that over the course of the next two decades, green hydrogen (using renewable energy) is likely to become cheaper than producing it using dirtier energy sources, such as coal and gas. The paper's attention, then, turns to how countries across the world are developing national programmes. It gives details on programmes in more than 32 countries as well as more than a dozen bilateral partnerships. The paper also examines several multi-party partnerships. However, there remain several gaps: The partnerships largely ignore developing countries, seldom involve joint technology development and do not focus on regions likely to have the highest demand for clean fuels for industrial development.

In order to counteract these gaps, the paper outlines a six-step approach to designing a robust and inclusive alliance, from an inventory of actions to technology assessments, from multi-party technology partnerships to pooled resources, and from jointly held intellectual property to alliance-wide standard setting. The alliance is designed on a networked governance model rather than a large bureaucratic institution, in order to prioritise scale of actions, speed of deployment, and the handling of risks at the frontiers of disruptive technologies.

2. The state of play

Hydrogen demand grew steadily from less than 20 million tonnes (MT) in 1975 to 52.5 MT in 2000. After stabilising for some years, demand again picked up and reached 74 MT by 2018 (see figure 1) (IEA, 2019). The global hydrogen market in 2018 was valued at USD 135.5 billion and is expected to grow at 8 per cent annually until 2023 (ESMAP, 2020).

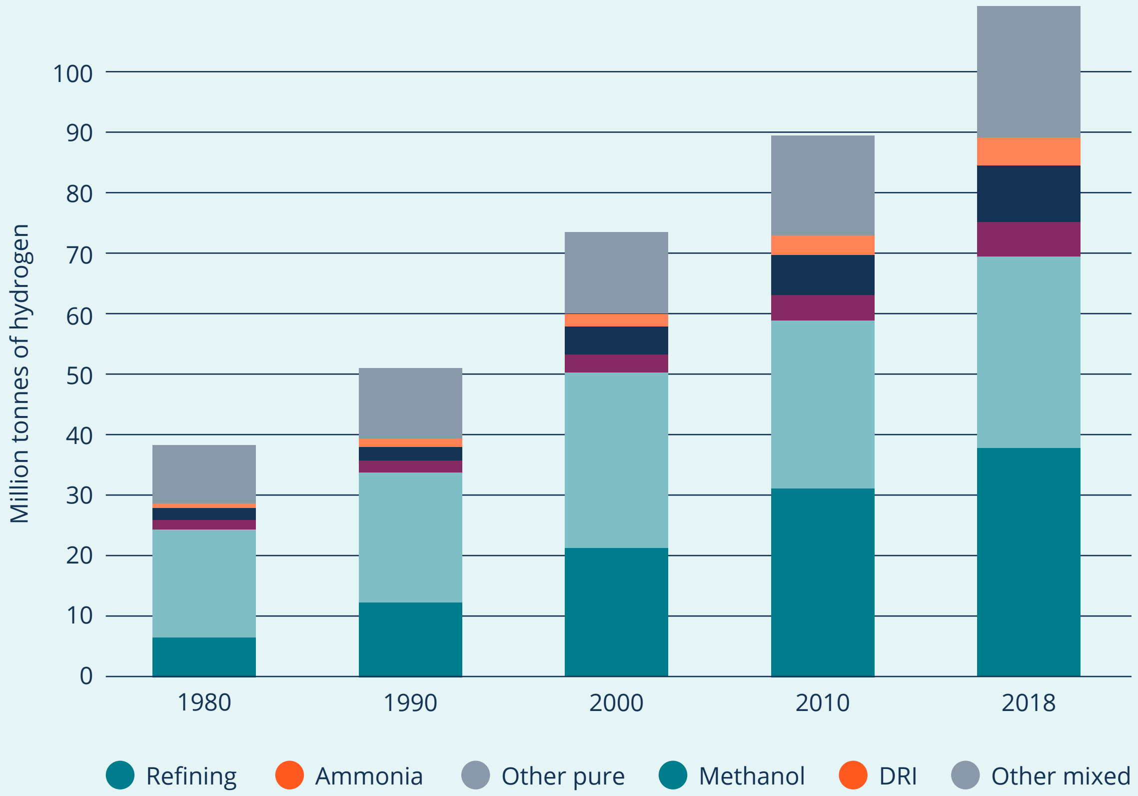
Figure 1. Global demand for pure hydrogen, 1975-2018



Source: IEA

The bulk of hydrogen production has been used for ammonia production and oil refining, accounting for two-thirds of hydrogen usage (see figure 2) (IRENA, 2019). But the future outlook signals rapid increase in hydrogen demand as well as sectoral shifts with transport, power, synthetic fuels and buildings emerging as major hydrogen consuming sectors. In the IEA's latest report on net-zero emissions pathways, hydrogen demand rises from less than 90 MT in 2020 to over 200 MT in 2030 and reaches 528 MT by 2050 (IEA, 2021). Just a year ago, its sustainable development scenario had forecast 520 MT of hydrogen only by 2070 (IEA, 2020).

Figure 2. Hydrogen use trends

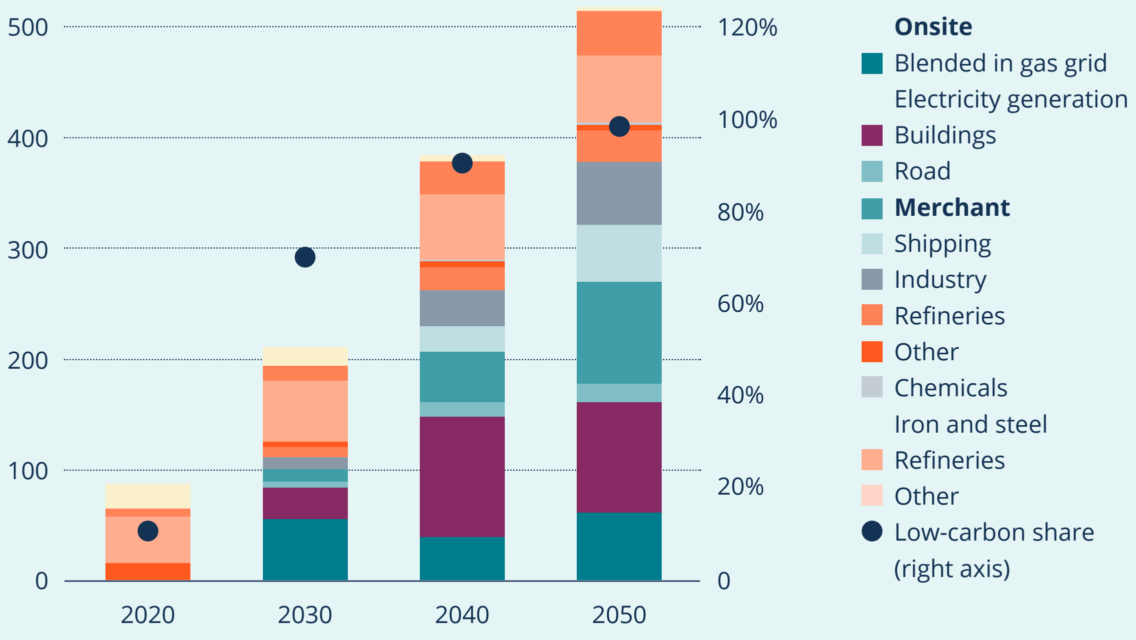


Source: IRENA, 2019

The pressure for the planet to reach net-zero emissions by 2050 adds to the importance of hydrogen in the energy mix. From negligible applications in end-use sectors, more than half of hydrogen demand is expected for “merchant” uses by 2030. These applications include blending in the gas grid, power generation, road transport (15 million fuel-cell vehicles by 2030), aviation and shipping, industry and refineries. By 2050, their share rises to 75 per cent, that is the hydrogen is produced for sale elsewhere rather than being used on-site (see figure 3). Under this scenario, the direct use of hydrogen in the transport sector would account for 39 per cent and industry would use another 35.4 per cent of hydrogen. The power and building sectors would account for almost 19.3 per cent and 4.3 per cent of demand, respectively.

For now, regional demand for hydrogen is concentrated in developed countries and China. But climate policies and carbon pricing are likely to influence regional shifts as well. Analysis from BP (BP, 2020) considers two scenarios — rapid and net-zero. The Rapid Transition Scenario posts a series of policy measures, led by a significant increase in carbon prices and is supported by more targeted sector-specific measures, which lead to carbon emissions from energy use to fall by around 70 per cent by 2050. On the other hand, the Net Zero Scenario assumes that global carbon emissions from energy use fall by over 95 per cent by 2050. It also assumes that the policy measures embodied in the Rapid Scenario

Figure 3. Hydrogen and hydrogen-based fuel use jumps to meet net-zero targets



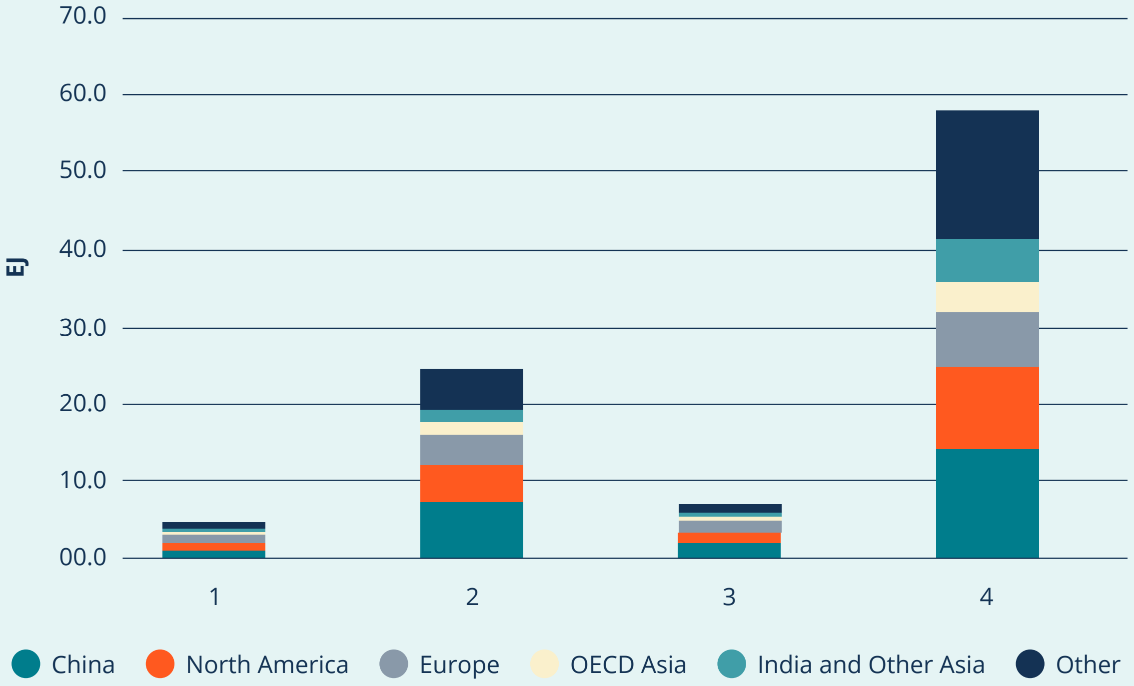
Source: IEA, 2021

are both added to and reinforced by significant shifts in societal behaviour and preferences. Under the rapid scenario, hydrogen use continues to be concentrated in China, followed by the United States and Europe. In fact, the share of these three regions jumps from 2035 (when developed Asia, India and other Asian economies are not that far behind) to 2050 (when the majority of global hydrogen use is in these three regions). However, under the net-zero scenario, not only does total hydrogen demand more than double in 2050 (compared to the rapid scenario), but the growth in developed Asia, India and other Asian economies, and the rest of the world is more pronounced (figure 4).

Moreover, it is critical that much of this hydrogen is produced using low-carbon sources. Currently, most of the hydrogen is produced from fossil fuel sources. Of this, 48 per cent comes from natural gas reforming, another 48 per cent from coal gasification, oil and other chemical processes, and only 4 per cent from electrolysis, which is a low-carbon production route (ESMAP, 2020). Almost 6 per cent of global natural gas production and 2 per cent of global coal production is used to produce hydrogen (IEA, 2019).

The IEA considers two low-carbon options to produce hydrogen, namely coupling the conventional technologies with carbon capture, utilisation and storage (CCUS) or generating hydrogen through water electrolysis (see next section). (Low-carbon hydrogen could also be produced from methane pyrolysis, where carbon ends up as solid rather than as CO2, with 4-5 times lower electricity

Figure 4. Hydrogen use by region



Source: BP Energy Outlook, 2020

consumption than electrolysis and potentially lower hydrogen production cost.) Over the past decade, production of low-carbon hydrogen stayed mostly constant. However, to meet global net-zero ambitions, the IEA projects that low-carbon hydrogen would have to increase rapidly in all end-use sectors, from 9 MT in 2020 to 150 MT in 2030 and 520 MT by 2050. Moreover, the share of electrolysis in producing green hydrogen jumps from 5 per cent now to 54 and 62 per cent, respectively, for 2030 and 2050 (IEA, 2021).

These three trends — the expected shifts in sectoral allocation, geographical spread, and low-carbon production — are going to serve as the foundations of a new wave of hydrogen production and consumption in the coming decades. Several economies have adopted hydrogen policies and strategies in recent years and have published roadmaps and vision documents, at times earmarking large financial outlays to support industrial pilots and commercial scale of hydrogen-based technologies. Yet, the transition of energy systems towards large-scale adoption of hydrogen and the internal shift towards green hydrogen is not a given. If the three shifts do not unfold concurrently, the world could get locked into a new energy source but one that remained fossil fuel-dependent. Equally, if the new demand centres for hydrogen are not party to the technological developments, their continued use of fossil fuels, especially in heavy industry and long-distance transport, could imperil efforts to put the planet on a climate-friendly pathway. The next two sections explore these themes.

3. What is green hydrogen?

Hydrogen produced from 100 per cent renewable energy resources is referred to as “green hydrogen”. As mentioned, green hydrogen is produced using a process called electrolysis, which uses 100 per cent renewable energy and water. Other renewables-based methods exist to produce green hydrogen, such as biomass gasification and pyrolysis, thermochemical water splitting, photocatalysis, supercritical water gasification of biomass, combined dark fermentation and anaerobic digestion and hydrogen extraction from waste. While being renewable technologies, these are not mature at a commercial scale yet.

Green hydrogen has a vast and growing spectrum of applications (figure 5). It can be used as a feedstock in various industries ranging from chemicals to steel and can also be converted into energy carriers like ammonia, methanol and others when produced at a competitive cost and large scale. It can be used in fuel cells, which can be further used across a wide range of stationary and transport applications. As a chemical, green hydrogen can help to reduce GHG emissions arising from the current use of “grey hydrogen” (see Figure 7) in oil refining, ammonia and methanol production.

The only commercially proven technology is electrolysis, using water and renewables-based electricity. The installed capacity of electrolysers has rapidly grown from less than 1 MW in 2010 to more than 25 MW in 2019 (Bermudez & Hasegawa, 2020). Figure 6 showcases the past and projected growth in electrolysis capacity.

Figure 5. Green hydrogen: end uses across the energy system

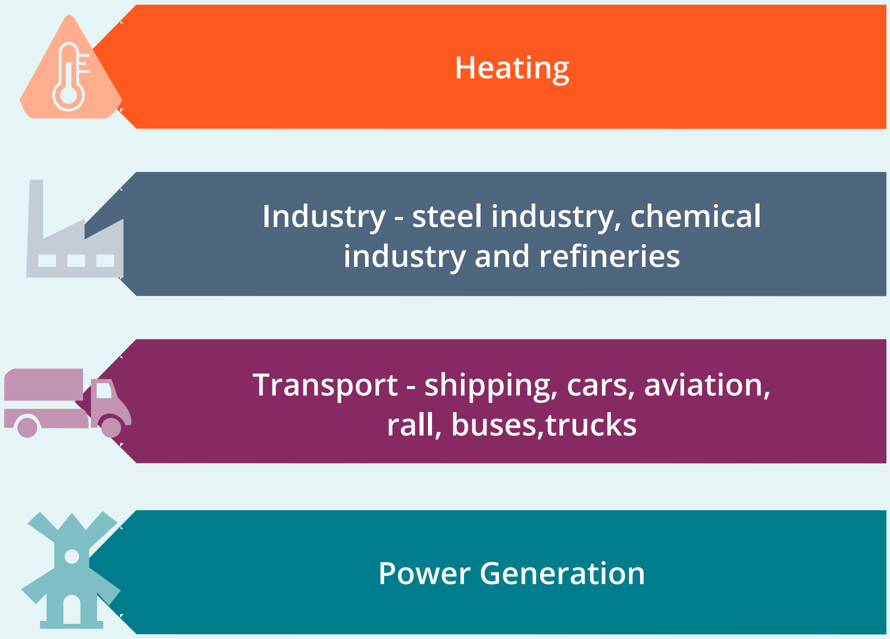
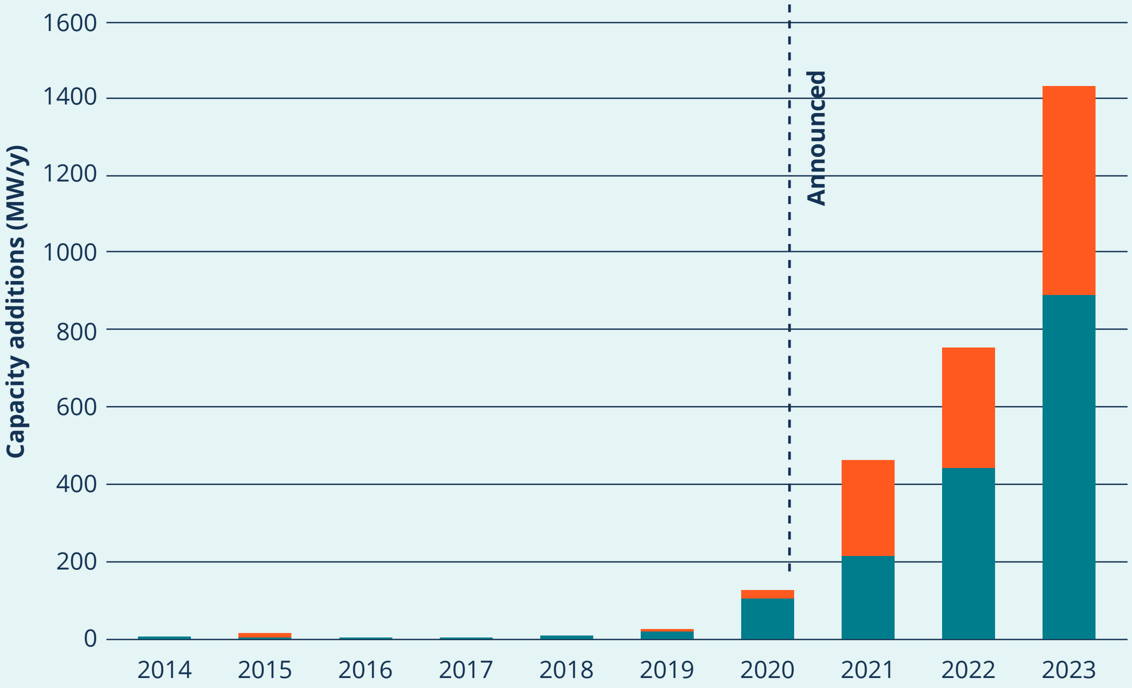


Figure 6. Global electrolysis capacity becoming operational annually



Source: IEA

Box 1. A debrief on electrolysers

Electrolysers are electrochemical devices, which take electrical power and water and use an electrolyte and membrane to separate hydrogen molecules (generated in the cathode) from oxygen molecules (generated in the anode).

Over the years the general principle of electrolysers has remained the same, but the technology has evolved since 1800 when it was first developed. Typically, there are four main technologies which differ from each other on the basis of the electrolyte and temperature of operation, which further leads to the selection of different materials and components used.

Water electrolysers have components at three levels:

- **The cell** is the core, comprising two electrodes (cathode and anode) immersed in a liquid electrolyte or adjacent to a solid electrolyte membrane, two porous transport layers, and bipolar plates that provide mechanical support and help with the distribution of flow.
- **The stack** includes multiple cells connected in series along with spacers, seals, frames and end plates.
- **The system l**evel includes equipment for cooling, processing of the hydrogen, converting the electricity input, treating the water supply and gas output (IRENA, 2020).

This system is fed by purified water using circular pumps or gravity. The water then reaches the electrodes, where the water is split into hydrogen and oxygen, with ions crossing through an electrolyte. Additionally, the membrane plays an important role by keeping the produced gas (hydrogen and oxygen) separate.

Alkaline and Proton Exchange Membrane (PEM) are already commercial and in the past two years additional electrolyser technologies have become available such as Anion Exchange Membrane (AEM) technology and Solid Oxide Electrolysis (SOE).

The increasing demand of green hydrogen globally is leading to a significant decline in the cost of electrolyser equipment. Globally, deployment of water electrolysis has grown from of 32.7 MW of cumulative installed capacity (2000-2013) to over 260 MW of installed and committed capacity in 2014-2019 (ESMAP, 2020).

In the past two years, electrolyser capacity has scaled at a significant rate. New feasibility studies have been announced for 250 MW electrolyser capacity in the Netherlands and 12 GW in Pilbara, Australia. The decrease in the cost of renewable electricity is also translating into lowering the production cost of green hydrogen.

What is different about green hydrogen?

Hydrogen comes in different shades, depending on the production process and the use of alternative energy sources. Figure 7 distinguishes between grey, blue, turquoise and green hydrogen. Grey hydrogen uses fossil fuels for production (i.e., hydrogen is produced from steam methane reforming or coal gasification). Blue hydrogen is produced via natural gas or coal gasification and is combined with carbon capture and storage (CCS) technology. Both result in substantial CO2 emissions. When natural gas is passed through molten metal to release hydrogen gas and solid carbon, it is known as turquoise hydrogen.

The fundamental breakthrough with green hydrogen is the use of renewables-based electricity in the electrolysis process. The benefits are many. Green hydrogen has the benefit of eliminating GHG emissions but also reducing local air pollution because of zero tailpipe emissions. It also has other benefits, such as contributing to energy storage and providing power system flexibility. Since renewable energy sources are far more distributed than fossil fuels, green hydrogen can also contribute to energy security. It also has substantial potential to contribute to economic growth, job creation and industrial competitiveness (IRENA, 2020).

Figure 7. Shades of hydrogen

Grey Hydrogen	Blue Hydrogen	Turquoise Hydrogen	Green Hydrogen
Process: SMR or gasification	**Process:** SMR or gasification with carbon capture (85%-95%)	**Process:** Pyrolysis	**Process:** Electrolysis
Source: Methane or coal	**Source:** Methane or coal	**Source:** Methane	**Source:** Renewable electricity
Entails substantial CO_2 emissions	This is an option to produce hydrogen with lower GHG emissions	Turquoise hydrogen combines the use of natural gas as feedsock with no CO_2 production	This is the net zero emissions route

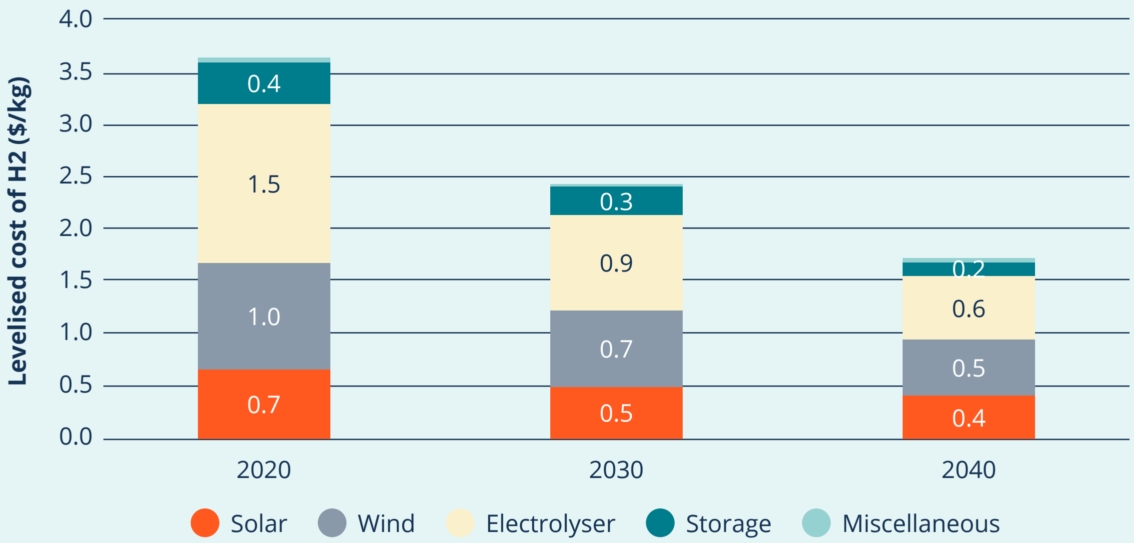
Source: IRENA

Cost differentials across countries

But costs matter too. For the short-to-medium term, combining conventional technologies with CCUS is still the main route for low-carbon hydrogen. Green hydrogen is more expensive currently than the other processes. Its production cost depends on various factors like investment cost of electrolysers and the capacity utilisation factor of electrolysers. One of the main factors affecting the cost of green hydrogen is the cost of electricity produced from renewable energy for the electrolysis process (see box on electrolysers). Thanks to these factors, green hydrogen costs lie in the range of USD 3-7.5 per kg (IEA, 2018).

The cost of electrolysers has the highest share in the total production cost. This is followed by the costs of wind and solar power. A CEEW analysis of the Jamnagar refinery in western India (see figure 8) found that electrolysers accounted for nearly 45 per cent of the levelised cost of hydrogen in 2020. With falling technology costs, this share would drop to about 35 per cent by 2040, while the total cost is expected to fall from USD 3.6/kg in 2020 to USD 1.7/kg in 2040.

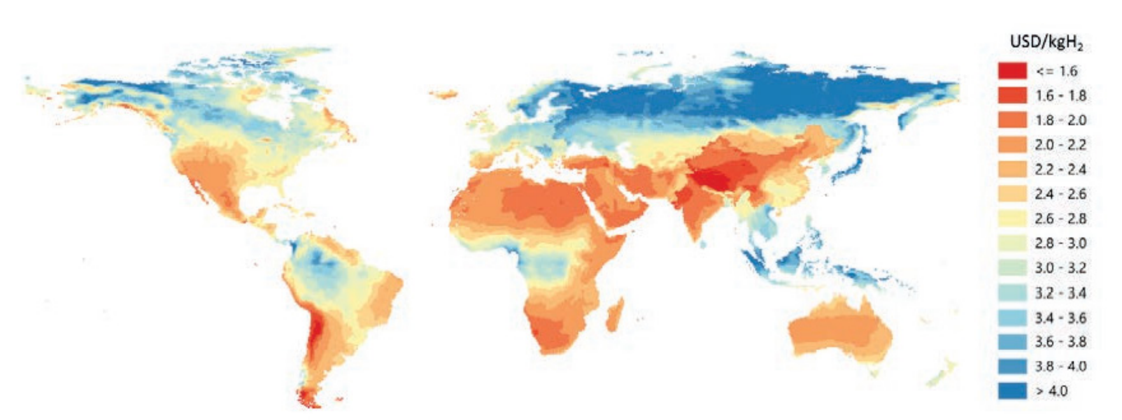
Figure 8. Production cost trend for Jamnagar (India)



Source: CEEW analysis

Falling costs of solar PV and wind can become a low-cost supply option for hydrogen in regions with favourable resources and conditions. Figure 9 represents the cost of hydrogen across geographies from hybrid solar PV and onshore wind systems in the long run. It is evident that most regions within the tropics, with high solar insolation, have the potential to produce green hydrogen at less than USD 2.8/ kg, and many regions can do so at USD 2/kg, the key cost barrier that many believe must be breached in order to make green hydrogen commercially viable at scale. Several projects on green hydrogen have been announced in various parts of the world with promising areas future expansion being Australia, China, Mongolia, New Zealand, North Africa, the United States and others (see Section IV).

Figure 9. Cost differentials across countries



Notes: This map is without prejudice to the status of sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area. Electrolyser CAPEX = USD 450/kW_e, efficiency (LHV) = 74%; solar PV CAPEX and onshore wind CAPEX = between USD 400-1 000/kW and USD 900-2 500/kW depending on the region; discount rate = 8%.

Source: IEA 2019

Cost differentials for key industries

Hydrogen can be used across various energy system applications ranging from integration of renewables to transportation and heavy industrial manufacturing. In order to understand the cost differentials and economic viability of green hydrogen for key industries, CEEW focused on three applications in India: Heavy duty vehicles in the transport sector, ammonia and steel manufacturing processes. The emerging economy context gives a more realistic picture for other developing and emerging economies, which would not have easily available capital resources to deploy towards a disruptive but expensive technology.

Consider fuel cell electric vehicles (FCEVs) that use hydrogen. When compared to battery electric vehicles (BEVs), FCEVs offer various advantages in terms of longer range and faster refuelling time and have the same benefit in reducing tailpipe emissions. Currently, FCEVs running on green hydrogen are not cost competitive with BEVs and other fossil fuel-based vehicles. But for distances of 400 kms and above, FCEVs could break even with BEVs. Additionally, studies (IEA, 2019) suggest that FCEVs could be cost competitive for heavy duty vehicles (commercial vehicles) with longer travel range and route flexibility in the near term.

India’s industrial sector is heavily dominated by fossil fuels with coal and petroleum fuels contributing approximately 60 per cent and 20 per cent of the energy demand, respectively. With a decline in the cost of electrolysers and renewable electricity, green hydrogen could replace fossil fuels like coal and coke being used in the iron & steel and ammonia manufacturing by the 2030s.

According to current trajectories, the cost of producing hydrogen in various locations of India would lie in the range of USD 2.5-3.5 per kg by 2030 (Biswas, et al., 2020). At the given prices of hydrogen, the cost of green steel would lie in the range of USD 466-540 per tonne of steel. The cost of steel produced using the conventional blast furnace (BF-BOF) route is lower at USD 370-450 per tonne. However, the cost of the natural gas-based route would be around USD 450-510 per tonne. As prices of green hydrogen fall to USD 1.7-2.2 per kg by 2040, green steel cost would be USD 408-445 per tonne of steel. This would ensure that green steel becomes cost competitive with all conventional methods of producing steel at all locations in India.

Another application where hydrogen could be cost competitive in future is ammonia production. The cost of producing green ammonia could be less than USD 400 per tonne in most of the locations in the western part of India by 2030 (Biswas, et al., 2020). Hydrogen is expected to break even with conventional production routes with a subsidised natural gas price of USD 6.5/MMBtu.

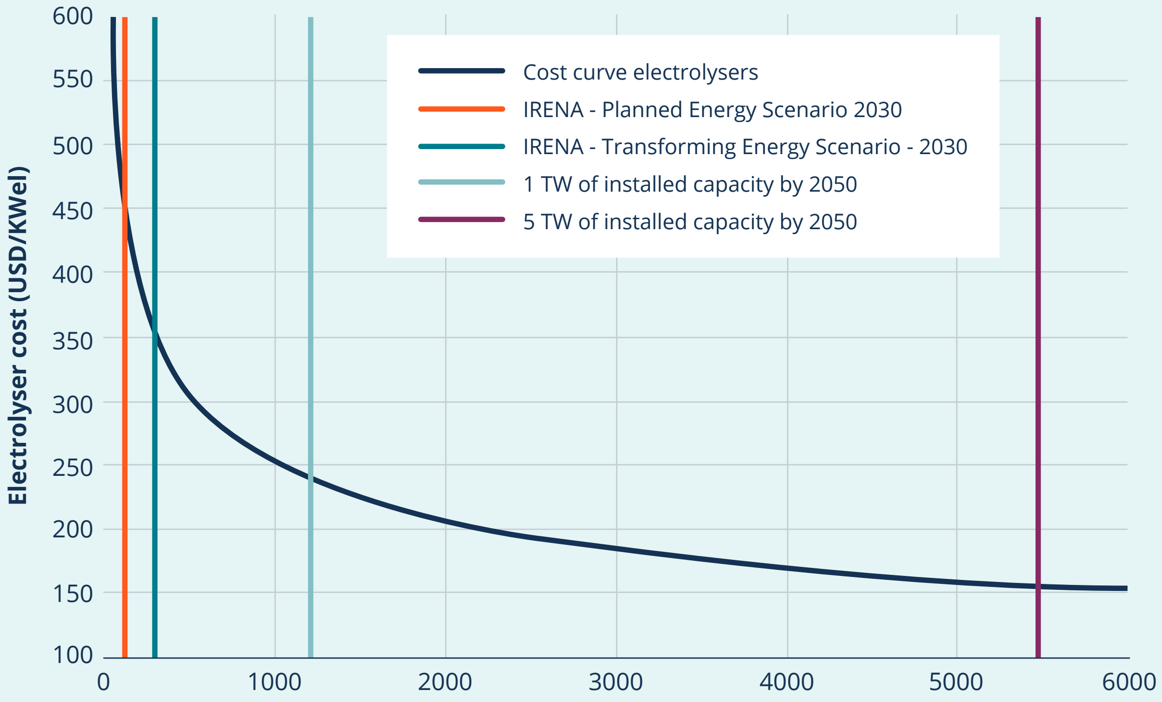
Future projections

Several countries are betting on hydrogen as a viable source of energy in the future and are already adopting or investing in hydrogen across various sectors. In the coming years electrolysers are expected to have a similar learning curve as witnessed in the case of solar PV and are expected to experience a similar decrease in cost with large scale deployment.

The learning curve or experience curve refers to the decline in production cost as the cumulative capacity for a specific technology increases. The cost of electrolysers could reduce by 40 per cent by 2030 with 100 GW of capacity deployment; and in a close to zero emissions system, the cost of electrolysers is expected to reduce by about 70 per cent by 2050 with a deployment of 1700 GW (IRENA, 2020). These estimates are in line with the estimates provided by the Hydrogen Council which aims at 60 per cent reduction in cost by 2030.

Figure 10 shows the decrease in the cost of electrolysers based on the learning curve. With such huge reductions in the cost of electrolysers in the future, many countries are being bullish about the potential use of green hydrogen, as discussed in more detail in section IV.

Figure 10. Relationship between cost of electrolysers and deployment of electrolysers



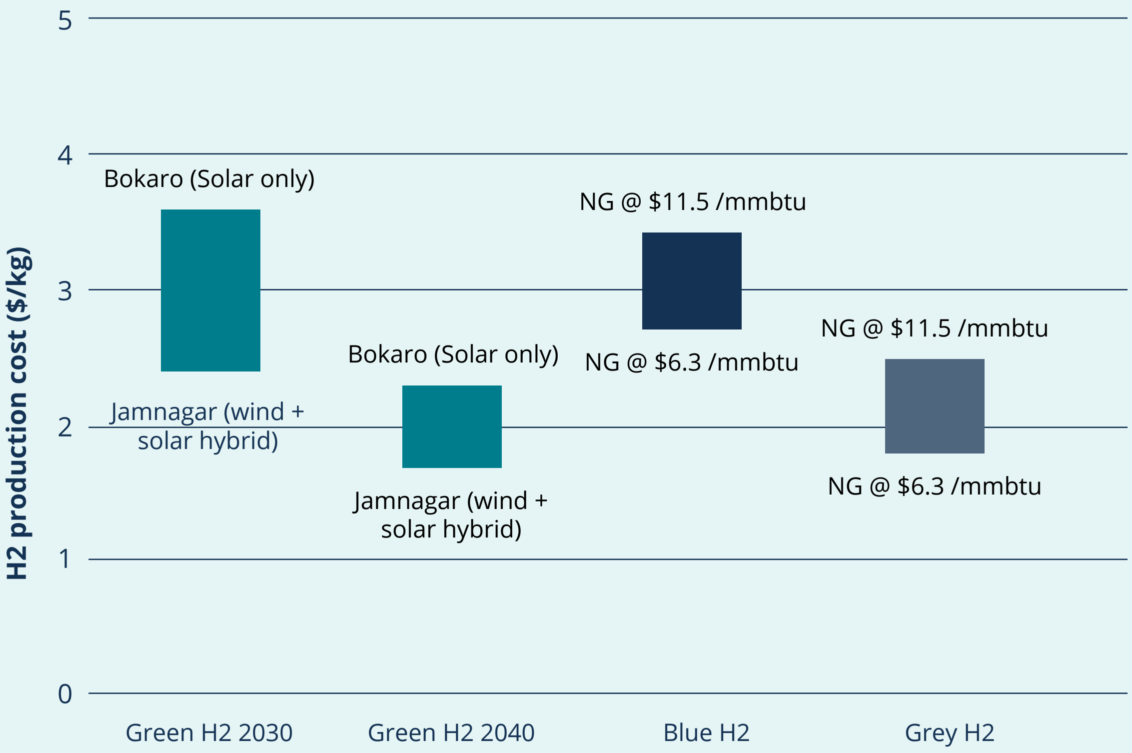
Source: IRENA

Is there room for grey/blue H2?

How competitive is green hydrogen compared to grey and blue hydrogen? Currently, industrial hydrogen in India is produced using a conventional method of Steam Methane Reforming (SMR), which produces grey hydrogen. The price of producing hydrogen is a function of the cost of natural gas. In India the price of natural gas differs across various industries depending on the priority accorded to each sector. Assuming a price of USD 6.3/MMBtu for priority sectors, such as for fertilisers, and USD 11.5/MMBtu for industries using liquefied natural gas, CEEW arrived at a hydrogen cost in the range of USD 1.76/kg for priority sectors and USD 2.37/kg for industries using LNG (Biswas, et al., 2020).

However, the SMR process also generates carbon dioxide. The cost of blue hydrogen with carbon capture and sequestration jumps up to USD 2.74/kg for the priority sectors and USD 3.35/kg for the rest (see figure 11). By contrast, with solar and wind hybrid plants, green hydrogen production cost falls to about USD 2.4/kg by 2030 in India, making it competitive with blue hydrogen. With only solar, the production cost would be higher, around USD 3.6/kg. But by 2040, the hybrid and solar-only plants can achieve a production cost of USD 1.7/kg and USD 2.3/kg, respectively. In both cases, green hydrogen is likely to become more competitive than blue as well as grey hydrogen.

Figure 11. Production cost comparison (2030)



Source: CEEW analysis

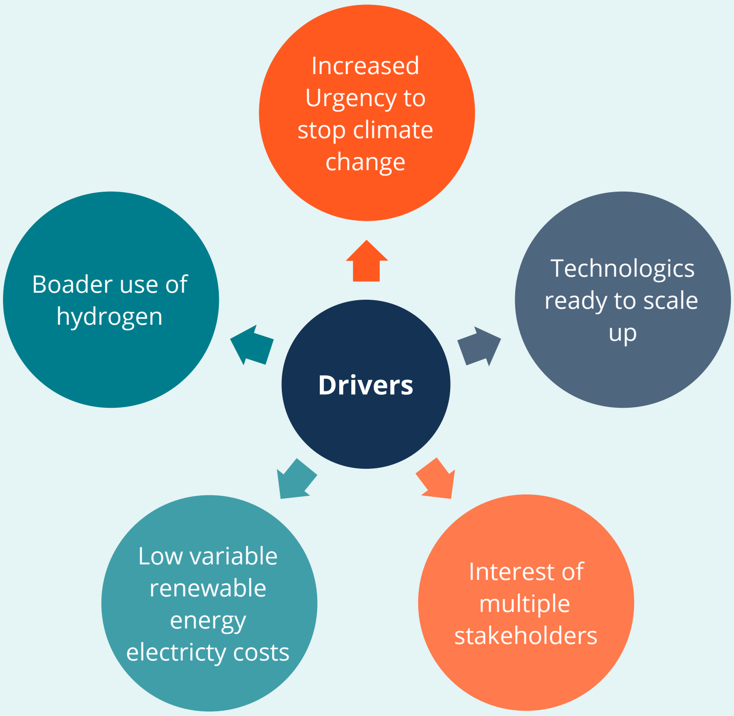
4. What is different this time

The hydrogen buzz is not new. There have been several waves of interest in hydrogen over the past half century. Is there anything different this time that energy planners should take seriously?

The first wave of interest in hydrogen arose during the 1970s thanks to petroleum shortages and the oil price shocks, along with concerns about air pollution and acid rain. Various developments took place, including the launch of International Journal of Hydrogen Energy in 1976 and the IEA's hydrogen and fuel cell technology collaboration programme in 1977. The Hydrogen Technology Collaboration Programme (HTCP) was established to provide technical expertise in hydrogen R&D and has an operating history of more than 30 years. It has 25 contracting parties (23 countries plus the European Commission and the United Nations Industrial Development Organisation) and six sponsor members.

The second wave made an appearance in the 1990s due to increasing concerns about climate change, with focus on areas like carbon capture and storage, renewable energy and alternative transport fuels. During this period some governments started allocating funds to explore various areas such as hydrogen storage and uses. Some automakers also displayed hydrogen-based concept cars at motor shows. But by the second half of the decade, with oil prices remaining low, the economic case for the technology remained weak and these projects did not become mainstream (IEA, 2019).

Figure 12. Drivers of green hydrogen



Source: CEEW Research & Analysis

A third wave, in the early 2000s, came along with renewed concerns about climate change and started translating into policy actions focused on the transport sector. There were also concerns about peak oil once again. But by 2010, the threat of peak oil had abated, climate policies remained uncertain with the failure of the Copenhagen negotiations, and technological progress in battery electric vehicles continued. Consequently, expectations about the rise of hydrogen as an alternative fuel source abated for the third time.

As illustrated earlier, several governments have started introducing national programmes and targets (especially since 2019) during what could be considered a fourth wave of interest in (green) hydrogen. In the past few years, various governments across the globe have adopted hydrogen policies and strategies and have made announcements related to hydrogen (specifically 2019). Global spending on hydrogen-related research and development has also risen.

The drivers for the latest push stem first and foremost from technological breakthroughs (figure 12) (IRENA, 2020). Hydrogen and fuel cell technologies have seen significant progress in terms of efficiency, cost reduction and reliability. The capital cost of electrolysis has decreased by 60 per cent since 2010, resulting in a fall in the cost of hydrogen from USD 10-15/kg to USD 4-6/kg bringing it temptingly close to parity with fossil fuel-based end-use applications. This has been aided with the fall in renewable energy costs as well. The other key driver is the push for commitments to achieve net-zero GHG emissions in the coming decades. As of 23 April 2021, 44 countries and the European Union have pledged to meet net-zero targets. Many major emitters have recognised that without significant industrial decarbonisation, pronouncements of net-zero would have little certainty. This creates a demand pull, not just a technology-based supply push, for disruptive technologies like green hydrogen. As discussed earlier, new sectoral applications are emerging, which broaden the potential market for green hydrogen, and has created a wider range stakeholders with interest in promoting green hydrogen.

Who is doing what?

The supply and demand drivers of green hydrogen technology interact with the policy and market frameworks that countries around the world are developing. Our research finds at least 32 countries plus the European Union with national-level policies and strategies for hydrogen, either under development or already having been announced (see Annexure 1). In some cases the ambition is transformational. Canada expects that hydrogen could provide up to 30 per cent of its end-use energy by 2050. Chile, with a smaller economy, is focused on overseas markets, hoping to export USD 2.5 billion of hydrogen and derivatives. Australia is looking to hydrogen for energy security and also targeting exports on a massive scale; and Morocco hopes to supply green hydrogen to the European market across the Mediterranean.

Not all of these country-level initiatives are low-carbon. For instance, the US has an ambitious plan to make the production, transportation, storage and use of hydrogen more efficient. It has price targets in all dimensions of the hydrogen value chain, from USD 2/kg for production and USD 2/kg for delivery, to USD 300/kW for electrolyser capital cost to 80/kW for fuel cells that can support long-distance freight transportation. But its hydrogen programme is not restricted to green hydrogen. Oman's ARA Petroleum and Japan's Sumitomo Corporation are experimenting with producing hydrogen using flared gas. However, Oman has recently declared its intention to build one of the world's largest green hydrogen plants, powered by 25 GW of renewable power by 2038 (Paddison, 2021).

Still, at least 24 countries and regions have specific programmes, targets and pilots focused on green hydrogen. The European Union plans to install 6 GW of electrolyser capacity by 2024 and 40 GW by 2030, by when it hopes to produce 10 MT of green hydrogen. This will involve massive investments, up to USD 430 billion in renewables and USD 53 billion in electrolysers. France, alone, is targeting 6.5 GW of electrolyser capacity by 2030, as part of a national strategy that is backed by EUR 7.2 billion of promised investment from the government. As part of its COVID-19 economic recovery package (worth around USD 165 billion) Germany has proposed USD 11.4 billion for hydrogen and has launched three large-scale green hydrogen projects. Spain is relying significantly on EU funding for its renewables-based hydrogen and wants a quarter of the hydrogen consumed by industries to be green by 2030. Portugal is targeting 2-2.5 GW of electrolysis capacity by 2030. Italy’s major gas majors, SNAM and ENI, are part of different consortia on green hydrogen; Italy hopes to attract EUR 10 billion in investment by 2030.

Outside Europe, attention shifts to Asia. Japan has already started producing green hydrogen using solar energy at a facility in Fukushima since March 2020. In pursuit of robust hydrogen supply chains, Japan is also developing bilateral programmes with several countries, including Australia and New Zealand. South Korea is also promoting R&D in green hydrogen combining production, battery storage and final use cases. In 2020 Saudi Arabia announced the world’s largest green ammonia project, which will draw on 4 GW of renewables capacity for electrolysis and produce 1.2 MT of green ammonia annually. The UAE has also launched a project with the Dubai Electricity and Water Authority and Siemens on solar-powered green hydrogen.

In South America, Brazil has signed agreements with Australia’s Energix and Germany’s Siemens Energy to build green hydrogen projects. Argentina, Colombia and Uruguay have smaller programmes planned. South Africa is planning a Platinum Valley, an industrial cluster to bring together hydrogen applications and leverage its resources to produce green hydrogen.

As is evident, most of the countries investing in green hydrogen are developed economies. They have extended well beyond just national policies/programmes to establish pilot projects and, in some cases, are deploying the technology in various applications on a commercial scale. In Australia (with AUD 500 million allocated) there is funding for 16 projects; in the EU 250 projects have been funded already. Pilots at scale also manage to bring in a large number of research institutions and industry partners. Germany’s three large-scale projects involve 230 institutions and firms. Sweden’s HYBRIT project — a joint project of SSAB, LKAB and Vattenfall —is building a rock cavern storage facility for fossil-free hydrogen gas, as a precursor to manufacturing green steel. A demo plant is planned by 2025, fossil-free steel to be introduced in 2026 with wholesale transformation by 2045.

Further investigation reveals that many of these countries are rightly focused on the full value chain of green hydrogen (see table 1), extending from targets for reducing the price, increasing installed capacity of electrolysers, aiming to ramp up hydrogen production, building the transportation and refuelling infrastructure, and exploring different industrial applications. From Australia to Chile to Japan, the aim is to reduce hydrogen costs to under USD 2/kg, at times targeting USD 1.5/kg. Again, several countries hope to build large electrolyser capacity, from 2-2.6 GW in Portugal to 5 GW in Chile and Germany to 6 GW promoted by the EU (and produce 10 million tonnes of green hydrogen by 2030). South Korea leads the pack in its aim to deploy a vast network of 1200 hydrogen refuelling stations by 2040; Japan hopes to have 320 stations by 2025 alone. In terms of applications, many countries focus on the heavy transportation uses of green hydrogen. Japan, South Korea and the Netherlands aim to sell thousands of hydrogen fuel cell forklifts, trucks and buses and millions of fuel cell cars by 2030 or 2040. But, like Sweden, Germany has its eye on industrial uses. By 2050 it estimates that 80 TWh of green hydrogen would be needed for steel production and another 22 TWh in for refineries and ammonia production.

Who is collaborating?

In this wave of hydrogen-related research and deployment efforts are not restricted to country-level programmes. At least 13 bilateral partnerships can be identified (table 2). The nature of these collaborations vary. Some examine joint R&D or sharing technical knowledge to develop clean hydrogen technologies. Germany is involved in many of these partnerships, with France, Morocco and the United States. Others are cooperating on the hydrogen supply chain, especially over long distances. Japan is particularly involved in such partnerships with Australia, Brunei and Norway. The EU is also exploring these partnerships with the Middle East and North Africa. Other partnerships are more transactional, focused on creating trading opportunities in large demand centres, such as between Portugal and the Netherlands or from Australia to Germany. Russia wishes to promote natural gas sales into northern Europe and potentially use the pipelines to transport hydrogen in future. But if such hydrogen were produced using natural gas, it would not qualify as green.

There are also multi-country or multi-firm alliances that have sprouted across the world (table 3). In 2003, the U.S. Department of Energy and Department of Transportation facilitated the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), which now has 21 member countries and the European Commission. It seeks to standardise methods, codes and regulations with the aim to scale deployment. The aim was to develop common codes and standards and share information, on best practices but also the benefits and challenges on scaling up commercial hydrogen and fuel cell technologies. Its membership is open to national government entities.

Recent years have witnessed more activity. In 2017 the Hydrogen Council was established. It was a CEO-led initiative, which now has 109 members in more than 20 countries, representing USD 6.8 trillion in market capitalisation. Structured mostly as an advocacy group, it provides guidance on deploying hydrogen solutions and promotes collaborations between companies, policymakers, international organisations and civil society organisations.

Major economies have promoted their own alliances. China launched a hydrogen alliance in 2018, which has 87 members globally, but the aim is to primarily inform China's national policy. In 2020 Japan launched the Japan Hydrogen Association, with 87 industrial members. In the same year, the European Clean Hydrogen Alliance was launched and already has more than 1000 industry partners, business councils and research and civil society organisations. For these latter efforts, the aim is to scale up deployment on commercial terms — and in the European case, directly linked to promoting the EU's new industrial policy and giving it global leadership in this domain.

In 2021, soon after India announced an intention to establish a National Hydrogen Energy Mission, several conglomerates (including Reliance, Adani and others) forged another alliance (The Economic Times, 2021). Also in 2021, the UAE launched the Abu Dhabi Hydrogen Alliance to bring together large investment and energy firms.

Another platform is a newly proposed Global Green Hydrogen Council (GGHC) to promote sustainable production and use of green hydrogen and drive deep decarbonisation across industry. GGHC is promoted by Australia-based Fortescue Future Industries. Funded through corporate membership contributions and grants from governments and philanthropic organisations, it is expected to be formally launched in August 2021.

Perhaps the most important initiative has been the Green Hydrogen Catapult, launched in December 2020. The initiative is led by the world's biggest green hydrogen project developers and partners, namely ACWA Power, CWP Renewables, Envision, Iberdrola, Ørsted, Snam, and Yara. It has been facilitated by a collection of UN agencies, the High-Level Champions for Global Climate Action, the Race to Zero coalition, and the Climate Ambition Alliance. In contrast to the other alliances and groupings, it has clear targets for deployment (25 GW of renewables-based hydrogen production capacity by 2026) and cost reduction (under USD 2/kg by 2026). This would mean attracting USD 110 billion in investment and creating 120,000 jobs. The member companies intend to work across different dimensions, from developing project capacity, solving early market challenges, sponsoring targeted collaborations and increasing supply chain resilience.

Table 1: Several countries are focused on the full value chain of green hydrogen

S.NO.	Country Name	Hydrogen Price	Electrolysis Capacity Additions	Hydrogen Production	Infrastructure	Industrial Applications
1	**Australia**	AUD 2 per kg and below				
2	**Chile**	less than USD 1.5 per kg	5 GW electrolysis capacity by 2025 & 25 GW target by 2030	0.2 MtH2/ year by 2025		
3	**European Union**		6 GW of electrolyser capacity by 2024 and 40 GW by 2030	1 million & 10 million tonnes of renewable hydrogen per year for 2024 & 2030 respectively		
4	**Germany**		5GW of electrolyser capacity by 2030 & 10 GW by 2035-40	14 TWh of green hydrogen production by 2030-35	**Refueling station:** 400 by 2025	80 TWh of green hydrogen demand expected from steel production by 2050 and 22 TWh from German refinery and ammonia production
5	**Japan**	Green hydrogen: production cost of USD 3.3 per kg by 2030 & Hydrogen power generation cost of USD 0.16/ kWh by 2030			**Refueling station:** 160 by 2020 & 320 by 2025	• **FC Bus:** 1200 by 2030 • **FC forklifts:** 10,000 by 2030 • **FC Cars:** 800,000 by 2030
6	**The Netherlands**		500 MW of installed electrolyser capacity by 2025 & 3-4 GW by 2030		**Refueling station:** 50 by 2025	• **FC Bus:** 300 by 2025 • **FC Trucks:** 3500 by 2025 • **FC Cars:** 300,000 by 2030
7	**Portugal**		2-2.5 GW of electrolyser capacity by 2030			Blending: 2 per cent to 5 per cent blending in industries
8	**Republic of Korea**				**Refueling station:** 1200 by 2040	• **FC Bus:** 40,000 by 2040 • **FC Trucks:** 30,000 by 2040 • **FC Cars:** 2,900,000 by 2040
9	**India**	Goal-oriented research & development		Creating volumes and infrastructure	**Refueling station:** 2 (current status) framework for standards and regulations for hydrogen technologies	**FC Bus:** 10 (current status) Aims to demonstrate niche applications (including for transport, industry)
10	**China**				**Refueling station:** 35 (current status)	**FC Cars:** 10,000 by 2020

Source: Authors' compilation

Table 2: Bilateral partnerships on hydrogen		
S.NO.	**Partnership**	**Description**
1	**Portugal - Netherlands**	A memo of understanding was signed between the two countries on green hydrogen exports from Sines electrolyser project in Portugal to Netherlands
2	**Germany - Morocco**	A partnership agreement was signed between the countries which aims to develop production of green hydrogen and develop projects and research related to it
3	**Australia - Germany**	This is a research project which aims to study the potential for imports to Germany
4	**Germany - USA**	The partnership aims at technical knowledge sharing (electrolysis research)
5	**Germany - France**	France is planning to collaborate with Germany in the development of clean hydrogen technologies as a part of the Europe's green recovery plan.
6	**Japan - Australia**	Japan got into a joint venture with Australia for development and demonstration of a liquified hydrogen supply chain
7	**New Zealand - Japan**	A memo was signed between the countries to carry out green hydrogen pilot project
8	**Japan - Brunei**	Japan's AHEAD launched its pilot project to bring hydrogen from Brunei to Tokyo Bay with the aim to use it as a fuel for power generation
9	**Japan - Norway**	The main objective of this partnership is to show that liquid hydrogen can be produced using renewables in Norway and can be delivered to Japan on tankers. Under this partnership, Kawasaki Heavy Industries (KHI) has teamed up with Nel Hydrogen with backers including Mitsubishi Corp and Norway's Statoil. Nel aims to supply liquified hydrogen to Japan at a price cheaper than that of hydrogen produced in Australia
10	**United States - The Netherlands**	This partnership aims to address the key hydrogen R&D areas and foster new hydrogen value chains worldwide
11	**Europe - North Africa**	This regional partnership aims to speed up the deployment of green hydrogen projects and value chains
12	**Europe - Middle East**	This regional partnership aims to speed up the deployment of green hydrogen projects and value chains
13	**Russia - Germany**	The two countries are already working on hydrogen development for the energy sector. They expect the Nord Stream II pipeline to bring in Russian gas to Germany and will act as a future hydrogen import route

Source: Authors' compilation

Table 3: Multi-party hydrogen cooperation platforms

Name of Association	Country of origin	Year of formation	Geographical coverage	Scope	Type of members	Total Members	Typical activities
Abu Dhabi Hydrogen Alliance	UAE	2021	National	Production and end-use consumption	Industry	Mubadala Investment Company, Abu Dhabi National Oil Company (ADNOC) and ADQ	R&D and deployment
China Hydrogen Alliance	China	2018	International	Entire value chain	Industry, Government	China Energy Corporation plus 18 sponsors; now 87 members	Research and information national strategy
European Clean H2 Alliance	Europe	2020	National	Entire value chain	Ministry, Industry, Academia, Civil Society, Financial houses, Business councils	Industry - 651 Public authorities - 60 Research - 87 Civil society - 13 Financial - 17 Business councils - 157	Commercial scale up
Global Green Hydrogen Council	Australia	2021 (to be publicly launched in August 2021)	International	Promote sustainable production and use of green hydrogen, mitigating climate change and delivering reliable and secure clean energy	Government, multilateral organisations, businesses, institutional investors and civil society		5 key work streams: global green hydrogen charter; global green hydrogen finance pledge; creating hydrogen markets; hydrogen accreditation and standards, advocacy and policy
Green Hydrogen Catapult	High-Level Champions for Global-Climate Action; Race to Zero; Climate Ambition Alliance	2020	International		Industry	7 core partners ++	Deployment; cost reduction
Hydrogen Association of India	India	2009	National	Entire value chain	Industry, Academia	Reliance ++	R&D
Hydrogen Council	Belgium	2017	International	Entire value chain	Large multinational, innovative SME's, investors	Companies -109 Countries - 20+	Promotes collaboration between governments, industries and investors. It provides guidance on accelerating the deployment of hydrogen solutions
India H2 Alliance	India	2021	National	Entire value chain	Industry		Policy; demonstration projects; national H2 fund
IPHE	United States is a founding member of IPHE	2003	International	Production and end-use consumption (primarily mobility sector)	Intergovern-mental partnership	22 countries	Research, standardisation of methodology, and developing codes and regulations
Japan H2 Association	Japan	2020	National	Entire value chain	Industry	87	Commercial scale up

Source: Authors' compilation

5. Can we reimagine collaborative action?

On the face of it, there is no dearth of hydrogen programmes or partnerships across the world. The national targets and bilateral/plurilateral platforms are signs that the fourth phase of hydrogen R&D, investment and deployment is being taken seriously by many parties. Yet, a major shift towards hydrogen is not a given. In this section we examine the challenges with the way the collaborations have been designed.

What is missing in the existing hydrogen platforms?

First, path dependency in national programmes can prove to be a barrier. Since a few advanced economies have established their own programmes (and are attempting to build parallel networks), they would not wish to compromise on those ambitions. However, it could result in sub-optimal outcomes related to technology choices, end uses and standards. These include continued reliance on blue hydrogen rather than investing in reducing costs of green hydrogen. There could be limitations in the sectoral applications, with a lot of focus having continued in the transportation sector while other end-use sectors receiving lesser attention until recently. Production standards, storage and transportation safety protocols could also differ from country to country or from one major company to another. Much more coordination would be needed among industry leaders and partners to ensure that technical barriers to trade do not slow down the spread of green hydrogen technologies.

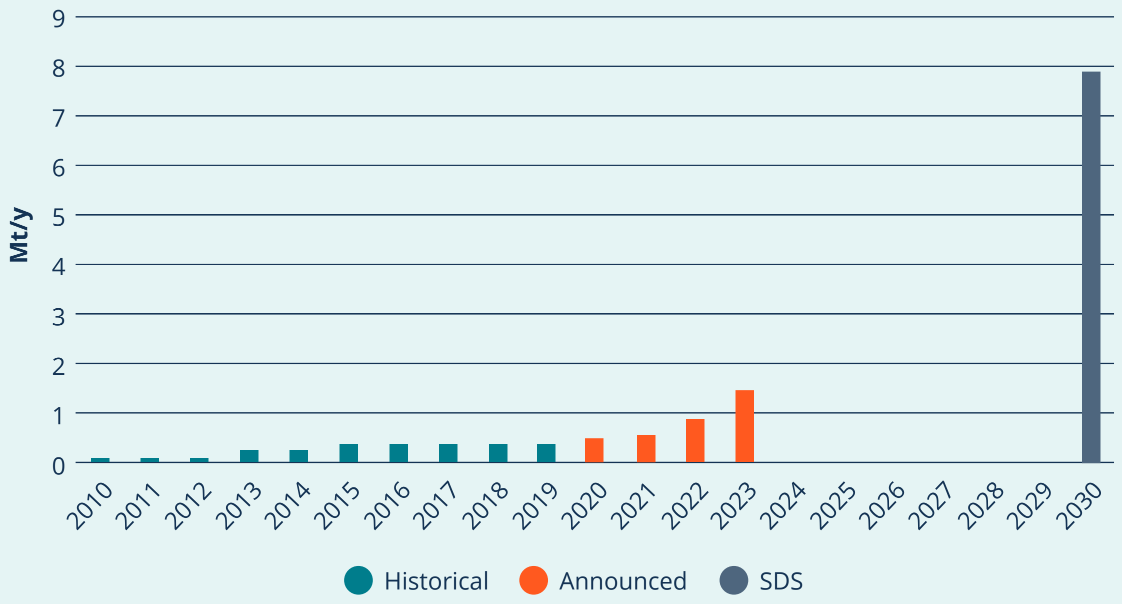
Intellectual property restrictions could further stymie the rate of growth. Since individual countries (and in some cases, just companies) have promoted many of the networks, they would have an interest in holding on to the patents. Meanwhile, many demand centres for green hydrogen, especially in developing countries, would be kept out of the green hydrogen development platforms.

The sheer scale of transformation has not been fully internalised. There is a dissonance between where the world needs to go and what the trends show. Under the IEA's sustainable development scenario, the volume of low-carbon hydrogen is expected to rise from 0.36 MT in 2019 to only 7.92 MT in 2030 (see figure 13) (IEA, 2020). This is in sharp contrast to the net-zero scenario from IEA, under which low-carbon hydrogen should be 150 MT by 2030.

Secondly, there is a gap between the geographical distribution of green hydrogen potential and the primary destination of investment and projects. BP's scenarios showed a major shift in geographical focus to Asia (not just China) for net-zero pathways. In fact, as figure 14 shows, the potential for producing green hydrogen varies by geography. Many countries in the tropics, particularly in Asia and then in northern Africa, have optimal renewable resources or renewable and other low-carbon resources for producing hydrogen.

But the bulk of the hydrogen programmes are concentrated in developed countries. Of the 33 countries and regions analysed above, only seven are in Asia, two of which are developed countries and three are major oil and gas producers. Similarly, only Morocco and South Africa feature on the African continent, even though many other regions could claim to be good sites for green hydrogen production.

Figure 13. Low-carbon hydrogen production under the sustainable development scenario

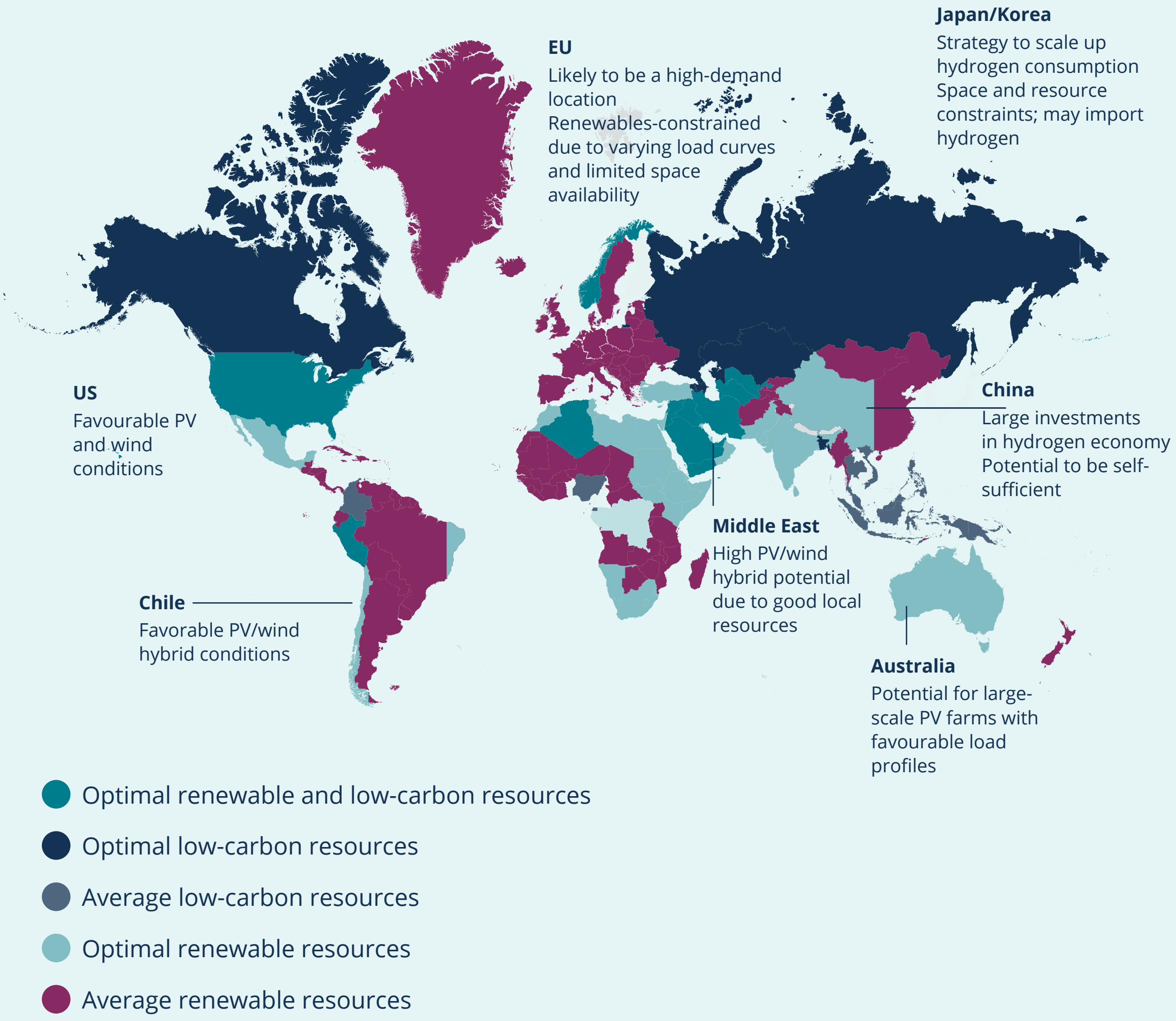


Source: IEA

As regards bilateral partnerships, nearly all of them are among developed countries. The multi-party partnerships have primarily been promoted to support national programmes of the sponsoring country, rather than as genuine multi-country collaborative efforts. Even the Green Hydrogen Catapult, while having strong targets for price cuts and deployment, is a platform promoted by companies primarily from advanced economies (Australia, China, Denmark, Norway, Saudi Arabia, Spain, Italy).

Thirdly, the biggest obstacle is the absence of leadership. If green hydrogen has the potential to be a foundational fuel for industrial and transport decarbonisation, its development and deployment must be treated as a global public good. The three general trends identified earlier (sectoral shift, geographical shift, and use of cleaner sources to produce hydrogen) will require dedicated effort. Otherwise, the scenarios for the long-term do not square with the efforts underway. Viewed this way, critical questions arise: Who would control the technology and how widely would it be disseminated? How difficult would it be for countries that do not have the technology to be able to reduce their emissions? If they did not have access to affordable green hydrogen technology, would they be subjected to trade barriers for continuing to use coal for steel production or diesel for long-distance freight? There is a need to avoid mercantilist instincts wherein technology development is restricted to a few countries, while trade dependence increases for a new kind of clean fuel. Such a scenario would result in new versions of energy insecurity and the resulting unwillingness to shift away from fossil fuels. Instead, a planetary-scale perspective is needed on how foundational fuels are developed and distributed.

Figure 14. Hydrogen production potential across regions



Japan/Korea
Strategy to scale up hydrogen consumption
Space and resource constraints; may import hydrogen

EU
Likely to be a high-demand location
Renewables-constrained due to varying load curves and limited space availability

US
Favourable PV and wind conditions

China
Large investments in hydrogen economy
Potential to be self-sufficient

Middle East
High PV/wind hybrid potential due to good local resources

Chile
Favorable PV/wind hybrid conditions

Australia
Potential for large-scale PV farms with favourable load profiles

- ● Optimal renewable and low-carbon resources
- ● Optimal low-carbon resources
- ● Average low-carbon resources
- ● Optimal renewable resources
- ● Average renewable resources

Source: Hydrogen Council

A Global Green Hydrogen Alliance

An alternative platform is, therefore, needed to overcome these challenges. A Global Green Hydrogen Alliance would be a multi-country, multi-institutional network to assess, develop and design affordable green hydrogen technologies that can be deployed at scale, in both advanced economies as well as in developing countries.

This prospective mission statement focuses on key aspects of what is missing in current efforts at scaling hydrogen technologies: They seldom involve many countries, particularly ignore developing countries, are not oriented towards joint technology development whose intellectual property can be shared, and do not focus on deploying the technologies in countries that will have the greatest demand for cleaner fuels for industrial development.

Building a new platform for green hydrogen could benefit from learning about why technological collaborations in the past have succeeded or failed. Research into dozens of such partnerships reveals six guiding principles of success (Ghosh, et al., 2019). These are: (1) establish clear objectives of the technology partnership; (2) target price reduction but evaluate progress against economywide costs and benefits to avoid locking into specific technology trajectories; (3) pool resources to make collaborations more inclusive, blend public and private finance, use contributions in cash and in kind, and establish rules to share intellectual property; (4) use innovative finance to underwrite risks and facilitate open technology platforms that allow a range of institutions to participate; (5) conduct regular risk assessments of disruptive technologies and establish clear liability clauses to allocate responsibility across partners in any research consortium; and (6) ensure participating countries/companies have voice in governance but that the initiative also promotes transparency to ensure that non-participating stakeholders are aware of the progress made and the risks entailed.

HISTORY'S LESSONS AND LEVERAGING INITIATIVES FOR NORTH-SOUTH COLLABORATION

Notwithstanding the challenges with the existing arrangements, why would advanced economies want to create new collaborative platforms or share technology with developing countries? The answer to this lies in three dimensions, namely tactical, operational and strategic/political.

At a tactical level, the Global Green Hydrogen Alliance would not substitute for the existing initiatives and platforms. Its purpose is to overcome the challenges that these initiatives continue to face. For instance, the Green Hydrogen Catapult is ambitious in its aims and has aggressive targets but limited scope in terms of the number of countries involved. There is little value in developing technologies without involving the countries where green hydrogen would be demanded the most.

At an operational level, no country has the resources to finance R&D and deploy test pilots across geographies on its own. This is why countries and companies have started to come together. However, their efforts will remain suboptimal if the regions with the best renewable resources are not included. Or where engineering and scientific talent might be available at far lower costs. Moreover, many disparate initiatives perpetuate the risk of a conflict of standards and potential technical barriers to trade.

The most important reason to develop a genuinely inclusive global platform is strategic and political. Industrial decarbonisation needs solutions for the technical requirements of high-intensity heat. It is also likely to become an arena for high-intensity politics. The energy security concerns around coal and oil have been significant drivers of geopolitics for more than a century. It is hard to imagine a low-carbon future without another foundational fuel like green hydrogen not being subjected to similar strategic concerns.

One option, then, is to pursue a mercantilist approach with each major economy trying to secure the resource and the embedded technology for itself. That would result in continued insecurity, competition for critical minerals, trade and other disputes, and tensions over technology theft and so forth.

An alternative would be to learn from history and design governance mechanisms to jointly develop the technologies of the future, while promoting competition at a firm level. The European Coal and Steel Community emerged from similar learnings. The International Energy Agency was also a joint response to the realisation that countries could not individually secure their energy needs without cooperation. Experimental work on nuclear fusion has also brought together countries by pooling resources and talent. Other areas of such strategic importance that have warranted collaborations between developed and developing countries include particle physics, genome sequencing, agricultural research and, most recently, vaccine development. The Global Green Hydrogen Alliance, by building on the existing initiatives and correcting for their governance failures, can be tactically and operationally more efficient, but it would be most critical as a governance innovation at a strategic level.

SIX-STEP APPROACH

Drawing on these lessons, principles and motivations, a Global Green Hydrogen Alliance would follow a six-step approach.

Step 1: Global inventory of hydrogen programmes and activities. In a rapidly evolving technology space, there is a need to reduce information asymmetry. The more is known about hydrogen-related programmes, the easier it would be to connect technology developers and firms with each other, creating conditions for further collaboration. A portal that is updated regularly can serve as a one-stop window to get information and get connected with other members. It can pull in information from other country- or region-specific initiatives and add value by creating a searchable directory of activities and participants.

Step 2: Periodic green hydrogen technology assessments. In line with increasing transparency, there is also a need to discuss monitor progress in various research domains related to the green hydrogen supply chain. As mentioned earlier, country programmes are targeting different stages of the value chain, from reducing electrolyser costs to focusing on storage and transportation facilities, to alternative end-use applications. An internationally peer-reviewed biennial technology status report would help members of the alliance be up-to-date about what gaps remain and what new opportunities exist for further joint research. This kind of assessment can also feed into the Paris Agreement's Global Stock Take (the first due in 2023) so that the global emissions gap can be evaluated against the technology gaps in green hydrogen.

Step 3: Bilateral/plurilateral partnerships between countries. Based on the gap assessment, R&D partnerships can be formed particularly with countries where hydrogen demand is expected to grow. As an umbrella network, the Green Hydrogen Alliance would not require all members to be involved in all projects. Various work programmes can be initiated by subsets of member countries/firms, with the rule being that any initiative would need sponsors from at least two countries. This would ensure that countries and companies are actively on the lookout for partners based elsewhere. It would also be in pursuit of the Alliance's mission of developing technologies at a cost that would make them viable for many developing countries. Towards that end, the work programmes can be designed to be dynamically inclusive by allowing new members to join at later stages.

Step 4: Pooled funds for enhanced joint R&D. The Green Hydrogen Platform could begin with a pooled fund of, say, $500 million to promote joint investments in research, development and demonstration. Members would be allowed to contribute in cash or offer their human resources and laboratory and industry facilities in kind. A portion of this pooled fund could be set aside as a corpus to underwrite R&D projects via partial risk guarantees. In addition, each work programme would use the funds allocated by their respective members and could also add to the funds via one-time participants in specific programme activities. This approach has a triple benefit. First, all members get access to partial risk guarantee. Secondly, members can boost their resources by partnering with other members who have indicated interest in particular areas of technology development. And thirdly, it would attract third parties who do not wish to be full-time members but would have the option to join specific projects.

Step 5: Rules of intellectual property ownership and licensing for large-scale deployment. The Green Hydrogen Alliance should facilitate technology partnerships wherein participating institutions retain their original IP while any new technology developed by a work programme consortium is jointly owned (Ghosh, et al., 2015). This approach has been followed in other global technology partnerships, such as the Consultative Group on International Agricultural Research, the Human Genome Project, the CERN particle accelerator, and the International Thermonuclear Experimental Reactor. Moreover, the Green Hydrogen Alliance should also develop general rules for licensing and sharing of intellectual property, including via open-source platforms, to facilitate collaborations across work programmes. In fact, joint programmes and transparency could dampen some of the concerns around IP theft.

Step 6: Alliance-wide standard-setting and inspections for safe storage and transportation. Hydrogen is particularly difficult to store and transport safely. A key role of the Green Hydrogen Alliance would be to establish technical supervisory committees, which would have the mandate to set standards and protocols, build capacity in developing countries to adopt these systems, and undertake periodic inspections to certify that participating countries/companies are complying with the established standards. This technical service could be undertaken while R&D programmes are underway, so that the associated risks are already mitigated by the time the technologies are ready for widespread deployment. This is also the advantage of conducting joint R&D across different countries, since at the R&D stage, the technologies can be tested under different conditions and the oversight capacity and safety protocols can be stress-tested before commercialisation.

NETWORKED GOVERNANCE FOR SCALE, SPEED AND RISK

How would the Green Hydrogen Alliance be governed? Unlike international organisations of the past, the Alliance's institutional design should prioritise scale, speed and risk.

Since the objective of the Alliance would be to get more parties involved in the development and deployment of green hydrogen, it must follow a governance model that allows for rapid scaling. None of the six steps outlined above requires a large, bureaucratic secretariat. Instead, the Alliance could be designed on a networked governance model, with a governing council overseeing progress made by individual work programmes. A small executive secretariat can facilitate the technical committees on funding, standards, intellectual property and so forth. The governing council, in turn, would get overall guidance from an assembly of all members, which would approve the work programmes on an annual basis. Most of the work would be done by institutions in member countries. In recent years, Mission Innovation and the International Solar Alliance have experimented with these types of governance models, albeit with variations, and avoided creating large international bureaucracies.

This networked model would also help with speed of technology development. The COVID-19 pandemic has demonstrated that faced with an existential crisis, vaccine developed can be fast-tracked and vaccine production can be globally outsourced. Despite the challenges of getting enough vaccines across to poor countries, much scientific progress has been made already that was considered not possible at the start of pandemic. Green hydrogen is not the same as vaccines. But it has the potential to significantly alter the equation in terms of rapid decarbonisation of hard-to-abate sectors. The pandemic offers us the lesson that a sense of urgency, mission direction and demand aggregation can all be principles applied even to a technology like green hydrogen. Under the Alliance, pilot programmes could up and running in developing countries by 2025.

With limited fiscal resources available that would have to be devoted to more immediate concerns of post-pandemic economic recovery, many developing countries might be averse to investing in technologies that are far out on the horizon. At the same time, the climate crisis is already making developing countries more vulnerable and threatening to undermine plans for industrial development. Under these circumstances, it is easier to see the value of pooling resources through a networked but global platform, rather than attempt to develop these disruptive technologies alone.

Finally, given the nature of the technology, the Green Hydrogen Alliance must have a clear approach to risk. Risks are of various kinds, starting with failures in technological development or in end-use applications. There are second-order risks associated with the adverse impacts of faulty storage or transportation of green hydrogen. There would also be tertiary risks involving, say, trade disputes or squabbles over licensing costs or sharing agreements for intellectual property. Set against these risks should be the assessment of the failure to combat climate change by not deploying technologies for industrial decarbonisation rapidly and at scale.

Such a risk-risk approach should drive the Alliance's partial loss guarantees, as described above. At the same time, risk and responsibility would go hand-in-hand. The responsibility assumed by each consortium would require transparency about research objectives, testing sites, deployment plans, etc. The Alliance's technical committees would have to strike a balance between regulatory oversight, excessively restricting research and being too permissive in testing and deployment without attention to standards. Once again, having more countries and companies involved through a platform like the Green Hydrogen Alliance, with a bias for transparency (steps 1 and 2) would be better than the same entities pursuing their own initiatives.

6. Conclusion

This paper exposes the dangers of being too sanguine about climate-related announcements without requisite resources, effort or partnership. The first is the belief that merely declaring aggressive targets for decarbonisation is sufficient to deliver results. The pathways to industrial and transport decarbonisation are extremely difficult and need serious attention on the technological front, especially the production of green hydrogen from renewable energy resources. The second danger is that, even if the need to develop disruptive technologies is recognised, there is premature celebration of hydrogen programmes and platforms that do not address underlying challenges. Deeper examination reveals that much of the activity is concentrated in developed countries in Europe and North America. Despite being a critical source of future demand, Asian countries are barely involved in the development, demonstration or deployment of green hydrogen technologies.

The Global Green Hydrogen Alliance would be designed to fill these gaps, rather than substitute for existing platforms. It is proposed as an initiative that is more transparent, genuinely inclusive, capable of pooling resources from many countries, and developing technologies that can be shared and deployed at scale. The failure of global governance in climate technologies is not the absence of initiatives, but the low ambitions and lack of inclusion of many extant offerings. The alliance offers a rethink and reimagination of how climate-friendly technologies can be developed at scale and with speed, while paying attention to the underlying risks. If successful with green hydrogen, such models of technological collaboration could also be used for other disruptive technologies, from batteries to greenhouse gas removal. Many climate technology platforms in the past have encouraged discussions but few have jointly invested in R&D and even fewer have shown how pilots and large-scale commercialisation can be the vision for such initiatives. The limitations in concretely and effectively delivering global public goods starts with the limitations in our imaginations, and, relatedly, in our ability to construct suitable, powerful and collaborative frameworks/capacities at the required planetary scale.

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Annexure 1

Country Name	Policies & Strategies	Future Targets/ Countries with green H2 production pilots and facilities
Argentina	National strategy is in preparation	• The various opportunities for low carbon hydrogen in Argentina include the following: potential to become low carbon hydrogen exporter, decarbonising chemical industry and decarbonising transport • Flagship Project: Hychico Hydrogen Plant • Hychico's main objective is hydrogen production from wind energy in Patagonia • Hychico's hydrogen plant started operating in January 2009 and is located approximately 20 km away from Comodoro Rivadavia, Province of Chubut and it is the first phase of the "Large Scale Clean Hydrogen Production in Patagonia Argentina" pilot project
Australia	National Hydrogen Strategy, November 2019	• H_2 under 2, which targets a production cost of AUD 2 per kg, to make hydrogen competitive across various sectors and applications • Government had committed AUD 500 million (USD 355 million) towards hydrogen projects • In 2020, the Australian Government announced an investment package worth USD 1.35 billion to support new energy technologies, under which USD 48.9 million was dedicated towards hydrogen export hubs (IRENA, 2020) • Australian and Victorian government are supporting a pilot project in Victoria's Latrobe valley which looks into full hydrogen supply chain • Largest commercial green hydrogen project proposed in Australia is a 15GW wind & solar project in the Pilbara (International Trade Administration, 2021)
Austria	The hydrogen strategy is under development	• The government is preparing a national Hydrogen Strategy, currently subject to public consultation • NECP considers renewable hydrogen "as a key technology for sector integration and coupling" with a target of a renewable electricity-based hydrogen consumption of 1.1 TWh (4 PJ) in 2030 • Austria is in a favourable position given its current investments in hydrogen research and in pilot and demonstration projects as well as in infrastructure, e.g. hydrogen refuelling stations, transport and delivery infrastructure with the potential IPCEI Green Hydrogen at Blue Danube project, decarbonizing the steel industry, producing hydrogen from renewable sources, etc. • Austria's integrated oil firm OMV announced that it will partner with Austrian bank Kommunalkredit to invest in a renewable hydrogen project at its 200,000 b/d Schwechat refinery. The firms plan to invest a total of Euro 25 million to develop Austria's largest electrolysis plant at the refinery, expected on stream in the second half of 2023. The plant's 10MW electrolyser will produce up to 1,500 t/year of green hydrogen, which is derived using electricity produced from renewables
Belgium	Hydrogen Roadmap, 2018	Belgium published a government-approved hydrogen roadmap in 2018, with specific targets set for 2030 and 2050 and an associated Euro 50 million regional investment plan for power-to-gas

Brazil	Brazil's national energy policy council (CNPE) plans to issue hydrogen regulations by late June this year as part of a national hydrogen strategy	• Three preliminary green hydrogen projects have surfaced over the past few months:
		  • Australia's Enegix Energy reached an agreement with the Ceara state government to invest USD 5.4 billion in a green hydrogen project
		  • Brazil's state-controlled utility Eletrobras signed a preliminary agreement with Germany's Siemens Energy to develop a green hydrogen pilot plant
		  • Fortescue Future Industries Pty Ltd (FFI) and Porto do Açu Operações S.A. (Port of Açu), a subsidiary of Prumo Logistica S.A. (Prumo), have signed a Memorandum of Understanding (MOU) to assess the opportunity to develop hydrogen-based green industrial projects in Rio de Janeiro, Brazil (Argus Media, 2021)

Canada	Hydrogen Strategy for Canada, December 2020	• The strategy projects that hydrogen could deliver up to 30 per cent of Canada's end-use energy by 2050, while simultaneously abating greenhouse gas emissions • B.C., Manitoba and Quebec are potential sites for electrolysers that can produce green hydrogen • Vision for 2050: domestic supply > 20 Mt/ year, established supply base of low carbon intensity hydrogen with delivered prices of USD 1.50 – USD 3.50/ kg, greater than 5 million FCEVs on road, ~350,000 hydrogen sector jobs, Up to 190 Mt-CO2e annual GHG reduction • Evolugen, the Canadian operating business of Brookfield Renewable, and Gazifère Inc., an Enbridge company have announced plans to build and operate an approximately 20-MW water electrolysis hydrogen production plant in the Outaouais region. (Evolugen, 2021)

Chile	Strategy Document, November 2020	• 5 GW of electrolysis capacity by 2025 with a production of at least 0.2 MtH2/year • 25 GW of electrolysis target for 2030, with a hydrogen production cost of less than USD 1.5 per kg • Another target is exporting hydrogen and derivatives equivalent of USD 2.5 billion per year • The strategy significantly focuses on green hydrogen and directed towards exports • Enel Green Power along with AME (Chilean power company) announced plans for their first pilot project for green hydrogen production in Chile. The facility is expected to commission in 2022 (Enel Group, 2020)
China	Number of policies and government led programs have been introduced in China regarding hydrogen and fuel cell development China Hydrogen Alliance, 2018	Current Status: • Refueling station: 35 • FC Trucks: 1200 • FC Buses: 2800 • FC Cars: 50 Target • FC Cars: 10,000 by 2020 China Hydrogen Alliance: • was launched in 2018 by China Energy Corporation and other 18 sponsors. At present, the alliance has 87 members globally • The main responsibility of the alliance includes: study the development model of China’s hydrogen energy and fuel cell industry and provide policy suggestions for the national hydrogen development strategy and implementation plan
Colombia	The green hydrogen roadmap is in preparation and is expected to release in the first half of 2021	• The opportunities for low carbon hydrogen include: decarbonising mining industry and decarbonising transport • Colombia has agreed a green hydrogen research program deal with Chile. The country is also in the process of formalizing a deal with Germany and is working with the European nation on the roadmap • The government is working on a hydrogen deal with country’s largest oil and gas company Ecopetrol (Greenhalgh, 2021)
Denmark	Currently Denmark does not have any hydrogen strategy	• Denmark has the ambition to reduce its greenhouse gas emissions by 70 per cent by 2030 as per its NECP • Denmark is currently involved in various projects like the Green Flamingo, the Green Octopus and the Silver Frog IPCEI projects • Danish energy company Orsted is planning to develop a demonstration project which will harness offshore wind energy to produce green hydrogen. This project will be based at Orsted’s Avedøre Power Station, south of Copenhagen and the hydrogen produced will be used as a fuel for road-based transport
European Union	Hydrogen Strategy, July 2020	• 6 GW of electrolyser capacity by 2024 and 40 GW by 2030. • Production targets of 1 million and 10 million tonnes of renewable hydrogen per year for 2024 and 2030 respectively • Investments in renewable hydrogen worth USD 280-430 billion for electricity production and USD 30.5-53 billion for electrolysers by 2030 • Additionally, this strategy was released concurrently with another strategy called “Energy Systems Integration” • There are various projects that are being developed with the IPCEI (Important projects of common European Interest) framework. Eight such projects cover 17 EU member states and require 43 GW of renewable energy deployment for green hydrogen production • Few of these projects are: The Green Flamingos, The Green Octopus, The Blue Danube and others
Finland	National Hydrogen Roadmap, 2020	• National Hydrogen Roadmap focuses on an outlook for low carbon hydrogen production, hydrogen utilisation for green chemicals and fuels, as well as storage, transport and end use over the next ten years • Hydrogen is a part of the national energy and climate strategy of Finland. Finland does not have a separate hydrogen strategy • Finland’s targets are to become carbon neutral by 2035 and carbon negative by 2050

France	• National Strategy, September 2020 • Hydrogen Deployment Plan, 2018	• France has a target of 6.5 GW of electrolysis capacity by 2030 • The national strategy will see 7.2 billion euros invested in clean hydrogen infrastructure and research by 2030. The French Government has committed to investing 2 billion euros in the near term (up to 2022) • Targets (2023): FC Bus- 200, FC Cars- 5000, Refuelling station- 100 • Targets (2028): FC Bus- 800 to 2000, FC Cars- 20,000 to 50,000, Refuelling station- 400 to 1000 (IPHE, 2021) • In 2018, the government unveiled a Hydrogen Deployment Plan and EUR 100 million funding and 2023 and 2028 targets for low-carbon hydrogen in industry, transport and for renewable energy storage, including for islands
Germany	Hydrogen National Strategy, June 2020	• Funding worth USD 1.7 billion will be provided within the Hydrogen National Strategy up to 2026 • National targets include 14 TWh of green hydrogen production with 20 TWh of renewables by 2030-35. • Refueling station: 400 by 2025 • More than 80 TWh of green hydrogen demand is expected from steel production by 2050 and an additional demand of 22 TWh from German refinery and ammonia production • As a response to COVID-19, economic recovery package worth around USD 165 billion has been proposed with USD 11.4 billion dedicated towards hydrogen • Germany has launched three large scale projects on green hydrogen – H2Giga, H2Mare and TransportHyDE • The federal research minister has supported the projects with Euro 700 million in total • The projects will bring in 230 partners from research and industry and will run until 2025

India	India has recently announced the National Hydrogen Mission which aims for generation of hydrogen from green power resources	Current Status
		• Refueling stations: 2
		• FC Bus: 10
		• **National Hydrogen Mission**
		  • The Union Budget for 2021-22 has announced a National Hydrogen Mission for generating hydrogen from green power resources
		  • The proposed mission would aim to lay down Government of India's vision, intent and direction for hydrogen energy and suggest strategy and approaches for realisation of the vision. The mission aims to develop India into a global hub for manufacturing of hydrogen and fuel cells technologies across the value chain
		  • Major activities under the Mission include: creating volumes and infrastructure; demonstrations in niche applications (including for transport, industry); goal-oriented research & development; facilitative policy support; and putting in place a robust framework for standards and regulations for hydrogen technologies
		• The India H2 Alliance, led by Chart Industries and Reliance Industries, has come against the backdrop of the proposed National Hydrogen Mission, which may mandate fertiliser, steel and petrochemicals industries to shift to green hydrogen

Italy	National Hydrogen Strategy, 2020	Key Targets: • Targeting investments worth EUR 10 billion up to 2030 • 5 GW of electrolysing capacity to extract gas from water over 2021-2023 • Hydrogen to make up 2 per cent of Italy's final energy demand by 2030 • Eliminate up to 8 million tons of CO2 by 2030 • The strategy is expected to create more than 200,000 jobs and generate up to 27 billion euros for Italy's gross domestic product (International Trade Administration,, 2021) Investments in green hydrogen by private stakeholders • Italian gas group SNAM has been experimenting with a 10 per cent mix of hydrogen as part of its natural gas network and about 50 per cent of the investments planned in SNAM's 2020-2024 program are dedicated to making its infrastructure hydrogen-ready • SNAM is part of a new initiative, called "Green Hydrogen Catapult", with a few industrial leaders in green hydrogen including ACWA Power, CWP Renewables and others. The objective of the initiative is to stimulate the development of 25 gigawatts of green hydrogen production capacity by 2026 and bringing the current cost below USD 2 per kg • Italy based global utility Enel is working with oil and gas giant ENI on development of green hydrogen projects. The two pilot projects will include an electrolyser of about 10 MW each and are expected to generate green hydrogen by 2022-23

Japan	• Basic Hydrogen Strategy, December 2017 • Strategic Roadmap for Hydrogen & Fuel Cells, March 2019	• National target – Developing commercial-scale supply chains for handling and distribution of 0.3 million tonnes of hydrogen by 2030 • A joint venture with Australia for the development and demonstration of a liquefied hydrogen supply chain lasting until FY2020, paving the way for commercialization • Deployment target of FCEV targets of 0.2 million units and 0.8 million units by 2025 and 2030 respectively • A total of 100 commercial filling stations have been setup through a joint venture of 11 companies named Japan H2 Mobility, LLC. The company further aims to build an additional 80 fuelling stations by 2022 • Aim to commercialise hydrogen power generation and achieve hydrogen power generation cost of USD 0.16 /kWh by 2030 • A project at Fukushima Hydrogen Energy Research Field (FH2R) can produce green hydrogen using solar power. This project was launched in March 2020
Morocco	Partnership Agreement with Germany, June2020	• The aim of this partnership is to develop the production of green hydrogen and set up research and investment projects related to it • These two countries plan to develop the first industrial green gas production plant in African Continent
New Zealand	Vision Document, 2019	• The government is aiming to achieve a net-zero carbon economy by 2050 • Regulatory review and amendments process: Gas Act, NZ Transport Rules and Legislation & Health and Safety legislation • International export agreements – Strategic focus to leverage the export markets for scaling up domestic production capacity during 2020 to 2025 • The country has setup a green investment fund to invest in businesses related to hydrogen • Tuaropaki Trust signed a memo with Obayashi Corporation of Japan to carry out green hydrogen pilot project • The construction of the hydrogen plant (1.5 MW) started in 2019 and was scheduled to be operational from 2020 (Hydrogen New Zealand, 2021) • Various other green hydrogen projects being explored include – Refining NZ green hydrogen study, Decarbonization of tourist transport, Balance agri-nutrients and hiringa joint venture and H2 Taranki roadmap (New Zealand Government, 2019)
Norway	Strategy Document, June 2020	• Promoting low-carbon transition through emissions pricing – government aims to increase the flat CO2 tax by 5 per cent every year till 2025 • Funding of USD 57.90 million allocated through the Research Council of Norway for research and development on hydrogen • PILOT-E – A collaboration between the Research Council of Norway, Innovation Norway and Enova, designed to achieve the green transition by accelerating energy technology projects throughout the development pathway from concept to market. A total of USD 8.2 million budgetary support has been allocated till date • Domestic ambitions to achieving a 50 per cent reduction in GHG emissions from the shipping industry by 2030
Oman	Currently Oman does not have any hydrogen strategy	• Sohar Port and Freezone have outlined ambitions to set up the country's first industrial scale green hydrogen plant at the industrial port on Oman's Batinah Coast • Sumitomo Corp (Tokyo) and ARA Petroleum LLC (Oman) which is an oil and gas producer in Oman, launched a feasibility study on hydrogen hybrid project based on local production and consumption model in Oman in January 2021. To add, 300 to 400 tons of hydrogen are expected to be produced annually from associated flare gas generated at the site (Sumitomo Corporation, 2021)
Portugal	Portugal National Hydrogen Strategy (EN – H2)	• The country's strategy focuses on green hydrogen • The target includes a goal for electrolysers (2-2.5 GW) by 2030 • Another important target includes various blending and quotas that will drive demand, including the following: 10 per cent-15 per cent H2 injection in natural gas networks, 1 per cent-5 per cent blending in transport sector, 2 per cent-5 per cent in industries and 1.5 per cent-2 per cent in final energy demand • This strategy is anticipating investments worth EUR 7 billion by 2030 • The Green Flamingo Project aims at a size of 1 GW electrolysis capacity by 2030, with an investment of EUR 57 billion (including renewable capacity) (IRENA, 2020). • Other projects include decarbonise the transport sector, use waste water for hydrogen production, implementation of a collaborative laboratory

Republic of Korea	Introduced its roadmap towards a hydrogen economy in November 2018	Key Targets: • Refueling station: 1200 by 2040 • FC Bus: 40,000 by 2040 • FC Trucks: 30,000 by 2040 • FC Cars: 2,900,000 by 2040 • Ministry of Trade, Industry and Energy (MOTIE) was expecting to invest USD 57.5 million as a part of the national green new deal package in 2020 • MOTIE's proposal includes the following: green hydrogen production and storage R&D support programmes (IPHE, 2020) • A RD&D project on green hydrogen production is being carried out with a budget of USD 12 million • The project comprises of the following: 3 MW electrolysis system, 600 kg hydrogen and 2 MWh battery storage and hydrogen utilization facilities (IPHE, 2020)
Russia	Roadmap, October 2020	• Launched a four-year (2021-24) action plan on hydrogen • Targeted approach towards a) strategic planning and monitoring of hydrogen energy development, b) measures to stimulate and state support for the development of hydrogen energy, c) formation of production potential, d) implementation of priority pilot projects in the field of hydrogen energy, e) scientific and technical development and development of high-tech solutions, f) improvement of the regulatory legal framework and the system of national
Saudi Arabia	At present Saudi Arabia does not have any national strategies and roadmaps	• On July 7, 2020, Saudi Arabia announced the world's largest green ammonia project at its mega project Neom • In partnership with Air Products and ACWA Power, the project will have the capacity to produce 650 tonnes per day of green hydrogen, utilizing 4 GW of renewable energy for water electrolysis. Further, this will enable the plant to produce 1.2 million tonnes of ammonia per year (KAPSARC, 2020)
South Africa	South Africa's Hydrogen Society Roadmap (HSRM) will be presented for Cabinet approval either before the end of the year or early next year (2022)	• The roadmap will outline how the country's resource advantages should be leveraged to produce green hydrogen, as well as to integrate hydrogen-related technologies, such as fuel cells, into various sectors of the economy • South Africa is planning to establish a Platinum Valley that will serve as an industrial cluster bringing various hydrogen applications in the country together and forming an integrated hydrogen ecosystem. This initiative is a part of the government's economic recovery plans (Republic of South Africa, 2020)
Spain	Hydrogen Roadmap, October 2020 - the Spanish government at the proposal of the Ministry for Ecological Transition and the Demographic Challenge ("MITECO"), approved the Hydrogen Roadmap	• In November 2020, the government announced that, for the period 2021-2023, EUR 1.5 billion of public funding would be allocated to boost renewable hydrogen, through the Next Generation EU, endowed with EUR 750 billion for the period 2021-2027 (of which EUR 140 billion will be allocated to Spain in the form of transfers and loans) • Key Targets: • Installation of at least 4 GW electrolyser plants by 2030 • Industry: minimum renewable hydrogen contribution of 25 per cent of the total hydrogen consumed in 2030 in all industries • Transport (2030) – FC buses- 150 to 200, hydrogen stations- 100 to 150, light and heavy-duty fuel cell vehicles- 5000 to 7500 (MINISTRY FOR THE ECOLOGICAL TRANSITION AND THE DEMOGRAPHIC CHALLENGE, 2020)
Sweden	At present Sweden does not have any national strategies and roadmaps for development in hydrogen and fuel cells	• HYBRIT project- this project has benefited from government contributions in building a pilot green hydrogen steel plant (IRENA, 2020) • The first commercial plant is expected in 2036 and the estimated cost of the pilot plant is USD 147 million

The Netherlands	Strategy on Hydrogen was presented by the Ministry of Economic Affairs and Climate Policy in March 2020	Key Targets: • 500 MW of installed electrolyser capacity by 2025 & 3-4 GW by 2030 • Refueling station: 50 by 2025 • FC Bus: 300 by 2025 • FC Trucks: 3500 by 2025 • FC Cars: 300,000 by 2030 • The total investment required to setup a green hydrogen economy in Norther Netherlands up to 2025 amounts to 17.5 to 25 billion euros • Over the past few years, the funding for hydrogen & fuel cells has increased. In 2018 a funding of Euro 7.85 million was received for the same. Some of the projects on green hydrogen include (TKI NIEUW GAS, 2021): • The Rotterdam Electrolyser- which focuses on ~200 MW electrolyser capacity in Rotterdam, project period is 2020-2023 • H2.50 – aims at building a 250 MW electrolysis plant in Port of Rotterdam, which will be able to produce 45,000 tons of green hydrogen annually, Project period is 2019-2022(Investment decision) • NorthH2- aims to generate 3-4 GW of wind energy to produce green hydrogen by 2030 and is aiming to produce 800,000 tons of green hydrogen by 2040, project period – 2020 to 2040
UAE	• Currently UAE does not have any hydrogen strategy • Mubadala Investment Company, Abu Dhabi National Oil Company (ADNOC) and ADQ have signed a Memorandum of Understanding (MoU) to establish the Abu Dhabi Hydrogen Alliance in January, 2021	• One of the key pilot projects taking place in Dubai is the first solar-powered green hydrogen project. This project represents a successful government and private sector collaboration as it is being deployed by Dubai Electricity and Water Authority (DEWA) and Siemens. Through this project, DEWA aims to explore the potential of developing a hydrogen economy in the UAE • The Emirates Authority for Standardization and Metrology (ESMA) has completed the first technical regulation of hydrogen-powered vehicles in the UAE, making the UAE a pioneer in the MENA region to establish such a regulation • The Abu Dhabi Hydrogen Alliance: • The Alliance partners will collaborate to establish Abu Dhabi as a trusted leader of low-carbon green and blue hydrogen in emerging international markets • This alliance will drive green hydrogen opportunities and adoption of roadmap for Abu Dhabi and the UAE • ADNOC currently produces around 300,000 tons of hydrogen per annum for its downstream operations, with plans to expand to more than 500,000 tons
United Kingdom	Hydrogen Strategy is expected in 2021 but the Government has already made its support for hydrogen clear	Key Targets: • UK is aiming for 5GW hydrogen production capacity by 2030 in partnership with industry • Savings of 41MtCO2e between 2023 and 2032 or 9 per cent of 2018 UK emissions • Support for up to 8,000 jobs by 2030 • This will be supported by a range of measures, including a £240 million Net Zero Hydrogen Fund and setting out of hydrogen business models and a revenue mechanism to bring through private sector investment (HM Government, 2020)
United States	Hydrogen Program Plan, November 2020	• The Hydrogen Program Plan focuses on advancing affordable production, transport, storage, and use of hydrogen across different sectors of the economy • Key Targets: USD 2/kg for hydrogen production and USD 2/kg for delivery and dispensing for transportation applications, fuel cell system cost of USD 80/kW with 25,000-hour durability for long-haul heavy-duty vehicles, electrolyser capital cost of USD 300/kW, 80,000-hour durability and 65 per cent system efficiency (U.S Department of Energy, 2020) • California Energy Commission (CEC) approved a USD 384 million plan for clean transportation focusing on the adoption of zero-emission cars and trucks to help California reach its emission reduction, energy, and public health goals. The plan includes USD 70 million for hydrogen refuelling infrastructure, as well as USD 129.8 million for medium- and heavy-duty zero-emission vehicles and infrastructure, and more. The funds will be available over the next three years. • California Fuel Cell Partnership outlined targets for 1000 hydrogen refuelling stations and 1,000,000 FCEVs by 2030 (IEA, 2019)

Uruguay	Strategy in preparation	• Uruguay will receive USD 10 million from United Nations Joint Fund for sustainable development goals to develop green hydrogen projects
		• Verne Project:
		  • A pilot project for electrification of transport through green hydrogen production has been announced. This project is being developed by Uruguay’s National Administration of Fuels, Alcohols and Portland, Uruguayan Power Utility UTE and The Ministry of Industry, Energy and Mining (MIEM)
		  • This project foresees setting up of green hydrogen production through a PEM electrolyser with a capacity of 500 kg/day
		  • The entities have also received financial support from the Inter-American Development Bank and the German Corporation for International Cooperation (Molina & Zarco, 2021)

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Endnotes

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2 Between peaking emissions and net-zero targets are long transition periods. It is 43 years for the United States, 46 years for Japan, 71 years for the EU and 77 years for the UK.

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