CRA Insights:
Energy

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Hydrogen
More than just a pipe dream

Summary

At present the use of hydrogen as an alternate fuel is mostly a niche offer. Efficient transportation and storage remain key issues, and full-scale adoption would be a major undertaking. However, full-scale electrification of transport and/or heating, which has happened in some places, is also a substantial investment; therefore, as is increasingly the case, hydrogen (particularly renewable-produced hydrogen) should be seriously considered as a part of our future energy mix as a solution to the energy 'trilemma': sustainability, security of supply and affordability.

Introduction

Many countries, the UK and other EU member countries in particular, are committed to The Paris Agreement and may have national, legally binding decarbonisation targets.[1] While progress has been made on the decarbonisation of power generation, 80% of final energy consumption globally is derived from solid and liquid fuels. (See Figure 1.) Without decarbonising fuel use, there is no guarantee that climate impacts will be contained.

Hydrogen is an alternative fuel that can be produced from renewables and can help address climate impacts. In this paper we explore some factors which may determine the use of hydrogen-based energy going forward.

Where does hydrogen fit in the decarbonisation agenda?

To date, there has been significant progress decarbonising electricity generation. The International Energy Agency (IEA) estimates that renewables contributed around 25% of total electricity generated last year, which represents a 25% increase from 2010 levels.[2] The trend is likely to continue, with renewables playing a more significant role going forward. At this stage, however, a

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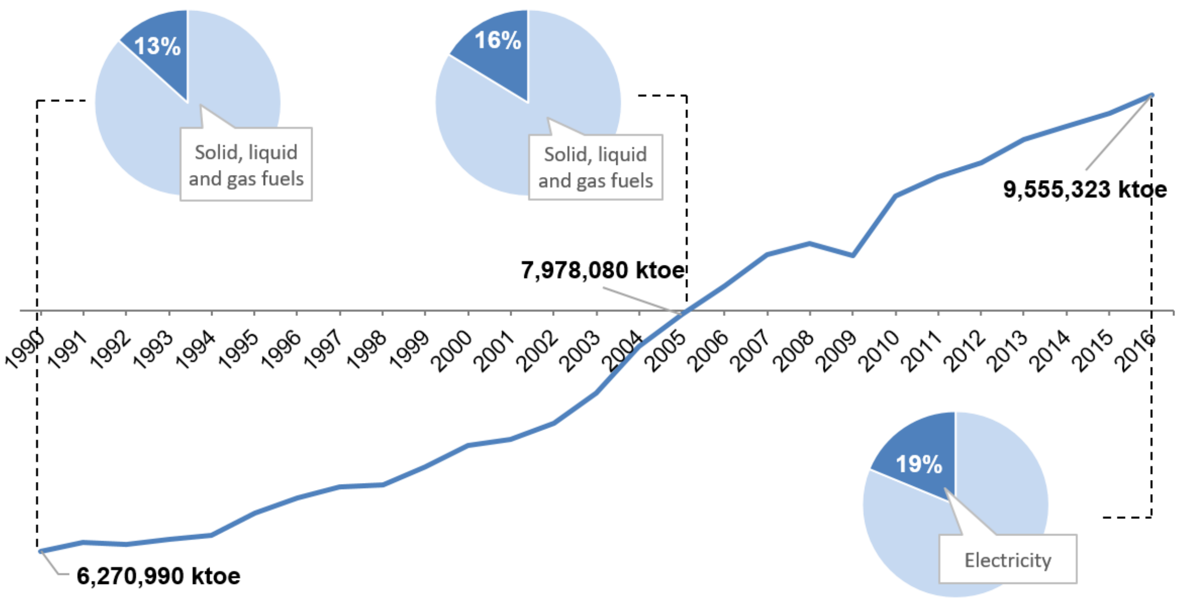
1 The Paris Agreement and national legally biding agreements, such as the UK's Climate Change Act (2008) or the EU's 20-20-20 commitment and declarations of a climate emergency, mean that countries have to seriously consider pathways to decarbonisation.

2 IEA.org statistics. We note that the IEA has generally taken a conservative stance towards renewable development.

large majority (c. 80%) of our final energy consumption is still derived from solid and liquid fuels, as shown in Figure 1.

Figure 1: Global final energy consumption over time[3]



Source: IEA

To meet decarbonisation targets aimed at ensuring that global temperature does not rise by no more than 2C (and preferably no more than 1.5C), we must consider alternatives to fossil fuels. Hydrogen could provide significant environmental value in sectors (shipping, air transport, space heating and industry) where full electrification may not be a viable option.[4] While hydrogen is not the only decarbonisation pathway for these sectors, it is operationally attractive because it can be a zero-emission alternative if produced sustainably through electrolysis[5] using renewable electricity. Hydrogen has the potential to resolve the energy trilemma of sustainability, security of supply and affordability as electrolysis technology becomes more advanced. In comparison, the combustion of biogas would still result in the release of emissions such as carbon dioxide; this would not be the case with hydrogen.

Hydrogen applications and associated challenges

Despite the theoretical promise of hydrogen, there are a number of commercial and technical challenges associated with the roll-out of hydrogen applications. In this section we explore potential applications such as natural gas replacement and fuel cell and distributed storage applications, and some of the associated challenges.

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3 The trend of higher consumption of solid and liquid fuels holds for OECD countries and also the EU28.

4 There are a number of sectors with a high reliance on fossil fuels for which electrification and /or decarbonisation is difficult e.g. shipping, air transport, space heating and industry.

5 The electrolysis of water is the process in which water is split into its two constituent elements – hydrogen and oxygen – when electricity is passed through it.

Hydrogen as a natural gas replacement

Hydrogen is seen as a decarbonisation pathway for replacing natural gas use. Such replacement would require a bulk supply of hydrogen and the construction or retrofitting of transmission and distribution infrastructure. It would require a guaranteed demand to make the necessary investments worthwhile. The high dependence on natural gas (in particular in cooler countries), makes this transition both an opportunity and a challenge.

There are three main methods for producing hydrogen in bulk: steam methane reforming with carbon capture and storage (SMR + CCS), electrolysis using grid electricity and/or renewable generation, and gasification and reforming of biomass.[6] These are discussed below.

In countries with limited or moderate renewables potential, it is forecasted that SMR + CCS will be able to provide hydrogen in bulk to the extent that it is able to replace natural gas, i.e. for heating and some industrial purposes.[7] However, the production of hydrogen in large amounts is therefore reliant on the successful deployment of CCS technology, as SMR on its own produces significant carbon emissions.

Because it is highly unlikely that demand for hydrogen can be predicted and supplied with perfect accuracy, having a bulk supply of hydrogen requires storage capacity. Large amounts of hydrogen have been stored in underground salt caverns for many years: hydrogen has been stored in solution-mined caverns at Teesside since as early as the 1970s;[8] however, having suitable geological sites for storage means that solutions requiring bulk hydrogen storage in salt caverns will not necessarily be viable for all geographies. It is also possible to store hydrogen within existing gas infrastructure, although some network reinforcement and renewal may be required for current gas infrastructure to be fit for purpose. Other storage methods aimed at storing smaller amounts of hydrogen, generally, involve liquefying,[9] compressing or combining hydrogen with other molecules.[10] All of these options are energy intensive and therefore less efficient overall

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6 *See* for example Committee on Climate Change, "Hydrogen in a low carbon economy," 22 November 2018, https://www.theccc.org.uk/publication/hydrogen-in-a-low-carbon-economy/.

7 Last year, c. 95% of hydrogen was produced via SMR, and 5% was produced using electrolysis. The vast majority of this supply however was not used for heating or industrial processes as envisaged in a large number of decarbonisation pathways. Rather, the largest consumer of hydrogen currently is the chemicals sector, where hydrogen is used to produce ammonia, amongst other things. *See also* European Commission, EU Science Hub, "Green hydrogen opportunities in selected industrial processes," European Commission, 26 June 2018, https://ec.europa.eu/jrc/en/publication/green-hydrogen-opportunities-selected-industrial-processes.

8 Foh, S., Novil, M., Rockar, E., and Randolph, P. Sat . "Underground hydrogen storage. Final report. [Salt caverns, excavated caverns, aquifers and depleted fields]". United States. doi:10.2172/6536941. https://www.osti.gov/servlets/purl/6536941.

9 To store hydrogen in liquid form, hydrogen gas needs to be cooled to about -250 C. In terms of power consumption, advanced facilities require c. 12 kWh/kg of hydrogen to cool gaseous hydrogen to its condensation point. It is an expensive and impractical form of storing hydrogen given today's energy costs.

10 The principle of chemically storing hydrogen is combining hydrogen with other elements to form a compound which is hydrogen-rich, for example ammonia, with one nitrogen atom and three hydrogen atoms (NH3). However, these methods are still in development stage, and the storage densities achieved at this stage are not sufficient to make these storage methods viable. The advancement of these methods, however, could make a global hydrogen economy possible. For example, Japan and Australia are considering a scheme where hydrogen would be produced sustainably with solar PV electrolysis in Australia, and then shipped to Japan in the form of a hydrogen-rich chemical. *See* Japan's Basic Hydrogen Strategy, Provisional Translation, 26 December 2017. Prepared by the Ministerial Council on Renewable Energy, Hydrogen and Related issues.

when compared to other future fuel alternatives such as biogas, which requires less energy to store and transport.[11]

The next step is to distribute hydrogen to final consumers. At present, some hydrogen can be transported via conventional gas pipelines: it is possible to blend hydrogen with natural gas to reduce carbon emissions. The UK allows up to 20%[12] of hydrogen to be injected into the gas network, while some countries in the EU may allow up to 25% depending on the suitability of the pipeline infrastructure.[13] For a full conversion to hydrogen, however, new transmission and distribution infrastructure consisting of polyethylene pipes will need to be put in place. This transformation is already underway in the UK through the Iron Mains Risk Replacement Programme (IMRRP)[14] which aims to convert all low-pressure gas distribution pipes to polyethylene pipes by 2032, mainly to reduce the risk of explosions from pipeline failure. As such, the UK's distribution network would be suitable for carrying hydrogen by 2032. In addition to network updates, consumer appliances, power generation and industrial equipment which previously relied on natural gas, would need to be retrofitted, modified or replaced to accommodate the use of hydrogen.

Replacing natural gas with hydrogen will require significant coordination between the private and public sector due to the sheer scale of new infrastructure and equipment needed. Despite the significant scale, such changeovers have historically been successful, for example the large scale change when the UK moved from coal gas to natural gas. Current analysis suggests that organising the transition in terms of hydrogen 'hubs' which are concentrated geographically could provide the necessary scale and demand to deliver a net beneficial project, even on financial metrics.[15]

Even with the benefits of concentrating the transition locally, replacing natural gas with hydrogen does present commercial challenges with respect to the amount of capital needed. In addition to significant capex, hydrogen demand needs to be secured to mitigate market risk. At a high-level, we consider the economics of a hydrogen transformation could be similar to the economics of gas infrastructure today. The business case is critically dependent on the level of potential secured

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11 Hydrogen fuel cells rely on compressed hydrogen and oxygen from the air. For this application, hydrogen is compressed at a very high pressure of 700 bar to maximise driving range. This is about seven times the pressure required in the high-pressure gas transmission network. The US Department of Energy estimates that this level of compression would require 1.36 kWh/kg of hydrogen. *See* DOE Hydrogen and Fuel Cells Program Record, 7 July 2009,https://www.hydrogen.energy.gov/pdfs/9013_energy_requirements_for_hydrogen_gas_compression.pdf.

12 Decarbonising the gas network, Houses of Parliament Post Note Number 565, November 2017, https://researchbriefings.parliament.uk/ResearchBriefing/Summary/POST-PN-0565#fullreport.

13 Only a limited concentration of hydrogen can be blended with natural gas if it is being passed through conventional gas transportation infrastructure. A high concentration of hydrogen introduces the risks of hydrogen leakage and damage to pipeline infrastructure.

14 The IMRRP was introduced in 2002 as a safety measure as the gas distribution network infrastructure reaches the end of its useful life. The programme is aimed at reducing the possibility of gas explosions by 60% from pre-2005 levels. *See* Health and Safety Executive, Iron mains risk reduction, http://www.hse.gov.uk/gas/supply/mainsreplacement/index.htm.

15 The H21 programme (sponsored by Northern Gas Networks and Equinor) as well as the Liverpool-Manchester Hydrogen Clusters Project (sponsored by Cadent) are two studies exploring the technical and economic feasibility of hydrogen hubs in the north of England. Both of these plans cover the transformation of domestic heating and natural gas supply to industry, thereby completely decarbonising gas use by switching to hydrogen. *See* Northern Gas Works, "H21 North of England – deep decarbonisation of heat to meet climate change targets," https://www.northerngasnetworks.co.uk/event/h21-launches-national/ and Cadent, "Reducing network carbon intensity with hydrogen," https://cadentgas.com/innovation/projects/reducing-network-carbon-intensity-with-hydrogen.

demand, in particular, the presence of 'anchor loads'— large consumers with long-term hydrogen supply contracts or large groups of smaller consumers with constant demand for hydrogen. Interestingly, hydrogen already plays a significant role in a number of industrial processes in chemicals production, steel making and oil refining, showing that there is the potential for securing 'anchor loads' for hydrogen projects. For these industries, having a bulk supply of hydrogen could provide for power, heating and feedstock needs, providing economies of scope.[16] Additionally, analysis by the UK's Department for Business, Energy & Industrial Strategy (BEIS) shows that hydrogen might be the only option for decarbonising industries which require combustion-based heating processes (e.g. furnaces and kilns) as electrification and biogas would not be able to produce sufficient heat.[17]

Fuel cell and distributed storage applications

Hydrogen is a versatile energy carrier and has applications beyond being a green alternative for natural gas. Hydrogen can complement transport electrification through hydrogen fuel cells (HFCs). A typical hydrogen fuel cell consists of a hydrogen storage tank and an electrolyser, which provides the necessary chemical reaction between hydrogen and oxygen to produce electricity. HFCs have one notable advantage over conventional batteries —conventional batteries experience a loss of charge if not used for a period of time; not so for an HFC. Hydrogen is therefore particularly suited to store energy over long periods of time and can be used for seasonal storage and balancing.

In transport, HFCs have additional advantages over the conventional battery in an electric vehicle (EV). HFCs have a shorter charging time compared to conventional batteries, minutes as opposed to hours it might take to fully charge an EV. HFC vehicles also have a longer range: the most popular electric car to date – the Nissan Leaf – has a nameplate range of up to 270km,[18] while the Toyota Mirai (which runs on a HFC) has a range of about 500km. This makes HFCs particularly attractive for long distance freight, and Toyota is currently developing a HFC truck.[19] Given the advantages of HFCs and the possibility for hydrogen derived from renewable generation (green hydrogen), many governments[20] are considering the role of hydrogen in personal and public transport. There have been a number of HFC vehicle support schemes across Europe and subsidies for HFC charging stations. In addition, major cities and regions including London, Beijing, Sao Paulo, Scotland, and cities in North America have trialled hydrogen busses in an

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16 Much of the hydrogen used today is in the chemicals and refining industries. 55% of hydrogen is used for ammonia production, about a quarter is used in refineries for the processing of intermediate oil products, and about 10% is used in methanol production. *See* Hydrogen Europe, at https://www.hydrogeneurope.eu/.

17 *See* supra note 6.

18 Nissan, Nissan Leaf, Range & Charging, https://www.nissan.co.uk/vehicles/new-vehicles/leaf/range-charging.html.

19 The principle of a conventional electric vehicle has not been applied to road freight and air transport because it is difficult to provide the battery capacity required without compromising the efficiency of the long-distance vehicle as a larger battery adds significant weight.

20 For example, China, Japan and Germany have rolled out hydrogen charging stations of hydrogen fuel cell cars. *See* "Highest increase of hydrogen refuelling stations in Germany worldwide in 2018 again," Globe Newswire, 15 February 2019, https://www.globenewswire.com/news-release/2019/02/15/1726095/0/en/Highest-increase-of-hydrogen-refuelling-stations-in-Germany-worldwide-in-2018-again.html; Ren Qiuyu and Li Liuxi, China's Largest Hydrogen-Fueling Station Opens in Shanghai, Caixin Global, 7 June 2019, https://www.caixinglobal.com/2019-06-07/chinas-largest-hydrogen-fueling-station-opens-in-shanghai-101424532.html; Tim Hornyak, "How Toyota is helping Japan with its multibillion-dollar push to create a hydrogen-fueled society," CNBC, 26 February 2019, https://www.cnbc.com/2019/02/26/how-toyota-is-helping-japan-create-a-hydrogen-fueled-society.html.

effort to lower emissions in cities. Importantly, there are lessons to be learnt from the roll-out of EVs. The success of EVs in certain countries can be largely attributed to a package of attractive tax breaks, purchase support schemes, and the timely roll-out of charging infrastructure.[21] Similar incentives may be needed for HFC vehicles to share the same success.

Fundamentally, HFCs are similar to batteries in that they function as an energy storage medium. As such, HFCs also have revenue opportunities in the electricity market. Based on current grid charging regimes, grid-scale electrolysers and HFC charging stations could stand to benefit from balancing revenues as the contribution of intermittent generation grows. Proven grid-based hydrogen applications may also contribute to the mitigation of asset-stranding risk of grid infrastructure, as it may help to reverse—to an extent—the exodus to private-wire solutions and behind-the-meter generation.

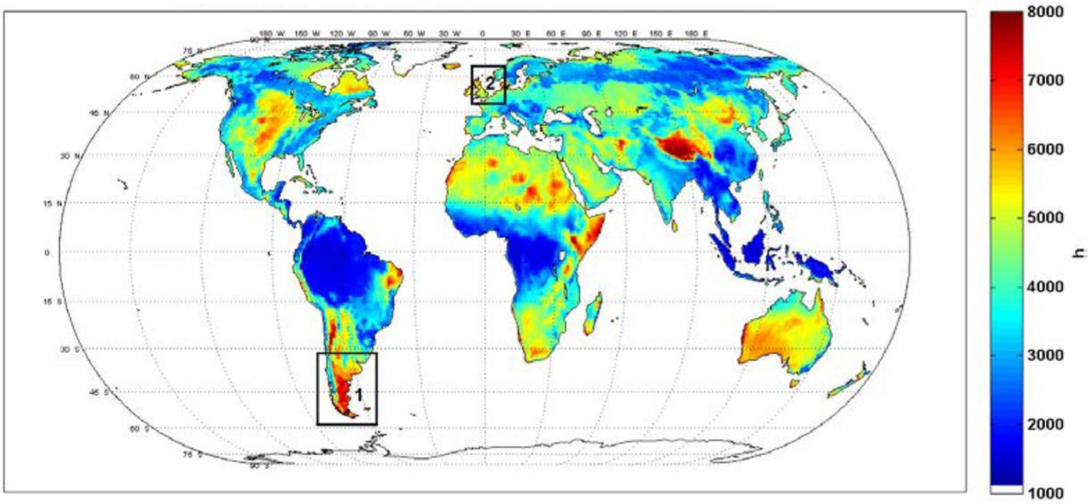
Trends to watch

We explore trends which could make hydrogen an attractive addition to the energy mix, including falling costs of renewables, growing interest in carbon capture and storage and rising carbon prices.

The falling costs of renewables

As discussed previously, many studies project that SMR + CCS will be the primary provider of bulk hydrogen in countries with low to moderate renewables potential.[22] However, this might not be the case in some locations where the renewable potential is high.

Figure 2: Wind and solar PV full-load hours



Source: Breyer and Fasihi (2017)

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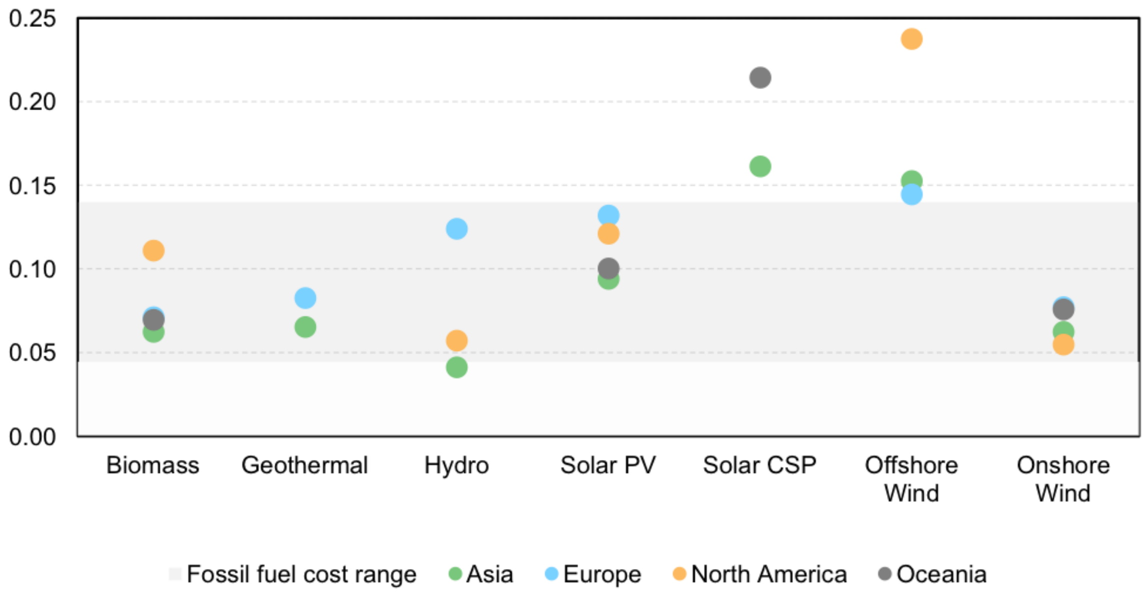
[21] Norway has the highest proportion of EVs. In 2018, EVs accounted for c. 40% of car sales. The growth of EVs in Norway can be attributed to a number of support policies. *See* The Norwegian Electric Vehicle Association, https://elbil.no/english/about-norwegian-ev-association/.

[22] *See* supra notes 5 and 11.

Figure 2 shows the combined total full-load hours for both wind and solar PV across the world. A full-load hour is an hour where renewable generation assets are generating at full capacity. A high number of full-load hours in some geographies have decreased the levelised cost of electricity (LCOE) of renewable generation. For example, Figure 3 shows that in 2016 the LCOE of solar PV was in the range of fossil fuel generation costs in Asia and Oceania. Onshore wind was in the fossil fuel cost range globally.[23]

Figure 3: LCOE (USD/kWh) for different technologies and geographical regions



Source: IRENA (2017). We note that the figure shows average cost and specific projects might differ.

At scale, these generation parameters would boost the viability of a bulk supply of green hydrogen. As such, we might expect larger deployments of green hydrogen in regions with high renewable potential going forward. In fact, with the advancement of chemical-based hydrogen storage, we might see a “redistribution of renewables” potential around the world via a global hydrogen market, where green hydrogen is produced and shipped around the world in the form of compounds e.g. ammonia. Ammonia is a potential candidate for transporting hydrogen as it is hydrogen-rich (consisting of three hydrogen molecules and one nitrogen molecule) and has been transported in bulk for many years as part of global fertiliser production. It also has a higher boiling point than hydrogen, making it significantly easier to liquefy. The next step is to extract hydrogen from ammonia, but extracting hydrogen out of ammonia has historically been an energy-intensive process, and could be prohibitively expensive. Research and development in this field however

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23 International Renewable Energy Agency (IRENA), Renewable Power Generation Costs in 2017, https://www.irena.org/publications/2018/Jan/Renewable-power-generation-costs-in-2017.

has potentially addressed this cost barrier. Siemens researchers have devised a method to convert hydrogen to ammonia for bulk storage or transport, with only a 10% energy penalty.[24]

The rollout of carbon capture and storage

Carbon capture and storage technology is fairly well developed and has been deployed in the oil and gas sector since 1996.[25] There are currently about 21 large-scale CCS facilities worldwide, with the highest density of CCS projects in North America due to the abundance of suitable sites, complementary industries and government support.[26]

In geographies with lower renewable generation potential, the viability of bulk hydrogen depends on the availability of CCS to accompany SMR. Japan is considering the hydrogen pathway due to its moderate renewables potential and high reliance on fuel imports. In 2012, the Japanese government coordinated the launch of the Tomakomai project. The project brings together the private sector, government, and academic institutions and it is aimed at demonstrating the feasibility of hydrogen production via SMR and carbon capture.[27]

Broadly, there are three main barriers which impede the development of CCS via the free market alone: limited revenues from emission reductions, significant capex requirement, and high project risk. These barriers can be overcome with relevant government interventions, but coordination is key to ensure the successful delivery of projects. For example, the UK has faced issues in the past with risk allocation in a CCS project where there were multiple participants along the value chain. This failure to allocate project risks ultimately led to the project being cancelled.[28]

Regardless of the critical role of CCS in the hydrogen pathway, it remains an important component to achieve carbon neutrality. For example, future energy scenarios developed by the International Environment Agency, the European Environmental Agency, and IRENA generally include some form of CCS as part of a suite of measures to maintain earth surface temperature from increasing beyond 2C.[29] Given the role of CCS more generally in broader decarbonisation, and the fact that it is an existing technology, we expect CCS technology will continue to develop and improve unless a cheaper, more efficient way of capturing carbon dioxide emissions emerges.

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[24] Jason Deign, "Siemens Tests Ammonia as a Form of Energy Storage for Renewables," GTM Research, 27 June 2018, https://www.greentechmedia.com/articles/read/siemens-ammonia-hydrogen-energy-storage#gs.v8ws39.

[25] Carbon capture and storage was first developed as a concept at Massachusetts Institute of Technology (MIT). The first CCS project was conducted in the Sleipner gas field, about 250km west of Stavanger, Norway. The CCS project was carried out by Statoil to reduce the amount of CO2 contained in the natural gas and light oil extracted from the Sleipner field. The product from the Sleipner field had unusually high concentrations of CO2 (about 9%) but sellable product required CO2 concentrations to be less than 2.5%. Statoil implemented CCS to avoid paying the carbon tax introduced by the Norwegian government around in 1991. The CO2 extracted from Sleipner product was therefore extracted and pumped back underground. The Sleipner project is the first commercial example of CO2 storage in a deep saline aquifer. *See* MIT, Carbon Capture & Sequestration Technologies, https://sequestration.mit.edu/.

[26] The US and Canada have multiple policies in play to help overcome barriers to investing in CCS, such as enhanced oil recovery, regulatory requirements, low cost capture and transport, tax credits and grant support. *See* Global CCS Institute, Policy Priorities to Incentivise Large Scale Deployment of CCS, April 2019, https://www.globalccsinstitute.com/resources/publications-reports-research/policy-priorities-to-incentivise-large-scale-deployment-of-ccs/.

[27] *See* Japan CCS Co., Ltd., https://www.japanccs.com/en/.

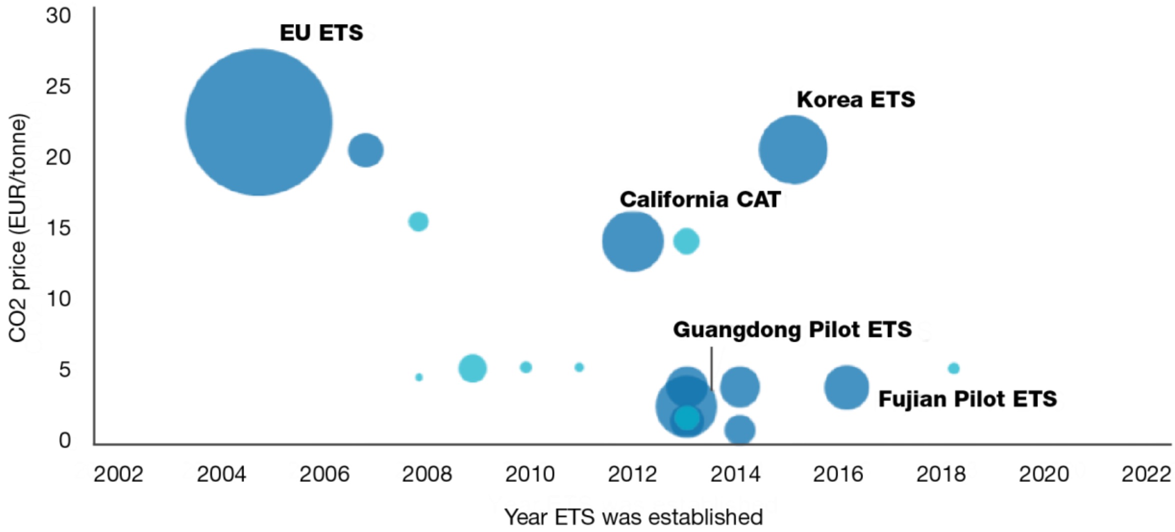
[28] National Audit Office, Carbon Capture and Storage: the second competition for government support, January 2017, https://www.nao.org.uk/report/carbon-capture-and-storage-the-second-competition-for-government-support/.

[29] International Energy Agency, World Energy Outlook 2018, https://www.iea.org/weo2018/.

Carbon prices

Many countries have implemented emissions trading schemes (ETS). Figure 4 shows the price of CO2 emissions as at February 2019 for various ETS; the year the ETS was established; and the size of the bubble indicates the relative amount of CO2 covered by each scheme. The EU ETS is the largest and only supranational scheme to date, and it covers about two gigatonnes of emissions.

Figure 4: CO_2 prices, traded volumes and development of ETS globally as at February 2019



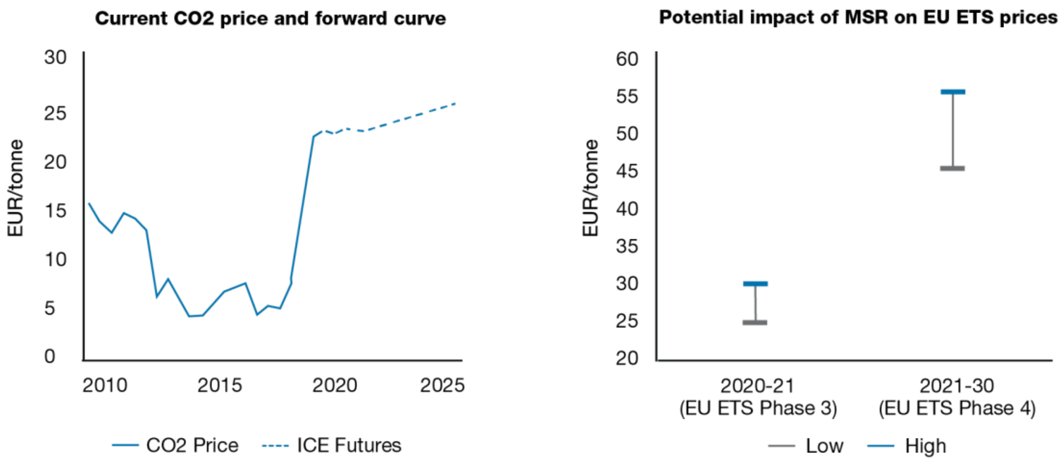
Note: Size of bubble denotes volumes of emissions covered by the ETS

Source: World Bank

We focus on the EU ETS here, given it is the largest scheme and includes countries with strong commitments to decarbonisation. Carbon prices in the EU ETS have been ticking up over time, but since January 2018 there has been a steady increase in the spot carbon price. To some extent, industry analysts consider that this spike may be a response to the market stability reserve (MSR), an EU policy decision to curb the number of tradeable certificates in the market to (a) correct for the initial surplus of certificates in the EU ETS; and (b) allow the EU to meet its decarbonisation targets by curbing the amount of emissions allowed in the traded sector.[30]

[30] The EU ETS currently covers CO_2 emissions from power and heat generation; energy-intensive industry sectors including oil refineries, steel works and production of iron, aluminium, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids and bulk organic chemicals; and commercial aviation. *See* European Commission, EU Emissions Trading System, https://ec.europa.eu/clima/policies/ets_en.

Figure 5: Forecast of EU ETS carbon prices



Source: Bloomberg, Carbon Tracker

Over time, if the carbon price moves up to a level that appropriately 'internalises' the negative costs of emissions, green technologies will be on a level playing field (cost-wise) with conventional fuels and generation, at least with respect to emissions. A study by the European Commission suggests that for this to happen, more comprehensive coverage of polluting activities and a higher degree of international emissions trading is required.[31] In fact, studies suggest that the carbon price has to be in the order of hundreds of Euros to establish parity between hydrogen-based technologies and natural gas.[32] The evolution of the carbon price and trading emissions schemes will likely have a significant impact on the competitiveness of hydrogen and other green technologies.

More than just a pipe dream

The nascent nature of hydrogen-based technology means that current cost estimates are high and subject to a significant degree of uncertainty. But this is the case with any new technology. Renewable generation was considered infeasible in the early 2000s, but in just 10 years, the levelised cost of renewable generation has fallen between 25% - 70%, and renewable contribution to electricity generation has more than doubled since 2010.[33]

As with renewables, however, it is clear that a transition to hydrogen would provide societal benefits which would not be taken into account by the market at this point in time. This is largely because greenhouse gas (GHG) emission pricing and trading has yet to provide a sufficient market signal to spur switching to cleaner fuels across the board. Given the market failures present, governments have a significant role to play in catalysing the hydrogen transition by coordinating the relevant parties and providing de-risking facilities for projects with significant capex. For most developed countries, however, the decarbonisation journey could be a tough

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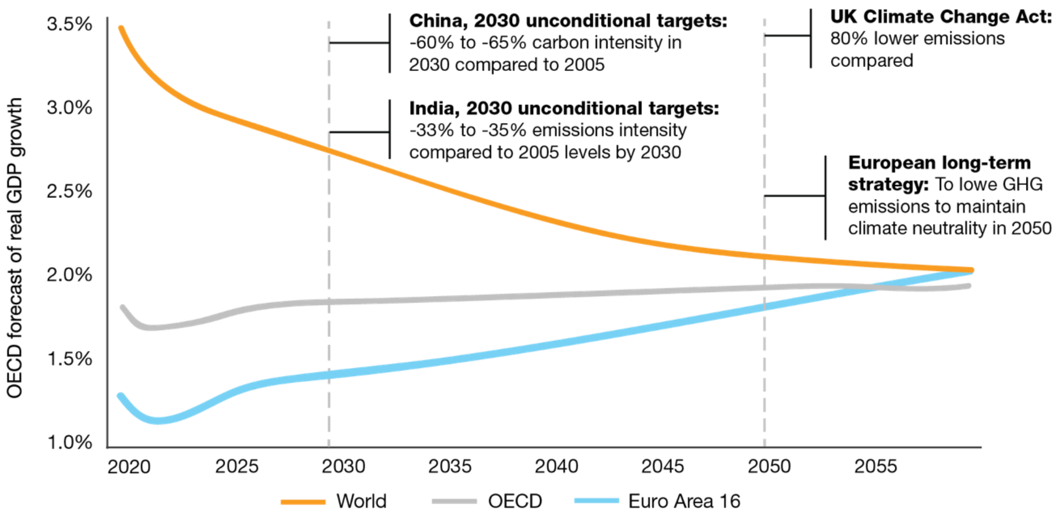
31 European Commission, "Green hydrogen opportunities in selected industrial processes", 26 June 2018, https://ec.europa.eu/jrc/en/publication/green-hydrogen-opportunities-selected-industrial-processes.

32 The CCC estimates that the carbon price shall be equal to £70-100/tCO2 in its analysis of hydrogen roll out. The Hydrogen and Fuel Cell Research Hub estimates that the carbon price would have to be around £250/tCO2. *See* supra note 5.

33 IRENA and IEA.

battle in the face of muted GDP growth and political resistance from large industries which are challenging to decarbonise.

Figure 6: Forecast of real GDP growth and selected climate commitments



Source: OECD and Climate Tracker

Developing countries may have a degree of flexibility in the design of their energy systems and could consider hydrogen based on a combination of renewables and/or SMR + CCS. Buoyed by healthy economic growth, developing countries could configure their energy systems on a 'no-regrets' basis given the current expectation of required decarbonisation targets. This may be particularly useful for economies that rely on hydrogen-intensive sectors such as steel making, e.g. China and India. This highlights the pivotal impact that location and existing economic activity could have on the business case for hydrogen. Taking advantage of economies of scale and scope will be key for the success of a coordinated transition to hydrogen.

A coordinated transition may not be the only way to reap the decarbonisation benefits which hydrogen has to offer. There are currently a number of hydrogen projects that have taken advantage of available resources and gaps in the market. For example, ITM Power, a company which produces grid-scale electrolysers for energy storage, operates on the basis that there is significant scope for grid balancing with the proliferation of intermittent renewable generation.[34] Orkney, a town in Scotland, has taken advantage of its significant wind and tidal energy potential to produce green hydrogen to power its ferries.35 Nouryon and Tata Steel in Amsterdam are partnering to produce and use green hydrogen for power, and in the various processes for making steel.[36] While hydrogen may not be a blanket solution to the decarbonisation challenge, it definitely offers both commercial and public benefits when deployed under the right circumstances.

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[34] ITM Power, Power-to-gas energy storage, http://www.itm-power.com/sectors/power-to-gas-energy-storage.

[35] Mure Dickie, "Orkney's ageing ferries look to ditch diesel for hydrogen," 26 December 2018, *Financial Times,* https://www.ft.com/content/2da8745a-0287-11e9-99df-6183d3002ee1.

[36] Jason Deign, "Tata Steel, Nouryon and Port of Amsterdam Plan the Largest Green Hydrogen Cluster in Europe," GTM Research, 19 October, 2018, https://www.greentechmedia.com/articles/read/tata-steel-nouryon-and-port-of-amsterdam-plan-largest-green-hydrogen-cluste#gs.xu6z2i.

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