Developments in the global hydrogen market: Electrolyser deployment rationale and renewable hydrogen strategies and policies

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This article explores the importance of renewable hydrogen in achieving a 'climate neutral' energy system, which will require a large amount of renewable electricity and a very large amount of renewable hydrogen. Because of the fundamental need for energy storage to match supply and demand, a two-carrier approach needs to be adopted, where both electricity and hydrogen are derived from renewable energy. National hydrogen strategies, electrolyser deployment plans and the actions required by governments to overcome the current policy vacuum are discussed. It is recommended that a cross-sector 'green electrons and green molecules' strategy is taken, and that policies are developed urgently for advancing the adoption of renewable hydrogen.

Introduction

People use energy in two forms, electrons and molecules, but only molecular energy is storable. Molecular energy is thereby the enabler for applications where a large temporal variation in demand must be satisfied, or where a fuel must be carried on-board a vehicle. In energy terms, its global market (mainly comprising oil, natural gas and coal) is at present nearly eight times the size of the electricity market.

To combat global warming, man-made greenhouse gas (GHG) emissions must be reduced to zero by mid-century and a climate-neutral, rather than a low-carbon, energy system implemented. There is thus an overarching need to transition away from fossil fuel combustion, and instead produce and use hydrogen (and fuels derived from hydrogen) to satisfy our future demand for molecular energy.

There are two main schools of thought regarding the production of hydrogen:

(1) electrolysis of water using renewable electricity; and
(2) reformation or partial oxidation of fossil fuels, where the resulting CO_2 emissions are captured and sequestered (CCS).

This article addresses the production of renewable hydrogen by water electrolysis as part of a general 'green electrons and green molecules' strategy for combatting global warming, while a further article will compare the pros and cons of these two approaches to hydrogen production.

Why renewable hydrogen, and why now?

The implementation of renewable power sources is accelerating, from a worldwide installed capacity of 1 TW in 2018 to an expected 2 TW by 2023, with 13 TW (or 65% of total final energy consumption) predicted for 2050.[1] For comparison, the global average power demand is currently about 2.6 TW.[2] By convention, renewable power sources are connected to the electricity grid, so that consumers can access and utilise renewable electricity independent of its origin. However, the expansion of variable wind and solar power is fundamentally constrained by the ability of end-users to consume electricity at the time of generation. At any given time, if renewable generation is plentiful but demand is low, the electricity is of little value or worthless. Integrating more renewables therefore serves to increase the availability and suppress the price of wholesale electricity outside of peak demand periods. Also, balancing challenges for the power system operator increase with installed capacity of renewables. Therefore, unless new controllable load of sufficient flexibility can be built up on the demand side and be operated mainly out of time phase with the existing demand profile, the curtailment of renewable generation will increase (as a function of the temporal mismatch between supply and demand), and so undermine the economic case for further renewables deployment.

In essence, electricity from solar and wind power sources is a short-life product of time-varying value. Fortunately, electrolysers can transform it into a versatile storable, long-life product of consistent value (renewable hydrogen), which can be used across the entire energy system to satisfy our demands for molecular energy [**Figure 1**]. So the role of electrolysis is to escalate renewables integration by converting green electrons into green molecules. The role of hydrogen is then to act as a second carrier of renewable energy into the energy system. It is strategically important for energy policy to recognise and exploit both roles.

On the demand side, renewable hydrogen is the key substitute for fossil fuels. If used as a chemical feedstock it provides a basis for decarbonising chemical products, such as methanol. If used as a fuel it can decarbonise all non-electrical end uses. If combusted it can eliminate CO_2 emissions and reduce atmospheric pollution. If used by fuel cell electric vehicles (FCEVs) it can halve transport energy requirements, reduce noise and eliminate pollution without compromising vehicle range or refueling time. If used as an energy store it can buffer the entire energy system with renewable energy. Therefore, alongside renewable electricity, renewable hydrogen holds the key to realising a climate-neutral energy system.

Towards a climate-neutral energy system

Switching to this two-carrier approach involves making three key steps. The deployment of

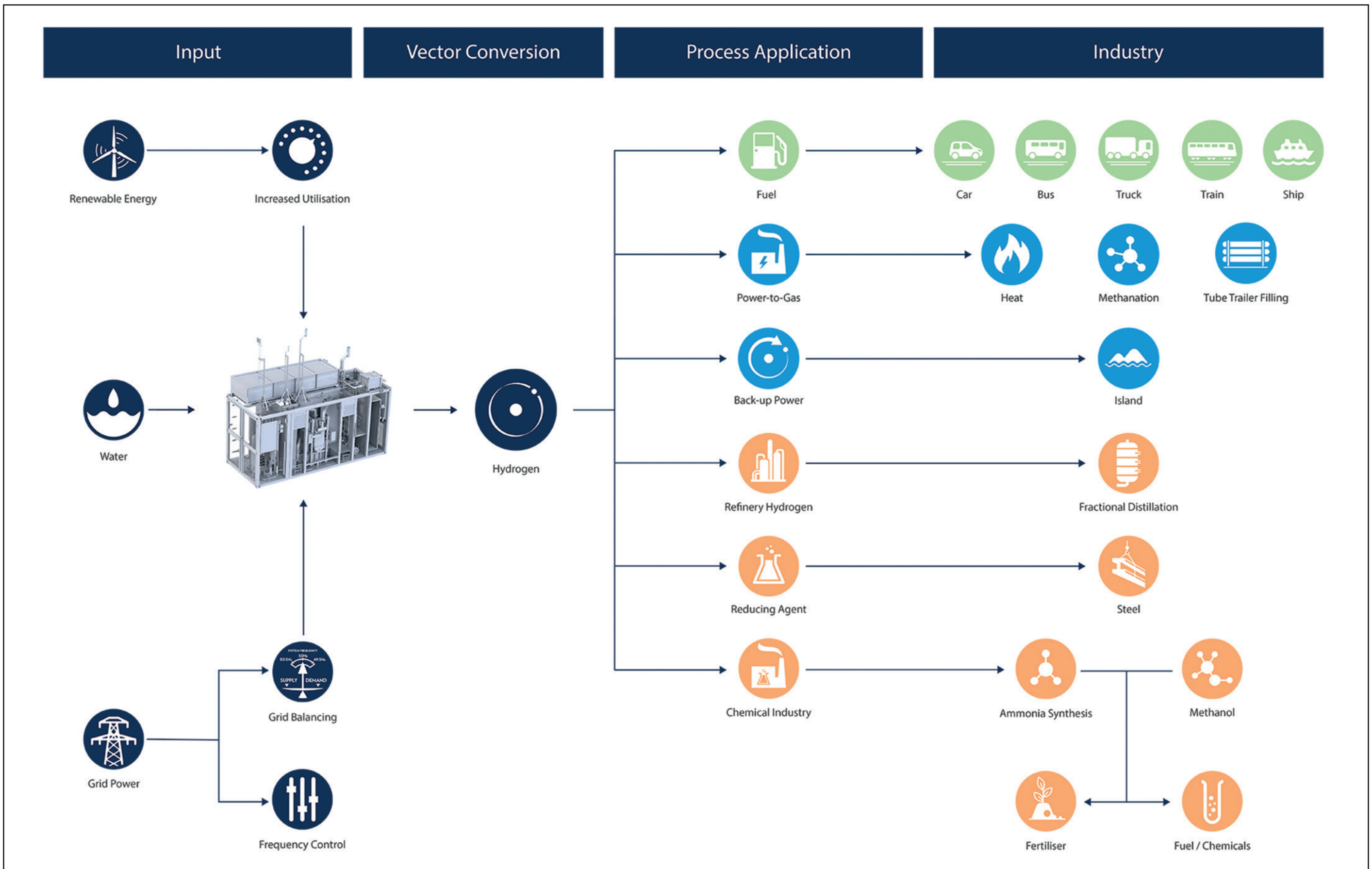

Figure 1. Renewable hydrogen feeding a climate-neutral energy system.

grid-connected electrolysers may be considered as the first step. Locating grid-connected electrolysers on-site or nearby the point of hydrogen consumption is readily achievable via the geographic spread of the electricity grid. Rapid-response electrolysers are also able to provide grid services to the balancing market, ranging from frequency response to negative reserve.[3, 4] This decentralised approach has been adopted in the UK for hydrogen refueling stations (HRS),[5] and various other applications have been demonstrated, such as injecting hydrogen admixtures into gas distribution networks via Power-to-Gas systems.[6] Importantly, this first step circumvents requirements for a hydrogen grid, transportation to site, or conversion to a hydrogen carrier. Therefore, it can begin immediately and the installed electrolyser capacity can be built up in a distributed manner while always maintaining a good match between hydrogen supply and demand. For the UK, it is estimated that 50–100 TWh of hydrogen can be produced in this way without overloading, or requiring expansion of, the electricity grid.

Embedding electrolysers in electricity grids will provide certainty of demand for integrating new renewables and a greater annual load factor for the grid (i.e. make better use of this existing asset). The link between grid balancing, renewables expansion and electrolysers should be a central consideration in the deployment rationale, to ensure the associated synergies are exploited in practice. Thereby the electricity grid can enable the delivery of both molecular energy and electrical energy, with hydrogen production occurring on-site adjacent to the demand points, or at a larger scale on a regional basis.

Nevertheless, the total demand for molecular energy is much greater than that which can be satisfied by embedding electrolysers in electricity grids. Renewable hydrogen will ultimately be required in very large quantities as a replacement fuel or feedstock for the transport, heat, refinery, fertiliser, steel and chemicals sectors [Figure 1]. For example, the current average global demand for natural gas alone is 4.4 TW, with a considerably greater peak requirement during winter.[7] As an early decarbonisation measure, renewable hydrogen may be injected into the gas grid via Power-to-Gas (P2G) systems – a clear 'sector coupling' option – where the electricity grid is effectively able to spill renewable energy into the gas grid to assist the decarbonisation of both infrastructures.[8, 9] However, in the longer term, hydrogen grids will be required for transferring large amounts of renewable energy, rather than natural gas grids.[10] Advantageously, hydrogen has a lower global warming potential than methane, and its combustion does not result in CO_2 emissions.

It is therefore desirable to generate hydrogen off-grid at scale in regions of high renewable resource and then transfer the energy by pipeline or ship, rather than electricity cable. Off-grid electrolysis, via dedicated wind and solar power generators, will substantially augment hydrogen production occurring on the demand side within electricity grids. It will ultimately enable the amount of renewable hydrogen production to exceed that of renewable electricity production, and so help the two-carrier approach match society's demand levels for electrical and molecular energy.

The implementation of large-scale electrolysis outside of the electricity grid will facilitate the production and transfer of very substantial amounts of renewable energy between countries and continents. In essence, it will open up a much larger global market for renewables and enable renewable energy to satisfy a very large proportion of global final energy consumption by 2050. Implementing off-grid electrolysis at scale may therefore be considered as the second step towards achieving a climate-neutral energy system.

In brief, off-grid electrolysers will: facilitate renewable energy capture in places where the electricity grid is weak or non-existent; avoid the need to extend or reinforce electricity grids; reduce power conversion losses between the power source and the electrolyser; and be compatible with long-distance, low-cost energy transfer by pipeline or via a hydrogen carrier. Off-grid electrolysers are therefore being developed for deployment in combination with solar photovoltaic (PV) arrays and offshore wind turbines.[11, 12]

By combining the first and second steps, countries can produce and import/export renewable hydrogen in large amounts. However, it will be necessary to also take a third step in order to buffer peak demands and manage the temporal mismatch between supply and demand. Extensive storage of renewable energy will be essential. The energy storage facilities must be able to accept time-varying charge-and-discharge profiles in order to satisfy diurnal and seasonal variations. This can be achieved by storing hydrogen in salt caverns and other suitable geological stores at TWh scale. A network of hydrogen storage facilities interconnected by a hydrogen transmission grid can absorb excess supply as it occurs, and cover periods of high demand when renewables availability is low.[10] In this way renewable hydrogen storage can act as the lung of a climate-neutral energy system.

The above rationale for reducing our dependency on fossil fuels and the environmental damage it causes is neither new nor radical. In 1923 Haldane was the first to offer a vision of windmills powering electrolysers in England, with electrolytic hydrogen being stored for use by industry, transport and heating applications.[13] Later, Bockris[14] introduced the term ‘hydrogen economy’ to describe an energy system where large amounts of renewable energy are transferred from remote sources in the form of hydrogen, in order to satisfy our massive consumption of chemical energy without using fossil fuels. Clearly, it is incorrect to use the term ‘hydrogen economy’ to describe the transfer of large amounts of fossil fuel for conversion to hydrogen.

National hydrogen strategies and deployment plans

In the above context, several countries have recently published or are developing hydrogen strategies which place emphasis on renewable hydrogen. In these, electrolysers are viewed as providing electricity grid operators with flexibility services and renewable generators with a new market, while the renewable hydrogen they produce is employed as a clean fuel, decarbonising agent, chemical feedstock, means of storing energy at scale, and in some cases a way of establishing large export markets for hydrogen technologies and renewable hydrogen.

The European Commission recently set out its vision of how the EU can turn hydrogen into a viable solution for decarbonising different sectors over time. The EC’s Hydrogen Strategy frames the ambition for hydrogen across Europe, and sets targets of at least 6 GW of electrolysis by 2024 and 40 GW by 2030.[15] It sees renewable hydrogen as the priority, and the most compatible option with the EU’s goals of climate neutrality and zero pollution. It calls for electrolysers to be progressively deployed at large scale alongside the roll-out of new renewable power generation, and estimates that Europe could invest up to €42 billion in electrolysers across the 2020s.

"Throughout history, fossil fuel molecules have been used to generate electrons. Now that electrons can be generated renewably, the energy transition relies on renewable molecules being generated from renewable electrons."

The EC also recently published its Energy System Integration package, which emphasises the adoption of more circular approaches, greater electrification, and the use of hydrogen where direct heating or electrification is not feasible.[16] It views electrolysers as playing a nodal role in the future energy system, and identifies up to 450 GW of potential offshore wind capacity and the opportunity to produce renewable hydrogen at scale in Europe by co-locating electrolysers with offshore wind farms. It estimates that 80% of gaseous energy use will be renewable by 2050, and in the short term wishes to re-examine the gas market’s regulatory framework to facilitate the uptake of renewable gases. It also aims to promote the financing of climate-neutral industrial clusters, and the production of fertilisers from renewable hydrogen.

In its hydrogen strategy the German government states that only hydrogen produced on the basis of renewable energies (‘green’ hydrogen) is sustainable in the long term.[17] It views hydrogen as a multipurpose energy carrier that can be used in fuel cells to power hydrogen-based mobility and serve as a basis for producing synthetic fuels, but also as a medium for storing renewable energy. It regards renewable hydrogen as an essential element of sector coupling for decarbonising applications where renewable electricity cannot be used directly (e.g. chemical processes like ammonia production, and iron reduction in the steel industry). Therefore, the objective of the German government is to use renewable hydrogen to support a rapid market ramp-up and to establish a home market for hydrogen technologies. Accordingly it has set an electrolyser deployment target of 5 GW by 2030, with a further 5 GW to be added by 2035. It has identified 38 measures and allocated €9 billion to achieving the hydrogen strategy, including €2 billion for international cooperation to facilitate importing renewable hydrogen. One example of the latter is the recent declaration of intent signed with Morocco, with an initial deployment of 100 MW of electrolysis powered by solar PV.[18]

France has also placed a focus on renewable hydrogen, with the government setting a target of deploying 6.5 GW of electrolysis by 2030, of which 0.87 GW will be installed by 2023.[19] It has identified reducing France’s dependency on imported oil and the adoption of hydrogen-fueled heavy vehicles as key objectives. It has allocated €7 billion to achieving the hydrogen strategy, and expects to invest the first €2 billion in industrial-scale electrolysis across the period 2020–2022.

The Dutch government views hydrogen as a crucial link in the chain to achieve a climate-neutral energy system.[20] It wants the Netherlands to adopt renewable hydrogen so that it may continue to act as an energy hub in the future due to its favourable location, its ports, and its extensive gas grid and storage capacity. A blending obligation for hydrogen injection into the gas grid at concentration percentages of up to 20% is currently being explored with respect to the required policy, legislation and market aspects. The Dutch ambition is to scale up electrolysis to approximately 0.5 GW of installed capacity by 2025, and to 3–4 GW by 2030. The government is also considering importing renewable hydrogen from Denmark and Portugal (e.g. it recently agreed to buy 8 TWh of surplus renewable electricity at a price of 12.5 €/MWh from the Danish government, in order to finance renewable hydrogen production at approximately 100 MW scale in Denmark, so that both countries can gain experience and knowledge[21]). In Denmark, a partnership of leading industrial companies has been formed, which aims to deploy 1.3 GW of electrolysis by 2030 and views the Netherlands and Germany as prospective export markets.[22]

The Portuguese government is aiming to deploy up to 2 GW of electrolysis and 7 GW of renewables by 2030. Portugal's excellent solar energy resource has so far enabled it to produce solar power at prices as low as 14.8 €/MWh, and low-cost solar hydrogen production is expected to commence in 2023.[23] At present, Spain and Austria have hydrogen strategies under consultation, with 2030 electrolyser targets of 4 GW and 1–2 GW, respectively.

Australia's National Hydrogen Strategy is focused on large-scale hydrogen hubs and the long-term potential of exporting large amounts of renewable hydrogen to Japan and South Korea.[24] The individual states are also setting their own hydrogen agendas.[25] In advance of the National Hydrogen Strategy, the Australian Renewable Energy Agency (ARENA) announced a change to its investment priorities to include 'accelerating hydrogen by helping drive innovation and hydrogen supply chains'. In New Zealand, the government has committed to a renewable hydrogen vision based on a combination of geothermal, hydroelectric, wind and solar energy.[26] New Zealand's hydrogen strategy consists of two parts: the hydrogen vision published in 2019, and a hydrogen roadmap which is under development.

As the world's largest producer of hydrogen, China is aggressively developing hydrogen and fuel cell applications, with the aim of hydrogen accounting for 10% of Chinese energy use by 2040. The 14th Five-Year Plan targets achieving 1 million FCEVs and 1000 hydrogen refueling stations (HRS) by 2030, with renewable hydrogen accounting for 50% of consumption. At the end of 2020, China will reduce subsidies on battery electric vehicles (BEVs) and transfer the funding to building hydrogen refueling infrastructure in order to facilitate mass production of FCEVs.[27]

In the UK, a Net Zero target for 2050 has been set by government, as advocated by the Climate Change Committee,[28] which called for the development of a hydrogen economy to service demands for some industrial processes, for energy-dense applications in long-distance heavy goods vehicles (HGVs) and ships, and for electricity and heating in peak periods. However, the government has not yet made any commitment to deploying electrolysers and renewable hydrogen. In its 2020 Future Energy Scenarios, National Grid indicated that large amounts of hydrogen can be produced from the UK's offshore wind resource, with opportunities to achieve the net zero target in advance of 2050 and export renewable hydrogen to Europe.[29] A recent report by the Offshore Renewable Energy Catapult concludes that there is sufficient offshore wind power to both meet UK energy needs in 2050 and export hydrogen worth £48 billion per annum.[30] The latter amount is similar to that achieved during the best years of UK North Sea oil & gas production, but the key difference is that the energy supply is inexhaustible. The required manufacture and deployment of electrolysers in conjunction with offshore wind turbines has been estimated to create 120 000 new jobs, replacing those lost in the oil & gas sector.[30]

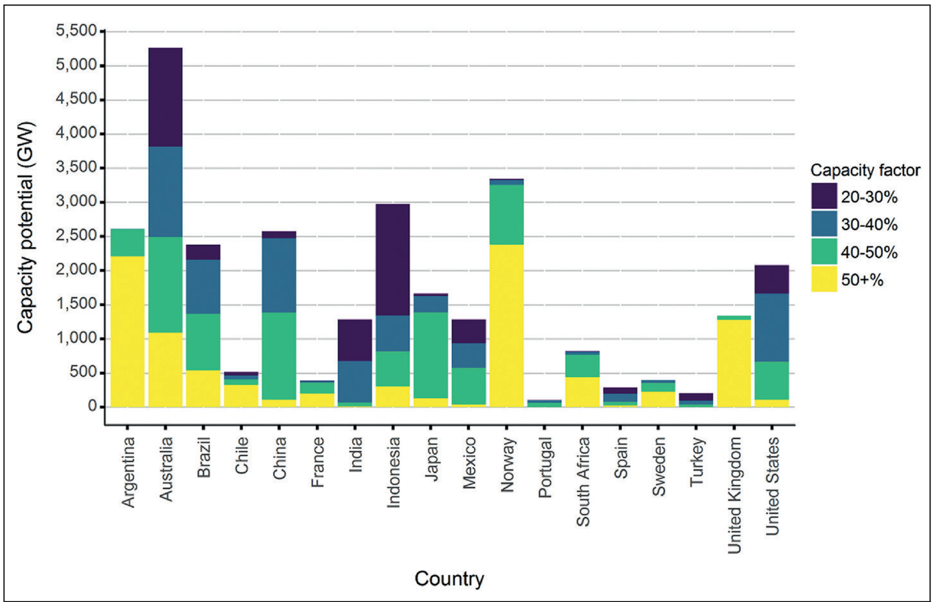

Figure 2. Offshore wind capacity potential by capacity factor for a range of high potential countries.[32]

Importing and exporting renewable energy

The import/export of renewable hydrogen will facilitate global renewable energy trading at scale. Although indigenous production is an important early step, a country's renewable resource potential [e.g. **Figure 2**] in relation to its energy consumption will tend to make it either a significant exporter or importer of renewable hydrogen. On this basis the main importers will be the EU, Japan, US and South Korea. For example, Japan currently imports around 90% of its energy needs, and sees hydrogen as an important source of emissions reductions.[31]

The co-location of electrolysers with renewable power sources in regions of high renewable resource is the key pathway for achieving low-cost renewable hydrogen production, but hydrogen will need to be transferred to other regions by pipeline, or transported by ship either in the form of a hydrogen carrier (e.g. ammonia, methanol, Liquid Organic Hydrogen Carrier/LOHC) or as liquid hydrogen. Australia, Saudi Arabia and Morocco have already recognised the long-term opportunity to produce and export renewable hydrogen at scale, but several other countries could be significant exporters, including Canada, Argentina, Norway, China, the MENA (Middle East and North Africa) countries, Ireland, Iceland and the UK. Given its close proximity to Europe and the established gas infrastructure in the North Sea, it should be noted that the UK has both a high offshore wind capacity potential (of ~1300 GW) and a relatively high average capacity factor,[32] which make it an economically attractive European location for producing renewable hydrogen.

A number of industry-led European initiatives are developing cross-border solutions to help facilitate renewable hydrogen production, storage and use. Hydrogen Europe recently presented a roadmap for deploying 80 GW of electrolyser capacity by 2030: 6 GW on-site plus 34 GW close to renewable power sources in Europe, together with a further 40 GW in Ukraine and North Africa, of which 32.5 GW will export hydrogen to the EU.[33] Much of this electrolyser capacity will feed a European hydrogen transmission system for transferring renewable energy at scale from regions of high resource to regions of high demand. The European Hydrogen Backbone initiative aims to establish a 23 000 km transmission system by 2040, comprising mainly 48 inch (122 cm) diameter pipelines each having a transfer capacity of 13 GW of hydrogen [**Figure 3**].[10] Also several IPCEI projects (Important Project of Common European Interest) are under development involving groups of EU countries, whose governments are aiming to achieve cross-border

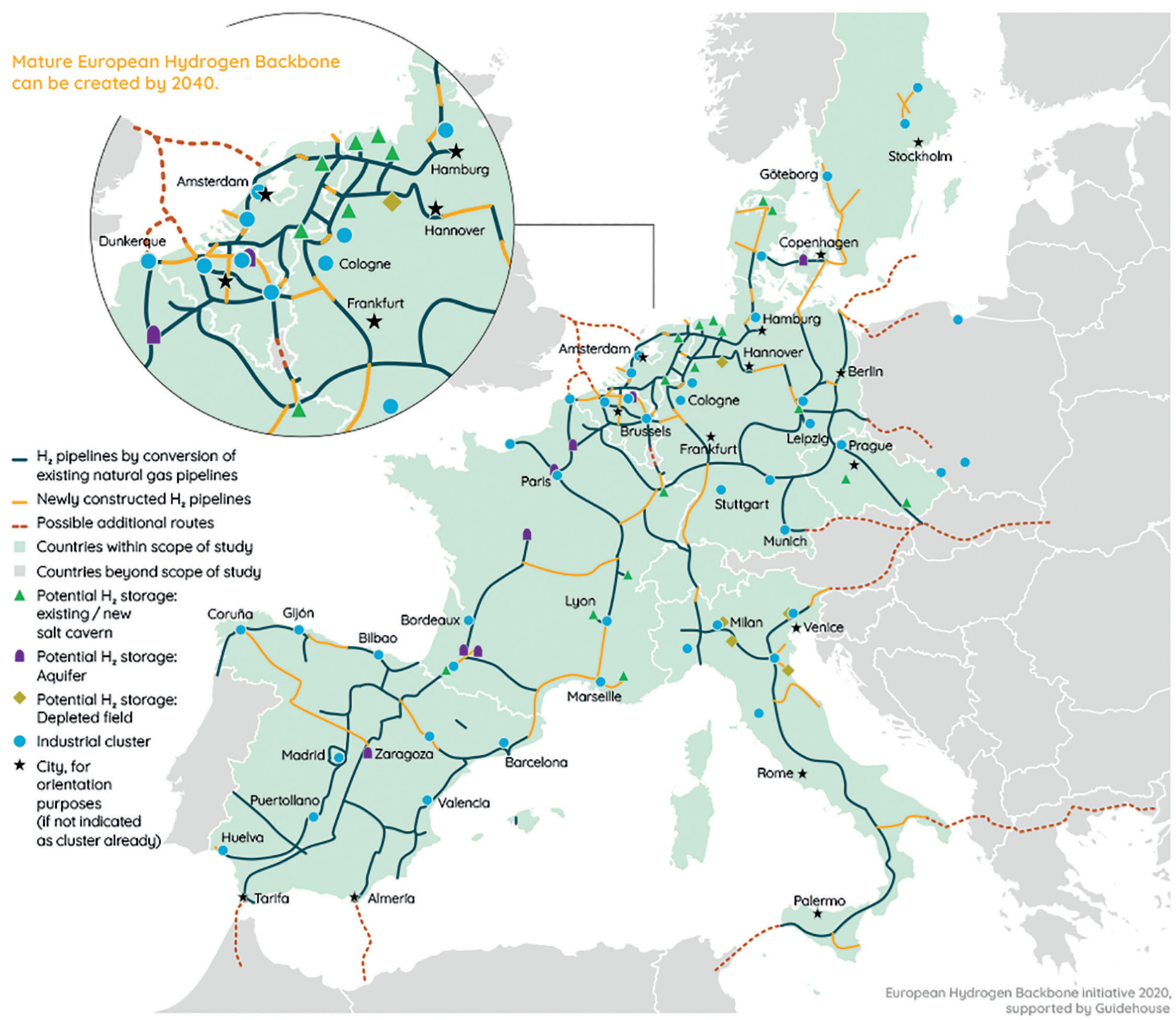

Figure 3. The proposed European hydrogen transmission backbone.[10]

solutions for producing, distributing and using renewable hydrogen at scale by 2030.[34]

Overcoming the policy vacuum

At present, there is almost a policy vacuum with respect to renewable hydrogen – appropriate frameworks and regulatory arrangements are needed urgently. Because the various sectors of the economy have not yet embraced renewable hydrogen, it cannot be managed by one centralised 'market design' policy (unlike electricity and existing fuels). Instead, the objective for policymakers should be to develop sector-specific and sector-coupling policies to facilitate early demand growth and hydrogen technology deployment, so that renewable hydrogen can ultimately become a mainstream commodity.

Various studies have offered future scenarios and reported wide ranges of GW or TWh values for hydrogen by a target year, but very few have suggested what policy measures will be required to achieve early market growth. It is essential that policies are applied alongside hydrogen technologies to enable a progressive decarbonisation of the economy.

It is suggested that separate policies should be innovated for three categories of demand-side hydrogen use:

(a) Existing industrial processes that require and are familiar with using hydrogen as a feedstock. These tend to be characterised by a high hydrogen demand per process.

(b) Hydrogen applications in the transport sector, where experience has been gained but the present demand per hydrogen refueling station (HRS) is low. Greater numbers of HRS and hydrogen vehicles are needed.

(c) Hydrogen via the gas grid for heat and power production, either as a hydrogen admixture in a methane grid or as 100% hydrogen in a hydrogen grid. The gas grid is a large potential sink for hydrogen, but there is a need for regulatory change because the present hydrogen demand is zero.

Action can be taken independently by each of these sectors; there are no interdependencies between them or prerequisites that inhibit making early progress. Three sets of policy measures are required to enable demand growth in each of these categories concurrently.

Policy relating to industrial processes

Several industrial chemical processes already consume hydrogen in large amounts (e.g.

for oil refining and for producing ammonia, methanol, hydrogen peroxide and hydrogenated fats). Globally the rate of hydrogen production based on fossil fuels is approximately 300 GW, with the main existing market being large-scale chemical processes. So progressively switching these from 'grey' to green renewable hydrogen is a clear decarbonisation pathway for policymakers to address.

The EC's Renewable Energy Directive II, which requires renewable energy to account for >14% of all transport fuels by 2030, permits renewable hydrogen to be used by oil refineries as an intermediate product in the production of conventional fuels.[35] This equates to a potential electrolyser market of up to several hundred MW per refinery, for an existing population of 85 refineries in Europe. However, as yet, there are no equivalent directives concerning chemical processes other than oil refining.

There are also several industrial thermal processes which could utilise renewable hydrogen to reduce GHG emissions, including furnaces where it can be used as a reducing agent for steel production, in float glass production, and in epitaxy in nanotechnology and semiconductor manufacture. For example, hydrogen-based direct reduction of iron ore is currently being considered in Australia and Germany, where hundreds of MW of electrolysis will be required per furnace. However, to achieve the decarbonisation benefits first requires the introduction of policies that incentivise the adoption of renewable hydrogen and penalise grey hydrogen consumption (e.g. by mandating a proportion of renewable hydrogen to be used by a certain target date).

Policy relating to hydrogen mobility

Hydrogen is currently being dispensed to vehicles with fuel cell electric powertrains (mainly cars and buses) via small networks of HRS in Japan, South Korea, the US (California), EU and UK. Substantial opportunities exist to decarbonise both heavy- and light-duty vehicles, but much larger HRS networks need to be established.

Hydrogen mobility is particularly desirable from the perspectives of consumers and fleet vehicle operators, because FCEVs offer long-range travel and rapid refueling (just like conventional vehicles, but unlike BEVs). HRS may be located at existing petrol stations, fleet depots and, where appropriate, greenfield sites. Locating electrolysers on-site at the HRS is a proven way of enabling the early market, but in time as demand grows it becomes economically advantageous to locate them more centrally and distribute hydrogen by truck. Substantial growth in the numbers of HRS is required if FCEVs are to become a mainstream option (e.g. from approximately 20 in the UK today to 1150 HRS by 2030[5]). However, to achieve this it is important for government to focus policy on the coupling between HRS deployment and FCEV deployment, so that the numbers of each are grown in unison.

In the UK, hydrogen has recently been added into the Renewable Transport Fuel Obligation,[36] but it currently applies only to implementations where a renewable power source and electrolyser are directly coupled. This severely restricts HRS providers from utilising the geographic spread of the electricity grid to build HRS close to the points of demand, and eliminates the opportunity for electrolysers to provide grid services to aid renewables integration. It is important to introduce policies that are sufficiently well thought through to ensure early market failure is avoided.

Policy relating to Power-to-Gas for the gas grid

Renewable energy can be transmitted in large amounts by electricity and gas grids, but only gas grids can provide enough energy storage capacity to absorb variable renewables and meet seasonal demand variations. This dependency is likely to continue because energy storage is a central requirement of any energy system. Future hydrogen grids will consist of high-pressure transmission pipelines for connecting the points of renewable hydrogen production with subterranean stores and then on to the demand centres. In this way the gas pipelines and geological stores can be the lung of the energy system.

In the short term, natural gas will continue to be used as a fuel, and so it is important to reduce its GHG emissions. This may be achieved with Power-to-Gas systems by injecting low-concentration hydrogen admixtures and synthetic methane (via the methanation of green CO_2 and green hydrogen) into gas distribution networks. Numerous Power-to-Gas systems have been demonstrated in Europe during the last decade, at hydrogen concentrations of up to 20%.[6, 9] Hence there is now an urgent need to adjust the regulatory framework to admit hydrogen admixtures; to introduce a Power-to-Gas operating model; to establish a remuneration mechanism that enables stakeholders to invest; and to set time marching targets for the amount of hydrogen injected per annum.

Conclusions

Throughout history, fossil fuel molecules have been used to generate electrons. Now that electrons can be generated renewably, the energy transition relies on renewable molecules being generated from renewable electrons. This is a key energy reversal that challenges conventional thinking.

To achieve a climate-neutral energy system will require a large amount of renewable electricity and a very large amount of renewable hydrogen. Maintaining the current focus on renewable electricity generation alone is counterproductive, because it results in an increasing mismatch between electricity supply and demand, which requires curtailment of generators, and this undermines the economic case for further deployment. Instead, to overcome this problem and open up a much larger market for renewable energy, a two-carrier approach needs to be adopted, where both electricity and hydrogen are derived from renewable energy.

Because there will be a fundamental need for energy storage in a future carbon-neutral energy system, and hydrogen can be stored geologically in large quantities, the global production of renewable hydrogen is likely to far exceed that of electricity. It is therefore important to (i) embed rapid-response electrolysers as controllable loads within electricity grids, and (ii) produce renewable hydrogen off-grid in regions of high resource to help satisfy demand from countries that cannot produce sufficient hydrogen indigenously. This combination of on-grid and off-grid electrolysis can enable hydrogen production to reach the multi-TW scale by 2050.

Internationally there is now considerable political will to implement renewable hydrogen. Several governments have recently published hydrogen strategies and set future deployment targets for electrolysers. However, very few have introduced policies for facilitating the production and use of renewable hydrogen in order to establish early markets in the various sectors of the energy system. It is recommended that a cross-sector 'green electrons and green molecules' strategy is taken, and that policies are developed urgently for advancing the adoption of renewable hydrogen in industrial processes, the transport sector, and the gas grid. Policy development and implementation should now be a priority for renewable hydrogen.

Due consideration should also be given to the non-renewable methods of hydrogen production, and comparisons made with the approach described here. These aspects will be covered in a further article.

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