Advancing Hydrogen:

Learning from 19 plans to advance hydrogen from across the globe

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ABBREVIATIONS

ATR	auto thermal reforming
BEV	battery electric vehicle
CAPEX	Capital Expenditure
CCGT	combined cycle gas turbine power stations
CHP	combined heat and power
CCS	carbon capture and storage
CCUS	carbon capture, use and storage – variant of CCS where carbon dioxide is used to produce other substances (e.g. synthetic methane)
EU	European Union
FCV	fuel cell vehicle – sometimes referred to as fuel cell electric vehicle (FCEV)
gge	gallon gasoline equivalent
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
kW	kilowatt
kWh	kilowatt hour
LNG	liquified natural gas
MW	megawatt
Nm^3	normal cubic metre a measure of gas output, where the word normal refers to the standard conditions for that context; typically in the case of gas flow measurement these are a temperature of 0°C and a pressure of 1.01325 bar
NoE	North of England
OPEX	Operating Expenditure
p	pence
PEM	polymer electrolyte membranes – a form of water electrolysis used to produce hydrogen
PV	photovoltaic
TWh	terawatt hour
SMR	steam methane reformation – a process used to produce hydrogen, commonly using natural gas
UK	United Kingdom
USA	United States of America
Wh/L	Watt-hour per litre
ZEV	zero-emission vehicle

EXCHANGE RATES USED IN THIS REPORT

Unless otherwise stated, foreign currencies in this report have been converted to Australian dollars using Reserve Bank of Australia (2019) exchange rates. Specific exchange rate values for the 12 months to March 2019 are provided below.

Foreign Currency	**Value (A$1=)**
Chinese Renminbi (RMB)	4.900
Euro (€)	0.6298
Norwegian Krone (NOK)[1]	6.090
Japanese yen (¥)	80.83
South Korean won (KRW)	809.25
United Kingdom pound sterling (£)	0.5563
United States dollar (US)	0.7283

[1] Spot price rather than past year average.

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EXECUTIVE SUMMARY

This report summarises 19 hydrogen strategies and industry roadmaps (including the EU's broader decarbonisation strategy) and is written with a view to helping people understand how nations, regions and industries are thinking about opportunities to become involved in this emerging industry. Its prime purpose is to act as a resource to assist those involved in the development of other hydrogen strategies and roadmaps.

Hydrogen has attracted significant attention as a future fuel because, when used, it does not increase greenhouse gas emissions. Hydrogen also offers a new way to store energy, generate heat, drive engines and create electricity. In recognition of these opportunities nations, regions and even cities have developed hydrogen strategies with the goal of using hydrogen as part of the decarbonisation of their economy. Various interest groups have also published industry roadmaps to promote the development of hydrogen technologies and their potential to lower greenhouse gas emissions.

The purpose of this report is not to assess the relative merits of the various strategies summarised. Nonetheless, the approaches that standout seem to have common features, namely

- The clear identification of strategic goals and the setting of targets for progress;
- Attention to the removal of barriers to progress;
- A focus on where the country's or region's comparative advantage lies in terms of hydrogen;
- Careful consideration of transitional logics and the sequencing of investments; and
- Ensuring that the scale of activities and resourcing is commensurate with strategies goals and targets.

Surprisingly, each of the strategies and roadmaps examined seem to have been developed in isolation from one another. There is little sense of collaboration or of the effects of one strategy on another having been taken into account.

Collectively, however, the strategies suggest that these efforts could lead to large scale and rapid deployment of hydrogen technologies from around 2030 onwards. In the period, between now and then the focus must be expected to remain on testing and developing technologies, and on ensuring that other enablers for the deployment of hydrogen are in place.

The key take-away findings from 19 international hydrogen strategies and roadmaps summarised are

1. There is considerable international interest in rapidly deploying hydrogen technologies over the next several decades in order to reduce carbon emissions, which could give rise to export opportunities for countries with a comparative advantage in producing hydrogen.

2. There is considerable uncertainty regarding how quickly hydrogen and competing technologies will develop in terms of their effectiveness and cost-efficiency. Such uncertainty needs to be taken into account in formulating a strategy, either by taking a technological neutral or flexible approach, or not overcommitting down particular pathways.

3. Hydrogen strategies should ideally be built upon areas of comparative advantage in terms of production and use.

4. Hydrogen strategies should also reflect the broader international environment, for example by drawing on hydrogen strategies in other countries.

5. The logistics of the transition to hydrogen should be a core focus of the strategy.

6. The scale of activities should reflect the scale of the transition being targeted.

7. Access to low cost, low GHG intensity electricity is likely to be critical to the potential for a hydrogen export trade into the medium term, and for the potential of hydrogen to make a meaningful contribution to domestic GHG reductions. Availability of suitable geological features for CCS is also likely to be an important cost driver.

8. International collaboration on standards for technology is potentially important not just for those countries that have comparative advantages in the development of the technology but also for potential users of the technologies developed.

9. International collaboration is also likely to be necessary on ways to measure and certify the GHG intensity of hydrogen supplies for end users.

Driving factors in strategy design and development

A major motivating factor behind most hydrogen strategies is the need to deliver aggressive carbon reductions by mid-century as part of the Paris Agreement to limit the increase in global average temperature to well below 2°C above pre-industrial levels.

The International Energy Agency (2019)(IEA) notes that hydrogen has experienced periods of policy focus before in the 1970s, 1990s and early 2000s which subsequently faded, but believes that fundamental conditions are much more supportive of a substantial role for hydrogen in the global energy system. Key reasons identified by the IEA include the ability of hydrogen to support deep carbon abatement by assisting in abatement in those sectors where abatement with non-carbon electricity has so far proved difficult; hydrogen's ability to contribute to the achievement of other policy objectives such as improving urban air quality and increasing energy security; hydrogen's ability to act as a store of renewable energy; and the ability of hydrogen to learn from the experience of renewable energy technologies in rapidly moving down the cost curve.

In recognition of this reality, many governments are looking to provide a supportive policy environment for hydrogen and related technologies, assist in the search for ways to overcome cost barriers and to help scale up production and create demand.

Another major factor driving some strategies is a desire to encourage the development and commercialisation of specific hydrogen technologies and associated industries as part of the search of new sources of economic growth and to ensure existing sectors remain globally competitive. Those who can develop and scale-up hydrogen technologies quickly may gain an early mover advantage including access to patents.

Other factors that motivate hydrogen strategies include a strategic goal to promote national and regional energy security by diversifying existing energy supply chains and facilitating the domestic expansion of renewable energy, and improving urban air quality by replacing fossil fuel-based transport and industrial activities with hydrogen alternatives.

At the heart of various strategies is a desire to gain a comparative advantage by focusing on particular technologies or sectors, and scaling up production and demand in order to reduce the cost of hydrogen technologies relative to existing carbon-intensive technologies. Others are focusing on existing areas of comparative advantage, such as automotive manufacturing, and a desire to keep this advantage should, for example, fuel cells come to play a significant role in the transport sector. A search for ways to reduce reliance on foreign technology and imports is also a specific feature of some strategies.

A major consideration for national strategies is how hydrogen will be produced, transported and stored, including the degree to which hydrogen can be sourced from domestic versus foreign sources, and whether hydrogen should be exported. This is a key deciding factor. The choice of whether or not to produce or, at least in the early stages, import hydrogen is a factor that can be used to classify strategies. Some countries are planning to import most of their hydrogen while others, for now, are focusing on seeking to become a significant exporter.

Some aspiring exporters think that they have a comparative advantage in hydrogen production because they have ready access to fossil fuels that can be converted to hydrogen and/or are already producing hydrogen from industrial by-products, while others have surplus renewable energy. Several of the strategies identify the further development of carbon capture and storage as a key consideration and a way for them to produce low or zero-carbon hydrogen from fossil fuels.

Production strategies

The main methods of hydrogen production being considered include:

- steam methane reforming (SMR);
- coal gasification;
- water electrolysis; and
- biomass gasification (biogas).

SMR and coal gasification are proven technologies but need to be combined with carbon capture and storage (and technologies that eliminate or at least minimise fugitive emissions associated with the production of the gas or coal that serves as the feedstock) if they are to provide a source of low or zero carbon hydrogen. Water electrolysis is an attractive option since it can be powered by renewable energy to provide a zero-carbon source of hydrogen. Although the costs of water electrolysis have declined significantly over recent years, data presented in the strategies suggest that the costs of water electrolysis are currently two to four times higher than steam methane reforming which represents a significant barrier to adoption. Figure E.1 maps out the future production pathways for hydrogen targeted in the various strategies. There is interest, also, in the development of other less well known methods of hydrogen production.

Figure E.1: Identified Production Technologies for Hydrogen by Regional Strategies

CURRENT PRODUCTION METHODS

- Steam methane reforming (i.e. natural gas reformation) without carbon capture and storage (CCS)
- Industrial by-product gasses and coke oven gases
- Coal gasification

FUTURE PRODUCTION PATHWAYS

	Industrial by-product and coke oven gases	SMR (generally with CCS)	Water electrolysis	Overseas renewables	Overseas fossil fuels (generally with CCS)
Brunei		✓			
China	✓		✓		
EU (Hydrogen Roadmap Europe)	✓	✓	✓		
EU (Decarbonisation strategy)[c]		✓	✓		
France		✓	✓		
Germany			✓		
Japan			✓	✓	✓
Netherlands		✓	✓		
Northern Netherlands		✓	✓		
Norway			✓		
Republic of Korea	✓	✓	✓	✓	✓
United Kingdom		✓	✓		
UK - Leeds (gas network)		✓			
UK - London		✓	✓		
UK – Northern England		✓			
United States of America			✓		
USA - California		✓			

Note: the Hydrogen Council and International Energy Agency roadmaps were not included in this as they are more global in nature.

Regardless of the method of production, all strategies and roadmaps predict a significant reduction in the cost of hydrogen over the next decade as production methods are scaled up and demand for hydrogen and its derivatives is nurtured. The South Korean and Japanese strategies, for example, anticipate cost reductions of 60% to 80% being realised over the next one to two decades. The general impression is that hydrogen technologies will become price competitive (i.e. approach commercialisation) beyond 2030.

Role of hydrogen in decarbonisation

Strategies and roadmaps generally identify five broad areas where hydrogen can be used to facilitate decarbonisation

- in existing gas networks where hydrogen can be mixed with natural gas as a way to lower greenhouse gas emissions from existing uses;
- in industry as an industrial feedstock and a source of heat;
- in transport, particularly in the medium to longer term;

- in homes and buildings as an energy source for space heating, water heating and cooking; and
- in energy production as an effective way to store surplus renewable energy.

The variations in end uses for hydrogen identified in the strategies are summarised in Table E.1, with more detailed descriptions of the potential end uses following the table.

Figure E.2: Key End-uses for Hydrogen Identified in Strategies

	<20% hydrogen in existing gas distribution and transmission pipelines[a]	100% hydrogen in existing gas distribution and transmission pipelines[a]	Long-term store of energy	Industrial heat	Industrial feedstock	Electricity generation	Household heating	Combined heat and power generators	Manufacture of fuel cell vehicles	Use of H2 for heavy vehicle transport	Use of H2 for small passenger vehicles	Hydrogen production for export
Brunei												✓✓
China					✓					✓✓	✓✓	✓✓
European Union (Hydrogen Roadmap Europe)	✓[b]	✓✓[b]	✓	✓✓	✓✓	✓	✓✓	✓✓		✓		
European Union (Decarbonisation strategy)[c]	✓[c]	✓✓[c]	✓	✓✓[c]	✓✓	✓	✓✓[c]			✓✓	✓	
France	✓				✓✓					✓✓	✓	
Germany (power-to-gas)		✓✓[d]					✓✓	✓✓				
Hydrogen Council	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
International Energy Agency	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
Japan	✓	✓	✓			✓	✓	✓✓	✓✓	✓✓	✓✓	
Netherlands	✓✓	✓✓				✓	✓			✓	✓	
Northern Netherlands	✓✓	✓✓	✓	✓	✓✓	✓	✓✓			✓	✓	
Norway										✓✓	✓✓	✓✓
Republic of Korea		✓✓		✓	✓			✓✓	✓✓	✓✓	✓✓	
United Kingdom	✓	✓✓		✓✓	✓		✓✓			✓✓	✓	
UK - Leeds (gas network)	✓	✓✓	✓				✓✓			✓	✓	
UK - London		✓					✓	✓✓		✓✓	✓✓	
UK – Northern England	✓	✓✓	✓	✓		✓	✓✓	✓				
United States of America						✓✓				✓✓	✓✓	
California			✓							✓✓	✓	

Notes: ✓✓ = primary use case assumed in strategy; ✓ = secondary use case assumed in strategy. These assessments of relative focus are necessarily subjective and reflect the focus of policy as outlined in the strategy document(s).

(a) Hydrogen concentration by volume rather than by energy.

(b) The targeted approach is to blend to 5 to 15% by volume up to 2030, with transmission to a full H_2 gas network between 2030 and 2050.

(c) Hydrogen (or 'e-fuels' derived from green hydrogen and 0 net GHG emission sources of carbon) only has a substantial role in 'high hydrogen' and 'e-fuel' scenarios. In other scenarios hydrogen would not be used in the gas distribution network, with the gas distribution network shut down and energy transmission (and localised uses derived from it such as industrial heat and household heating) fully electrified. In these other scenarios, the role for hydrogen would be focussed on industrial feedstock and transportation (particularly heavy transport).

(d) As synthetic methane or other 'e-fuels' derived from green hydrogen and zero net GHG sources of carbon.

Hydrogen as an industrial feedstock and heat source

Hydrogen is currently used as a feedstock for a number of industrial processes but is mostly produced from fossil fuel sources. Substituting low or zero-carbon hydrogen for fossil fuel-based hydrogen offers one method of reducing carbon emissions produced by industry. Other potential industrial uses for hydrogen include as an alternative to natural gas for low-temperature heat and electricity and combining it with carbon produced from industrial by-products to produce synthetic methane.

At present, technological uncertainty and cost advantages enjoyed by fossil fuels are major barriers to adopting hydrogen in industry, which is highly sensitive to cost increases given exposure to international competitive pressures. Countries are consequently taking a cautious approach on balance, although France has identified industry as the initial focus for its strategy given it is the main source of existing hydrogen demand and, therefore, offers the best hope for exploiting economies of scale in the short term.

Hydrogen for transport and mobility

Some countries and motor vehicle companies have adopted aggressive plans to phase out the sale of fossil fuel-powered cars in order to drive carbon abatement within the transportation sector. Generally, a mixture of battery electric and fuel-cell electric vehicles is being proposed to replace fossil fuel passenger cars. Many of the strategies observe that battery-powered cars will have an advantage over hydrogen-powered fuel-cell cars in the near future as they are being produced at greater scale leading to lower costs. In the medium term, many of the strategies expect hydrogen-powered fuel cell vehicles (FCVs) to play a much greater role due to increased production bringing down costs of ownership and due to the advantages of hydrogen in terms of faster refuelling times, greater driving ranges and relatively lower bulk and weight making it the preferred option for decarbonising heavy transport and long-distance transport.

Although the existing market for FCVs is quite small, several countries have ambitious plans to ramp up production and deployment of FCVs and hydrogen refuelling infrastructure over the next decade in order to reduce capital and operating costs. These plans are, in part, driven by industrial strategies to identify new growth areas for local automotive manufacturing sectors, and often extend to other forms of transportation, including trucks, buses, boats and trains.

Heating in homes and buildings

In some countries, heating is a major source of carbon emissions and a major decarbonisation challenge given the sheer scale of energy demand for heating, large daily and seasonal variations in demand (particularly in colder climates) which necessitates flexible and scalable heating solutions, and the existing supply flexibility and cost advantages enjoyed by fossil fuels. The partial or complete replacement of natural gas with hydrogen has emerged as an attractive option due to its ability to leverage existing infrastructure. Challenges associated with this option include the technical suitability of existing distribution systems to carry hydrogen (due to the risks of embrittlement), the need for hydrogen appliances, the high costs associated with current hydrogen production methods, and regulatory barriers preventing the use of hydrogen. As a result, a range of feasibility studies and demonstration projects have been commissioned to investigate the technical and economic potential of different approaches. In Leeds, UK, for example, conversion of an existing distribution system to pure hydrogen system is considered to be feasible.

The role of hydrogen in energy storage and power generation

Most strategies mention renewable energy, such as wind and solar, as the preferred options for decarbonising the electricity generation sector. However, the intermittent nature of these energy sources presents a challenge in terms of balancing the energy system. Using surplus renewable energy to produce hydrogen via water electrolysis (power-to-gas) has emerged as a potential long term, large scale storage option that can enable the use of a greater proportion of renewable energy in the electricity sector. Hydrogen is seen as particularly attractive since it enables ‘sector coupling’ whereby the hydrogen produced can be used to decarbonise other sectors.

The strategies indicate that while power-to-gas is not currently economic due to the high capital cost of electrolysers and the need for sufficient surplus renewable energy, a large number of demonstration projects are being commissioned in an attempt to demonstrate the technical feasibility of this approach, improve cost efficiency and trial different business models. In some countries and regions, there is also consideration of the potential role of fuel cells to provide residential, commercial and industrial customers with on-site access to electricity. At present, the strategies indicate that the cost of such systems is still prohibitive. Nevertheless, countries such as Japan and South Korea hope to bring down costs by scaling up production and the deployment of micro-CHP systems in residential and commercial buildings. The City of Leeds is in the advanced stages of planning to convert its gas network to 100% hydrogen.

Government grants and other forms of assistance

Many national strategies are being backed by substantial government financial support in order to enable private corporations to demonstrate hydrogen technologies, test them at scale and seek ways to reduce costs. Typically, these same governments are involved, through the subsidization of infrastructure and access to end-use technologies, in seeding demand and investment in end-use technologies.

At present, total funding commitments in many of the jurisdictions are almost impossible to determine due to a lack of opacity and complexity. The scale of government investment, however, currently appears small relative to the scale of energy system transformation required – perhaps reflecting the relatively early stage of hydrogen as an affordable source of energy. California has a 10-year funding commitment of USD10 million per annum to fund the construction of an initial network of hydrogen refuelling stations for FCVs. Investments being made by governments in the United Kingdom, France and Germany, for example, range from 0.0003 to 0.004% of Gross Domestic Product. In an Australian context, these commitments would range from annual spending of A$6 to $74 million. The total investment commitment from both the public and private sectors for large scale deployment of hydrogen technologies would be substantially larger than these initial investments. Many new assistance schemes are announced regularly. The IEA (2019) estimates that the global government budget for hydrogen and fuel cell RD&D was approximately US$700 million in 2018.

Beyond subsidising hydrogen technologies and supporting demonstration projects, other major roles for government mentioned in strategies and proposed in roadmaps include:

- providing clear decarbonisation pathways for industry and sectors;
- supporting research and development to overcome existing technological barriers and reduce costs;
- providing a supportive regulatory environment, and, in particular, removing impediments from current regulatory frameworks and guidelines so that issues in relation to the technical, safety and risks of hydrogen are recognised in respect of transport, storage and use;
- helping to promote public awareness regarding the role and safety of hydrogen in order to gain community acceptance and improve safety practices;
- incorporating hydrogen into existing education and training programs and curriculums; and
- providing coordination services for project proponents.

Some concluding observations

A surprising omission from many strategies is any explicit consideration of potential changes in carbon abatement policy and how rapid progress in the development of competing technological developments could impact existing hydrogen strategies. For instance, a decision to expedite carbon abatement would necessarily increase emphasis on the reduction of emissions from processes that are difficult to decarbonise via a simple shift to renewable electricity. Examples of such challenges include industrial and domestic heat, industrial feedstock and long-distance transport. In each of these cases, a shift to the use of hydrogen is a highly prospective option. Conversely, the collapse of one or more of the multilateral agreements being used to encourage the pursuit of rapid forms of greenhouse gas abatement could reduce the demand for low carbon technologies, in which case investment in hydrogen could be abandoned. Either way, we consider that all national strategies should be considered indicative and readers should expect significant revisions to occur.

The list of strategy uncertainties includes

- uncertainty about how quickly costs for hydrogen technologies will decline;
- uncertainty regarding whether key technologies will prove reliable or feasible at scale;
- uncertainty about how the effectiveness and efficiency of competing technologies may evolve; and
- uncertainty about the extent to which governments will seek to reduce greenhouse gas emissions and how quickly they will seek to do this.

One method of dealing with these uncertainties is to take a technology-neutral approach so that “all options are kept on the table.” An example here would be the setting of a national limit on aggregate emissions and leaving market-like processes to decide, for example, whether or not to invest in battery or fuel cell technologies. Another example in terms of hydrogen production is the United Kingdom’s Hydrogen Supply Programme which is trialling several approaches to the bulk supply of low carbon hydrogen in the hope that this will produce the most cost-effective solution.

Another broad observation that can be made is that regional strategies, such as those for the Northern Netherlands, Leeds, and California tend to be more specific and may be more readily implementable, given their ability to focus on specific local advantages and remove constraints to the development of a local hydrogen sector.

As a general rule, national-level strategies tend to be more aspirational and less focused. Arguably and in an ideal world, one would find regional strategies written in a manner that adds detail to a national strategy. In a number of cases, however, it appears that regional strategies are being developed in advance of a national strategy in a manner that may make the development of a national strategy easier.

Finally, although some strategies are formed on the search for a competitive advantage, international cooperation will be required to establish international standards and facilitate the development of international hydrogen supply chains. At this stage, national strategies seem to be relatively silent on the development of international appliance standards, etc. Early cooperation in this arena could assist with progress. Appropriate transportation and distribution infrastructure will need to be developed (e.g. liquid hydrogen storage, liquid hydrogen carriers, hydrogen pipelines and import terminals).

The potential success of these supply chains, and hydrogen technologies more generally, will be maximised by international collaboration and the sharing of knowledge. Indeed, the International Energy Agency recommends that hydrogen research, development and demonstration projects featuring international cooperation should be promoted in order to maximise the efficiency of funding.

SUMMARY ABSTRACTS

A summary of each of the strategies and roadmaps examined is included in the appendix to this report. To assist with the early appreciation of their content, each summary's abstract is presented below.

A. Brunei Darussalam

Brunei does not appear to have an overt hydrogen strategy but is seeking to be well positioned to supply hydrogen initially to Japan.

A white paper issued by the Energy Department in 2014 only makes a small reference to pioneering new fuel technologies including hydrogen:

> *"A variety of efficient end-use technologies and alternative fuels have been proposed to address energy-related environmental or supply security challenges in fuel use. Recently, hydrogen have received increased attention world wide because it offers a long term potential to radically reduce several important societal impacts of fuel."*

Brunei's main effort in developing a local hydrogen industry is its role in Japan's Global Hydrogen Supply Chain Demonstration Project – a world-first project that involves producing hydrogen from natural gas in Brunei, which will then be transported to Japan. In effect, Brunei is one of the initial beneficiaries of Japan's current hydrogen strategy, a major part of which involves developing international hydrogen supply chains.

B. China

China's hydrogen strategy is currently centred on developing an entire fuel cell technology and vehicle industry chain, including supply infrastructure. Government policy in terms of maintaining global competitiveness in automotive manufacturing is the main driving factor, while the need to mitigate climate change and improve urban air quality are also imperatives. It is expected that hydrogen will be sourced from coke oven and industrial by-product gases, and eventually from water electrolysis powered by renewable energy. Although the hydrogen FCV technology roadmap envisions certain technologies becoming commercially viable by particular milestone dates and provides unit cost targets for certain technologies, no specific unit cost estimates are provided for hydrogen production.

China appears to be ignoring opportunities to use hydrogen to manufacture steel, cement, etc., or to decarbonise urban heating.

C. European Union (Hydrogen Roadmap Europe)

The roadmap outlines an "ambitious scenario for hydrogen development in the EU" in order to contribute to the Paris Agreement aspirations for limiting global warming. It envisions generating 2,250 TWh of hydrogen within Europe by 2050 (approximately 24% of final energy demand), which compares with a business-as-usual demand scenario of 780 TWh by this date. The ambitious scenario involves deploying hydrogen technologies to decarbonise various sectors, especially the gas grid through blending and limited conversion to 100% hydrogen; transportation through adoption of fuel cells in vehicles and shipping and synthetic fuel in aviation; and in industry as a substitute for natural gas for high-grade process heat and as a feedstock in processes, either directly or with CO_2 as a synfuel or electrofuel. Given its suitability for energy storage, hydrogen is expected to play an important role in facilitating the transition to renewable energy generation, providing power balancing and buffering services, and additional generation capacity.

D. European Union (A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy)

This broader strategy is focussed on the set of scenarios that would allow the EU to achieve sufficient decarbonisation by 2050 to be consistent with a less than 2°C (and less than 1.5°C) increase in temperature from pre-industrial averages. The modelled decreases in emissions are 80%, 90% and 100% below 1990 levels. Although the strategy is one of overall emissions reductions, hydrogen and 'e-gas' (e.g. gas produced using zero-carbon energy such as synthetic methane) play an important role in many of the scenarios developed given their potential to substitute for greenhouse gas emissions in many sectors where it is considered likely that it will be difficult for electricity to do so cost effectively.

An important feature of the strategy of the effort to consider energy decarbonisation needs and approaches systemically from energy generation, through potential distribution and storage technologies, to users of the energy (and industrial feedstock).

E. France

The French national hydrogen roadmap is organised around three axes: hydrogen production by electrolysis for industry, in mobility as a complement to battery vehicles, and to assist the stabilisation of energy networks. The initial focus is on subsidising the deployment of hydrogen in industrial uses which are thought to currently have greater potential economies of scale and therefore commercial viability. Deployment will then extend to transport and energy network applications. An initial funding round of €100 million (AU$159 million) in funding has been allocated to support deployments throughout France across the three axes, and it is anticipated that should the first round be successful this will become an on-going commitment of annual €100 million funding rounds.

F. Germany

The *Power-to-gas system solution* report outlines the current state of this technology including remaining challenges. The conversion of renewable energy into hydrogen or methane (one of the few country-specific strategies to explicitly focus on synthetic hydrocarbons derived from hydrogen as well as hydrogen itself) using water electrolysis can connect renewable energy with other sectoral energy uses, including mobility, industry, heat supply and power generation. Considerable funding has been provided to support research and development in order to lower costs, improve energy efficiency and test potential business models.

G. Hydrogen Council

This report recognises the importance of hydrogen in the attainment of the goals set out in the Paris Agreement. It emphasises the role of hydrogen in power generation (grid balancing, buffering etc.), transport and mobility sector (FCEVs), industrial systems (hydrogen as feedstock) and application of hydrogen in the residential and commercial sectors (heating).

The report recommends the development of

- long-term and stable policy frameworks to guide the energy transition in all sectors
- incentive policies and increased coordination among sectors
- the harmonization of industry standards across regions and sectors to enable hydrogen technologies and take advantage of scale effects and decrease costs.

H. International Energy Agency

This roadmap and its 2019 update provides an exhaustive discussion of the nature, function and cost of key hydrogen technologies. It also identifies applications where hydrogen can offer maximum value-added. The roadmap takes a short term and long-term perspective on actions that are required to develop and deploy hydrogen technologies while taking into consideration global energy and climate goals. The roadmap also intends to promote stakeholder understanding of the business opportunities offered by hydrogen and the synergies they offer in existing energy systems.

This roadmap covers hydrogen-based solutions for both energy supply and demand. Within energy demand sectors, the roadmap covers transport, fuel cell micro co-generation in the residential sector and selected applications in the refining, steel and chemical industries. Within the supply sector, the roadmap covers variable renewable energy (VRE) integration and energy storage, comprising power-to-power, power-to-gas and power-to-fuel. The roadmap also covers hydrogen infrastructure such as transmission and distribution, storage and retail technologies. In addition, the roadmap also takes into consideration the main hydrogen generation and conversion technologies such as electrolysers and fuel cells. Recommendations in the update stress the importance of making the most of existing industrial ports to turn them into hubs for lower-cost; lower-carbon hydrogen; use existing gas infrastructure to spur new clean hydrogen supplies; support transport fleets, freight and corridors to make fuel-cell vehicles more competitive; and establish the first shipping routes to kick-start the international hydrogen trade.

I. Japan

Japan has developed a comprehensive strategy to guide the public and private sectors, with the ultimate goal being to "become the first country in the world to realize a hydrogen-based society" (MCREHRI 2017). The national strategy is multifaceted, involving strategies to develop international hydrogen supply chains, promote hydrogen adoption in power generation, transportation, heating and industrial processes, promote hydrogen technologies overseas, with the effect of promoting and enhancing the competitiveness of Japanese hydrogen and fuel cell technologies. The main thrust is to increase the cost competitiveness of hydrogen with existing energy sources by increasing economies of scale and overcoming technological barriers.

J. Netherlands

A need to reduce carbon emissions as part of the Paris Agreement and the adoption of hydrogen initiatives at the regional and international levels has encouraged the Netherlands to develop a national hydrogen strategy. The Netherlands has the potential to use its large wind energy to produce hydrogen. Much work needs to be done in respect of the development of technology, regulations, the market for hydrogen and government policies to enable the Netherlands to transition to a hydrogen economy.

K. Northern Netherlands

The Northern Netherlands is currently one of the largest conventional natural gas producing regions in Europe because of the Groningen/Slochteren gas field. However, gradual depletion of the gas field together with negative externalities from current production such as subsidence and earthquakes, and the current commitments to meeting the Paris Agreement targets has led to the region identifying hydrogen as an important future driver of the regional economy.

Comparative advantages in moving to hydrogen production (for local use within the Netherlands and export into Europe) include substantial local gas transmission infrastructure; strong local skills in chemical engineering and the gas industry; and a substantial local renewal energy resource which is beginning to produce more output than the local electricity transmission infrastructure can handle.

L. Norway

Norway does not presently have an explicit, comprehensive strategy for developing hydrogen infrastructure and related industries. Although an advisory body – the Norwegian Hydrogen Council – was established by the Ministry of Petroleum and Energy in the early 2000s and delivered two hydrogen action plans (the most recent being for 2012-2015), it appears there was not complete follow-through by authorities. Efforts to date have consequently been piecemeal, but more advanced than most other countries, with early efforts to demonstrate hydrogen technologies in automotive vehicles and shipping.

More recently, policy measures to promote adoption of zero-emission vehicles and a new programme to support the deployment of hydrogen stations have been introduced to promote the use of hydrogen-powered vehicles, while funding support has been provided to develop hydrogen-powered shipping.

Norway's considerable natural gas and renewable energy resources can be utilised to produce hydrogen on a large scale, and the country is currently participating in a Japanese pilot project that will produce hydrogen using renewable energy.

M. Republic of Korea

On 17th January 2019 South Korean President Moon Jae-in outlined a vision for developing a hydrogen-based economy. The core elements of the plan include:

- increasing production and adoption of hydrogen fuel cell vehicles;
- increasing production and adoption of fuel cells for power generation, and for use as combined heat and power plants for residential use; and
- building a hydrogen production and distribution system.

The strategy involves providing incentives and subsidies to increase volume and achieve economies of scale on both the supply and demand sides in order to lower production costs, accelerate the self-proliferation of hydrogen technologies, and increase exports.

N. United Kingdom

The United Kingdom industrial and clean growth strategies seek to maximise the economic and social benefits to the UK from transitioning to a clean-energy economy and to achieve this transition at the lowest possible net cost to UK society. "Low carbon" hydrogen has been identified as a potential clean technology that can decarbonise the industry, heat and transport sectors. Research and demonstration projects are being funded under a range of programs covering these sectors in order to enable learning and development and overcome cost disadvantages relative to existing carbon-intensive technologies. It is currently expected that the main form of hydrogen production will be Steam Methane Reforming of natural gas with carbon capture, usage and storage.

O. Leeds, United Kingdom

The H21 Leeds Citygate Project is a proposal to convert the existing natural gas network in Leeds to 100% hydrogen.

A detailed technical and economic study has determined that the project is feasible.

The finalised conversion area comprises 264,000 meter points, representing approximately 660,000 people.

The strategy involves producing hydrogen using Steam Methane Reformers using natural gas; sequestration of carbon emissions under the North Sea; salt cavern hydrogen storage to meet inter-seasonal and intraday demands; a hydrogen transmission system to connect the SMRs and salt caverns to the distribution network; and appliance conversion for the domestic, commercial and industrial sectors.

The combination of SMRs and carbon capture and storage (CCS) would provide a 73% reduction in carbon emissions.

P. London, United Kingdom

The three main objectives of the report were to:

- show how hydrogen and fuel cell technologies can help solve London's challenges in terms of population growth and environment;
- provide evidence to support the case for continued investment in hydrogen fuel cell technology by public and private sector organisations in the transport, transportable and stationary sectors; and
- to spread awareness about these hydrogen technologies to persons and stakeholders who are not familiar with the sector.

London considers itself a leader in deploying zero-emission hydrogen and fuel cell technologies in urban operation. London has achieved a presence in harnessing benefits using hydrogen technology as demonstrated by establishing 3 hydrogen stations; operation of multiple fuel cell vehicles (8 buses, 15 vehicles from global OEMs, and 10 hydrogen-diesel vans); 3 large-scale fuel cell combined heat & power plants (largest number in one European city with a combined total capacity of 1MW); and sale of hundreds of unsubsidised portable power units.

Q. North of England, United Kingdom

The H21 North of England (NoE) strategy is in many ways a large-scale extension of the Leeds specific strategy summarised above. The H21 NoE Project is 13 times larger in terms of energy and 14 times larger in terms of meter points than the H21 Leeds project. The H21 NoE focuses on the development of the engineering solutions necessary to enable conversion of the existing gas networks across the North of England to hydrogen between 2028 and 2034. In so doing, the project would decarbonise 14% of the UK heat and 17% of all domestic gas meter connections in the UK. The project also has the potential to be the world's (to date) largest Greenhouse Gas Reduction reduction project. Fully implemented, a reduction of 12.5 Mtpa in CO_2 emissions would be achieved. H21 NoE also lays down the blueprint for decarbonising 70% of all UK meter points by 2050 via a six-phase hydrogen roll out strategy. H21 NoE's goal is to transition to a 100% sustainable and global hydrogen economy by 2100.

R. United States of America (Hydrogen and Fuel Cells Program Plan)

The U.S. hydrogen strategy is formulated on the basis of reducing greenhouse gas emissions through increased use of hydrogen and fuel cells. The U.S. has identified stationary power and transportation as the two most important sectors where the use of fuel cells and hydrogen can be applied. It has a long-running hydrogen and fuel cells program which seeks to improve the cost efficiency and effectiveness of fuel cell and hydrogen production technologies.

S. California, USA

California has a strong policy commitment towards climate change issues and intends to source 100% of its energy from renewable sources by 2045. Transportation is the largest source of greenhouse gas emissions in California. Excess energy from the state's abundant wind and solar energy resources can be used to produce hydrogen, which can, in turn, be used to power fuel-cell vehicles. This approach to decarbonising transport can help California reach its clean energy targets without leaving a carbon footprint. The Californian Government sees its current role as supporting infrastructure development which would currently not be commercially viable given the early stage of market development.

Contents

LEARNING FROM OTHER HYDROGEN STRATEGIES AND ROADMAPS

1 INTRODUCTION

The Council of Australian Governments (COAG) is in the process of developing a National Hydrogen Strategy. It is anticipated that this Strategy will highlight the opportunities that hydrogen represents for Australia in the development of a hydrogen export industry coupled with the role of hydrogen in mobility, in domestic gas networks, in providing heat to industry and in supporting electricity generation. The development of the regulatory and other arrangements necessary to allow the use of hydrogen gas within Australia may also become part of the proposed strategy. It is anticipated that the final Strategy will be formally approved in December 2019 following a process of engagement and consultation. This document has been prepared with a view to assisting those involved in the development of this strategy as well as supporting those engaged in broader energy policy development.

Over recent years many countries, states and even cities have developed hydrogen strategies while various interest groups have developed industry roadmaps which fulfil a similar role. Some recent national strategies have been backed by investment commitments in order to demonstrate hydrogen technologies, test them at scale, or support their growth to the point where market forces can sustain them. And there is a high degree of optimism that the costs of hydrogen supply and related technologies can be reduced over the next several decades, enabling a hydrogen economy to emerge.

These existing overseas strategies and initiatives provide an opportunity for Australia to learn from and understand the foundations upon which other strategies are being built and where returns are likely to be greatest. Gaining such an understanding will reduce the scope for misjudgement at a time when intentional and international arrangements for the production, trade and use of hydrogen are rapidly changing.

In light of the above, the Future Fuels Cooperation Research Centre (CRC) has commissioned the SA Centre for Economic Studies and Centre for Global Food and Resources at the University of Adelaide to undertake a review of official national strategies and industry roadmaps in order to understand and summarise the logic that underpins the development of each strategy. This information will, in turn, act as an information resource for the development of the National Hydrogen Strategy.

The specific objectives of the research project are to:

- Produce a short summary of each strategy and roadmap with a focus on the elements of greatest relevance to Australia;
- Identify the concepts, drivers, assumptions and insights that led to the development of each strategy and roadmap;
- With a focus on but not limited to the production of hydrogen and means for its use, identify a set of lessons and principles that those responsible for the development of COAG's National Hydrogen Strategy should take into account; and
- Identify opportunities to benefit from planned investments being made in other countries.

It is important to note that the current review is not exhaustive as it was undertaken in a compressed timeframe in order to inform the development of the National Hydrogen Strategy. Moreover, the review has generally been restricted to the analysis of key policy documents that specifically relate to hydrogen strategies, supplemented on occasion by reference to other relevant documents and articles. In some cases, the analysis is based on secondary documents including unofficial translations. As such the summaries in this report would benefit from further analysis and review. This is especially so as policy support for hydrogen technologies may be driven by various national policies and strategies, especially those related to energy security and affordability, industry development, and environmental sustainability and pollution prevention, which in turn can make it difficult to unravel the full scope of a nation's hydrogen policy.

Furthermore, while efforts have been made to identify data relating to the cost-effectiveness of particular forms of hydrogen production and associated technologies, no attempt has been made to undertake a thorough assessment of the relative cost-effectiveness and energy efficiency of such technologies as this is beyond the scope of the research task.

In identifying relevant strategies and roadmaps particular attention was paid to those strategies that have or are being developed in several European and Scandinavian countries, the United Kingdom, Japan, Korea and China. Prominent regional initiatives being developed by states like California and cities like Leeds and London are summarised. Although Brunei and Norway do not have existing or current national strategies *per se*, they were included due to notable hydrogen initiatives being recently implemented in these countries.

The remainder of the report is organised as follows. Section two provides a synthesis of the key themes, insights and underlying fundamentals that emerged from the analysis of strategies and roadmaps considered in this report. Each of these individual strategies and roadmaps is in turn summarised in the appendices (in alphabetical order by country, with regional strategies appearing after the national strategy, if any, for their country). Section three provides a brief conclusion, highlighting key takeaways from the analysis of strategies, which are also emphasised in section four which highlights the key implications for stakeholders. Finally, section five identifies the potential for future work.

2 SYNTHESIS OF STRATEGIES AND ROADMAPS

Driving factors

There are several distinct factors which motivate the development of national hydrogen strategies. Policy makers are often motivated by a combination of these factors, which in turn influences the style of strategy that is pursued.

The IEA (2019) notes that hydrogen has experienced periods of policy focus before in the 1970s, 1990s and early 2000s which subsequently faded, but believes that fundamental conditions are much more supportive of a substantial role for hydrogen in the global energy system. Key reasons identified by the IEA include the ability of hydrogen to support deep carbon abatement by assisting in abatement in those sectors where abatement with non-carbon electricity has so far proved difficult; hydrogen's ability to contribute to the achievement of other policy objectives such as improving urban air quality and increasing energy security; hydrogen's ability to act as a store of renewable energy; and the ability of hydrogen to learn from the experience of renewable energy technologies in rapidly moving down the cost curve.

Aggressive carbon abatement at least cost

A common motivating factor, especially for high-income economies, are ambitious carbon abatement commitments that have been made as part of the Paris Agreement to limit the increase in global average temperature to well below 2°C above pre-industrial levels, particularly the commitments for 2030 to 2050. Many countries in Europe have committed to reducing greenhouse gas emissions by 80% of 1990 levels by 2050. Some countries propose to go even further. Norway has a conditional target of carbon neutrality by 2030, while recent legislation proposed by the French and UK governments would commit their countries to carbon neutrality by 2050.

Across the majority of strategies, the additional opportunities hydrogen provides for reducing GHG emissions outside of electricity generation are a key reason for the renewed focus on hydrogen and zero net carbon synthetic fuels derived from it. Overall, hydrogen appears to be seen along with electricity produced from a renewable source, as the best source of energy and heat for a low or zero-carbon economy. The problem – addressed via each strategy – is the fact that production techniques that use renewable energy such as hydrolysis are not yet price competitive. Without significant progress in the development of hydrogen technologies, however, there is a sense that it might not be politically feasible to deliver the 2050 Paris target.

Carbon abatement efforts to date have focused on the easiest and most cost-effective pathways e.g. improving energy standards and increasing solar and wind power generation. In order to meet longer-term carbon abatement targets, existing and new low carbon technologies, processes and systems will need to be developed and deployed at scale. The strategies examined suggest that these solutions need to not only work as well as existing technologies but that they also need to be as cheap as possible so that future carbon abatement efforts (i.e. the transition to a low carbon economy) are achieved at the lowest possible cost to society. That is, hydrogen is seen as a way of decreasing the cost and increasing the net benefits of carbon abatement.

Hydrogen has been identified as a promising future low carbon technology given that it produces no greenhouse gas emissions when burned with oxygen, and can be used as an energy carrier to store, transport and use various renewable and low carbon fossil energy sources. It can potentially be deployed to decarbonise industry, transport and heating for homes and buildings – several areas which currently present significant carbon abatement challenges. Hydrogen can also accommodate the expected rapid growth of intermittent renewable energy by providing long term, large scale storage (i.e. balancing and buffering services), particularly for those economies where there is a substantial differential in energy demand between seasons.

In order to encourage the development of hydrogen as a potential carbon abatement solution, governments are choosing to subsidise hydrogen technologies so that they can compete with fossil-fuel based technologies, and to achieve economies of scale through increasing demand faster than would occur through the operation of markets in order to reduce costs. Reducing costs across the whole hydrogen energy supply system – from production to transportation and storage and distribution – and a suite of end-user hydrogen technologies (e.g. fuel cell vehicles, combined heat and power fuel cell systems) is a fundamental aim of most strategies. In addition, governments are helping to remove barriers to hydrogen adoption by seeking to eliminate regulatory obstacles, assuring public safety, and funding research and development in order to overcome existing technical barriers.

Industrial strategy to grow exports, maintain competitiveness

A number of strategies are designed to encourage the development and commercialisation of specific hydrogen technologies and associated industries as part of the search for new sources of economic growth and to ensure that existing sectors remain globally competitive.

Typically, these strategies focus on scaling up hydrogen technologies in order to reduce costs which will enable firms to export hydrogen technologies and services. Such opportunities will naturally be greatest for those who can scale up the quickest, securing a first-mover advantage and access to patents. Hence countries such as South Korea, Japan and China have ambitious goals for ramping up the production of fuel cell vehicles (FCVs) and related technologies, while Japan has a comprehensive strategy to become the world's first "hydrogen-based society". It is notable that these strategies also build on existing national comparative advantages.

A desire to remain competitive and not fall behind other countries appears to be motivating some policy makers. Some strategies (e.g. France, South Korea) observe that global competition has intensified within the hydrogen space over recent years. As industrial sectors are highly globalised there is a risk that local firms and industries will become marginalised if they are unable to maintain technological progress and cost competitiveness with their overseas competitors. In this sense, the adoption of a hydrogen industrial strategy represents a defensive measure.

Export opportunities are not restricted to those countries who are seeking to grow domestic manufacturing capability by developing and commercialising hydrogen ***technologies***. Countries such as Japan and South Korea do not expect to be able to meet their future hydrogen fuel needs from domestic sources alone. This will provide opportunities for energy-rich countries to export hydrogen where it can be produced from renewable energy or even fossil fuel resources in a low carbon manner (e.g. by using carbon capture and storage).

Although the existing hydrogen economy is relatively small, there is a high degree of optimism regarding how quickly and large the potential export opportunities may arise. Hydrogen Europe (2019) estimates that the net export potential associated with its ambitious scenario for hydrogen deployment in the European Union could be as high as A$79 billion by 2030. It needs to be stressed also that hydrogen is already used in the chemical industry and, hence, there is considerable understanding about what is required to produce it.

Enhancing energy security

Countries such as Japan and South Korea rely on imports of fossil fuels for more than 90% of their primary energy needs. Such high dependence presents a security of supply risk and exposes these economies to volatility in global resource prices. For such countries, hydrogen can play a potential role in promoting national or even regional energy security.

The strategies show that there are two broad means by which hydrogen can promote energy security. Firstly, since hydrogen is an energy carrier that can be produced from various renewable and non-renewable energy sources, it can be used to diversify existing energy supply chains, both within countries and across borders. Secondly, it can improve energy self-sufficiency by facilitating the domestic expansion of renewable energy. Using surplus renewable energy to produce hydrogen through electrolysis (power-to-gas) enables long-term and large-scale energy storage, and therefore the means to redress imbalances in renewable energy demand and supply. The resulting hydrogen can be injected into the natural gas grid or used in transport or industry, displacing existing fossil fuel usage. It can also be used in fuel cells or combusted in gas turbines to generate electricity.

Reducing air pollution

Reducing air pollution and improving urban air quality is also a motivating factor for adopting hydrogen technologies, especially FCVs, in places such as China, South Korea and London. Air pollution from fossil fuel-based urban traffic and in some cases industrial activities and power generation negatively impacts urban amenity and public health. Battery electric vehicles and FCVs are expected to make a significant contribution to improving urban air quality. For example, South Korea estimates that the volume of particulate emissions could be reduced by up to 10% from current levels if its goal for the deployment of FCVs by 2030 is met.

Energy storage

One of the barriers to wider adoption of variable renewable energy technologies such as solar PV and wind power is the potential mismatch between electricity generation from renewables and energy demand. Whilst hydrogen’s ability to address this is only infrequently cited in country or region level strategies this has been identified as a potentially significant end-use in the international strategies developed by the EU (2018 and 2019) and the IEA (2019), with this end-use seen as particularly significant in colder northern regions where there is a significantly higher demand for stationary energy in winter than in summer (informal discussions with the IEA suggest that in some countries winter demand is six times higher than summer demand).

Exit from nuclear energy

Although not explicitly stated, in some countries the challenge of achieving carbon abatement and hence need to identify alternative low carbon energy sources has been compounded by moves to reduce dependence on nuclear energy amidst safety concerns following the Fukushima Daiichi nuclear disaster. Germany is scheduled to shut down its remaining nuclear reactors by 2022, while France recently announced plans to retire 14 reactors by 2035. Although Japan’s nuclear fleet was taken off-line for safety inspections following the Fukushima accident, reactors have been progressively restarted over recent years. Conceptually, hydrogen offers a means to replace electricity from nuclear sources but, as the production pathway relies on the use of surplus electricity to produce hydrogen which is in turn used to reproduce electricity during times of high demand, the case for including hydrogen in a denuclearisation strategy is weak unless it is expected that time variations between renewable energy generation and energy demand mean that there will be periods of very low-cost electricity.

2.1 Formulation of strategies

In developing hydrogen strategies there are a number of broad themes that are typically observed in the more effective strategies:

- what are the economy's comparative advantages with respect to hydrogen, and how can they be enhanced and maintained;
- identifying the key end-use cases for hydrogen;
- what infrastructure or policy changes are required to support the targeted role for hydrogen; and
- how will required hydrogen volumes will be sourced.

In considering these questions issues such as existing and future sources of energy, areas of comparative advantage and the relative cost-efficiency of competing technologies and/or overseas competitors are taken into account.

There are also several gaps that are apparent in the majority of the strategies, namely:

- Few of the strategies have clearly defined goals for the role of hydrogen in decarbonisation, perhaps reflecting technological and cost uncertainty;
- Strategies/roadmaps do not typically reflect the planned activities in other countries, missing opportunities for synergies and cooperation;
- The resources currently being committed (outside of R&D) are typically small relative to the ambitions of the strategies; and
- Few strategies have started to grapple with the logistics of the transition to hydrogen in the targeted sectors.

Comparative advantage and demand

At the heart of various strategies is a desire to gain a comparative advantage by focusing on the development of particular technologies or sectors, and scaling up production and demand in order to reduce the cost of hydrogen technologies relative to existing carbon-intensive technologies and competitors.

Existing areas of comparative advantage, and a desire to preserve these advantages going forward, often inform strategies that are motivated by industrial development goals. Hence, for countries with large automotive manufacturing industries such as South Korea, Japan, China and France, development of local manufacturing capability in respect of FCVs, and ambitious roll-out scenarios for FCVs, can together be seen as measures to ensure that local sectors do not fall behind competitors in the event these technologies take off. For countries without such manufacturing capabilities (which now includes Australia in the case of passenger cars), such imperatives are naturally less compelling.

Comparative advantage can also be seen more broadly, for example, California's population is currently heavily dependent on small passage vehicles, particularly some of its areas of highest comparative advantages such as IT where the key employers are often located in areas of low population density. Therefore in California's case maintaining its existing comparative advantages in a decarbonising economy relies on alternatives to internal combustion engines becoming cost-competitive, leading to a focus on the infrastructure needed to support FCVs.

Reducing reliance on foreign technology and imports is also a specific feature of some strategies. China's plan to develop an entire fuel cell vehicle technology and industry chain directly flows from its Made in China initiative to reduce reliance on foreign technology imports and climb up the global manufacturing value chain. Similarly, South Korea hopes to localise alkaline and polymer electrolysis parts, all parts of fuel cells for power generation, and hydrogen gas turbine technology.

As mentioned previously, reducing costs across the whole hydrogen industry chain is critical to enabling the adoption of hydrogen technologies. To the extent that multiple demands for hydrogen can be nurtured this will help to reduce unit costs through economies of scale effects.

Holistic approach

As hydrogen technologies are still in their infancy, strategies often take a holistic approach in terms of recognising that the whole hydrogen industry supply chain will need to be developed in order to facilitate end-use technologies. This includes not only how hydrogen will be produced, transported and stored, but also any other supportive infrastructure that will be needed to facilitate adoption (e.g. hydrogen refuelling infrastructure for FCVs, household appliances in respect of hydrogen substituting for natural gas in existing gas networks, refurbishment or replacement of transmission and distribution networks).

Key uses

Key uses for hydrogen generally focus on areas where hydrogen can be deployed to facilitate decarbonisation of energy systems, with a particular emphasis on those areas of decarbonisation where it is difficult to directly substitute electricity generated from zero-carbon sources. These applications include heat (both household and industrial), transport, industrial feedstocks, and energy storage to smooth differences between zero-carbon electricity and electricity demand. Potential applications are discussed in more detail in section 2.4 – sectoral developments.

Sources of hydrogen

A key consideration for hydrogen strategies is how the fuel will be sourced, including whether it will be produced locally and/or purchased from overseas. The answer will depend on various factors, including the potential to increase existing sources of hydrogen production which are concentrated in industrial applications; whether existing primary energy supplies that could be used to produce hydrogen are sourced domestically or from abroad; and the relative cost of potential domestic and international sources of hydrogen production.

Countries such as Japan and South Korea recognise that domestic sources will be insufficient to meet their expected future needs. These strategies consequently place a significant focus on developing international supply chains and associated transport and storage technologies in order to realise this vision. For example, Japan aims to develop a liquefied hydrogen supply chain by the mid-2020s, an organic hydride supply chain soon thereafter and has already commissioned demonstration projects in Australia, Brunei and Norway.

Energy mix

A country's energy mix in terms of the balance of primary energy sources – e.g. coal, natural gas, hydro, nuclear, solar and wind – that are used to satisfy energy demands has an important bearing on the formulation of strategies, in a couple of ways. Firstly, it influences the direction of decarbonisation efforts. For instance, power generation in Norway is based almost exclusively on hydropower, which means the country must focus on other areas such as transportation in order to achieve carbon abatement targets. Secondly, the energy mix influences decisions on production methods and sourcing. Thus countries with large natural gas and coal resources may look to combine these energy sources with carbon capture and storage in order to produce hydrogen, while countries with large or rapidly growing renewable penetration are interested in hydrogen as a means to provide large scale, long term storage for surplus renewable energy and are more focused on 'green' hydrogen production technologies.

Uncertainty

As hydrogen technologies are still somewhat in their infancy and have a long way to go before reaching cost parity with existing technologies, there remains a high degree of uncertainty regarding how quickly costs will fall, whether certain approaches will prove practical and can be scaled up successfully, and how competing technologies will affect uptake. Some strategies deal with such uncertainty by taking a cautious or even technological neutral approach. For example, the United

Kingdom's Hydrogen Supply Programme seeks to trial various approaches to supplying low carbon hydrogen in bulk in order to identify which approaches are most effective and least costly.

Uncertainties also exist in terms of long-term cost curves for various renewable energy technologies, and this could have a significant impact on the extent to which countries import hydrogen or generate it domestically.

2.2 Hydrogen production

Production methods

Table 1 summarises the current and future production pathways for hydrogen as envisioned by a selection of national strategies and roadmaps.

Hydrogen is currently mainly produced by reforming natural gas (also known as steam methane reforming or SMR), through coal gasification, and as a by-product of existing industrial processes such as the chlor-alkali process used to produce chlorine and caustic soda. Production using water electrolysis is very limited at present.

For countries with large industrial sectors (e.g. China, Japan), hydrogen can be produced as a by-product from other industrial processes in order to meet short term needs. However, industrial by-product hydrogen sources will be insufficient for those countries without large industrial bases. Even for those countries with relevant industrial production by-products will not generate sufficient hydrogen to meet the longer-term demands associated with ambitious hydrogen uptake scenarios. Other sources of cost-effective production at large scale will, therefore, be required. The main methods of production being considered in the strategies and roadmaps include:

- steam methane reforming (SMR) with CCS or CCUS;
- coal gasification with CCS or CCUS;
- water electrolysis; and
- biomass gasification (biogas).

SMR and coal gasification are proven technologies but need to be combined with CCS if they are to provide a low or zero carbon source of energy. Water electrolysis is an attractive option since it can be powered by renewable energy to provide a zero-carbon source of hydrogen. It is capable of meeting small scale production needs and is a promising pathway for those countries who are considering power-to-gas as a solution for storing surplus renewable energy. Although the costs of water electrolysis have declined significantly over recent years, the capital cost of electrolysers remains relatively high and a barrier to adoption (see next section). Biomass gasification generally attracts less attention in strategies, but is a potential option for large scale centralised production, with costs sitting somewhere between fossil fuel sources and electrolysis (Staffell et al 2019).

Adoption of particular production pathways will depend on the relative efficacy and cost efficiency of these production approaches, and how these attributes evolve over time. Most strategies anticipate that multiple production technologies will eventually be used, with different production methods entering commercialisation over different time periods. Generally speaking, steam methane reforming with CCS and coal gasification with CCS is expected to be deployed first due to current cost advantages, while water electrolysis using renewable energies is assumed to become competitive in the longer term.

Some nations are taking a technologically neutral approach to the identification of the most appropriate future production sources. That it, they are undertaking work (i.e. demonstration projects) in order to understand the costs associated with different approaches and the improvements that will need to be realised in order to reach commercial viability. For example, the UK is testing various bulk production methods under the Hydrogen Supply Programme, including biomass and electrolysis powered by nuclear energy. Meanwhile, Japan is exploring various production sources in respect of international supply chains including coal gasification (Australia), water electrolysis (Norway) and natural gas (Brunei).

Figure 1: Expected Production Technologies for Hydrogen

CURRENT PRODUCTION METHODS

- steam methane reforming (i.e. natural gas reformation) without carbon capture and storage (CCS)
- industrial by-product gasses and coke oven gases
- coal gasification

FUTURE PRODUCTION PATHWAYS

	Industrial by-product and coke oven gases	SMR (generally with CCS)	Water electrolysis	Overseas renewables	Overseas fossil fuels (generally with CCS)
Brunei		✓			
China	✓		✓		
EU (Hydrogen Roadmap Europe)	✓	✓	✓		
EU (Decarbonisation strategy)[c]		✓	✓		
France		✓	✓		
Germany			✓		
Hydrogen Council		✓	✓		
Japan			✓	✓	✓
Netherlands		✓	✓		
Northern Netherlands		✓	✓		
Norway			✓		
Republic of Korea	✓	✓	✓	✓	✓
United Kingdom		✓	✓		
UK - Leeds (gas network)		✓			
UK - London		✓	✓		
UK – Northern England		✓			
United States of America			✓		
USA - California		✓			

Note: the Hydrogen Council and International Energy Agency roadmaps were not included in this as they are more global in nature.

Cost of hydrogen production

The costs of hydrogen production into the future will be largely driven by trends in the capital cost of the conversion equipment and the cost of electricity (particularly the availability of extremely low-cost electricity even if only at particular times of day), and the utilisation rate of electrolysis systems. In the case of hydrogen extracted from fossil fuels the costs of the feedstock and the cost of CCS and the availability of suitable geological features for CCS will also be significant factors in the trajectory of hydrogen costs.

Notwithstanding variability across regions due to location-specific factors, cost estimates presented in the various strategies indicate that the costs of water electrolysis are currently two to four times higher than steam methane reforming. Data from the UK indicates that the cost of production using electrolysis is around four times the wholesale natural gas price – i.e. the current direct market competitor for hydrogen technologies – while the cost for SMR is approximately double the natural gas price. Specific current cost estimates include:

- UK Hydrogen Supply Program – £0.79 to £1.97 per kg for producing hydrogen using SMR of natural gas, £1.57 to £3.54 per kg for electrolysis, which compares with a wholesale price for natural gas of £0.15 to £0.31 per kg.[2]
- Renewable Hydrogen Roadmap for California – the levelized cost of production is estimated to be A$21.2 per kg for electrolysis using solar photovoltaic (PV) power, A$11.0 for electrolysis using solar PV and grid electricity, A$4.0 for biogas to hydrogen using SMR, and A$3.0 for reforming natural gas without carbon capture (these costs exclude storage and delivery costs).
- French Hydrogen Development Plan – for largescale industrial customers hydrogen derived from fossil fuels, such as reforming natural gas, is currently estimated to be A$2.4 to 4.0 per kg, while costs using electrolysis are estimated to range from A$6.4 to 9.5 per kg.
- Hydrogen Economy Roadmap of Korea – A$1.9 to 2.5 per kg for hydrogen derived as a product from industrial sources, A$3.3 to 6.3 per kg for natural gas extraction, and A$11.1 to 12.4 per kg for water electrolysis.
- Outlines of a Hydrogen Map for the Netherlands – A$1.6 to 2.4 per kg for centralised large scale production from natural gas using SMR, A$6.3 to 7.9 per kg for small-scale onsite SMR production by 2020, and a current cost of A$7.9 to 8.7 per kg for alkaline electrolysis and A$9.5 to 10.3 per kg for PEM electrolysis.

It is important to note that these costs estimates typically do not include compression, transport and storage costs which can be significant, especially over large distances. For instance, in the case of the Netherlands the total price of compressed hydrogen delivered to the refuelling station was estimated to be as high as A$7.9 per kg, which is well above the production cost for centralised large scale production using SMR and in-line with small-scale onsite SMR production (Gigler and Weeda, 2018). The large costs associated with transportation and storage may encourage on-site production of hydrogen as a more cost-effective solution.

The cost of hydrogen is expected to fall significantly over the next decade as bulk production is ramped up and demand nurtured. The South Korean and Japanese strategies anticipate cost reductions of 60 to 80% being realised over the next one to two decades. The general impression is that hydrogen technologies will become price competitive (i.e. approach commercialisation) beyond 2030. For example, France anticipates that electrolysis of water using renewable energies could be competitive by 2035, while Japan will expand demand and supply-side measures after 2030 in order to try to reduce the cost of hydrogen to a level competitive with traditional energy sources.

At a global level, the most recent production cost estimates are prepared by the IEA (2019) based on assumptions derived from European trends.[3] Point estimates are not provided, and so cost estimates have been read off the graph with associated potential for error, however, the estimated costs by production method converted to Australian dollar terms are:

- Electrolysis, grid electricity, median cost A$ 6.6/kg H_2 (sensitivity range A$ 4.5 to A$ 8.9)
- Electrolysis, renewable electricity, median cost A$ 3.8/kg H_2 (sensitivity range A$ 2.7 to A$ 5.5)
- Natural gas SMR without CCUS, median cost A$ 3.2/kg H_2 (sensitivity range A$ 2.1 to A$ 4.3)
- Natural gas SMR with CCUS, median cost A$ 3.4/kg H_2 (sensitivity range A$ 2.3 to A$ 4.4)

[2] Prices reported in the UK Hydrogen Supply Program are reported in pence per k/Wh equivalent; these have been converted to a price per kg of gas to facilitate comparison with the other estimates listed. Conversion used the conversion factors reported in Speirs, J., P. Balcombe, E. Johnson, J. Martin, N. Brandon and A. Hawkes (2017), 'A Greener Gas Grid: What are the Options?', Sustainable Gas Institute, Imperial College London, White Paper Series, July 2017; which was the original source of the cost estimates in the UK Hydrogen Supply Program. These were 1 kWh equivalent = 0.0254 kg of H_2 and 0.0649 kg methane.

[3] Key assumtions are a WACC of 8%, renewable energy cost of USD 40/MWh, 4,000 full load hours per year, GHG price of USD 40/t of CO_2-e, with sensitivity of USD 0/t of CO_2-e and USD 100/t of CO_2-e.

- Coal, without CCUS, median A$ 3.7/kg H_2 (sensitivity range A$ 2.1 to A$ 5.5)
- Coal, with CCUS, median A$ 3.4/kg H_2 (sensitivity range A$ 2.3 to A$ 4.5)

Specific cost projections and goals contained in the regional strategies include (but are not limited to):

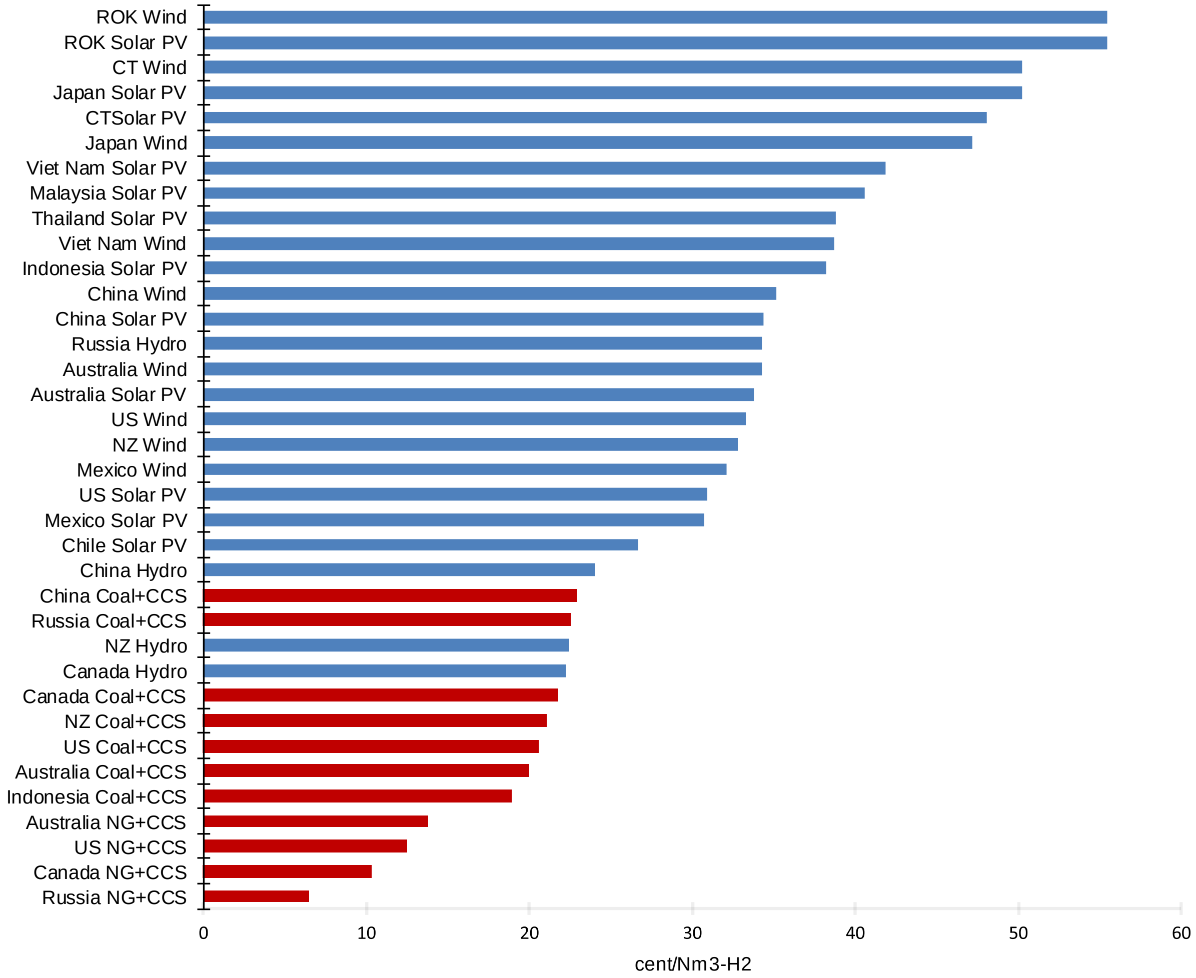
- French Hydrogen Development Plan – the cost of decarbonised hydrogen for transport distribution should reach a cost of A$11.1 per kg by 2030, a level comparable to energy for diesel vehicles. In terms of industrial production, the costs of water electrolysis are estimated to fall from a current level of A$6.4 to 9.5 per kg to A$3.2 to 4.8 by 2028, which is comparable to the current cost for large industrial customers that extract hydrogen from fossil fuels (A$2.4 to 4.0 per kg).
- Hydrogen Economy Roadmap of Korea – the production ramp-up targets should enable the unit price of hydrogen to fall from a current level of A$9.9 per kg to A$7.4 per kg by 2022, and down to A$3.7 by 2040.
- Basic Hydrogen Strategy for Japan – increased procurement should reduce the plant delivery cost from around 100 yen per Nm^3 to around 30 yen per Nm^3 by 2030 (from A$13.8 to A$4.1 per kg). Further scaling up efforts beyond this date should reduce the cost to 20 yen per Nm^3 in order to reach cost competitiveness with traditional energy sources.
- Outlines of a Hydrogen Map for the Netherlands – the cost of production using electrolysis is expected to fall from a current range of A$7.9 to 10.3 per kg depending on the production method (alkaline or PEM), to A$4.8 to 5.6 per kg by 2030 for on-site production at the MW scale.

It is not clear to what extent the differences in these regional projections from the IEA's projections reflect differences in timing or expected regional input cost differences.

Going beyond hydrogen strategies and roadmaps, the Asia Pacific Energy Research Centre (2018) recently estimated the future cost of carbon-free hydrogen production under alternative production approaches for APEC economies as part of a scenario analysis – see Figure 2. Based on a range of assumptions outlined in the report, production costs were estimated to range from US 7 cents per Nm^3 to 55 cents per Nm^3. Production costs using fossil fuels (7 to 23 cents per Nm^3) were generally lower than renewable energy approaches (22 to 55 cents per Nm^3), with hydroelectric power generation approaching the performance of fossil fuels.

Most significantly, Australia is estimated to have some of the lowest potential production costs with coal and natural gas using CCS. The study concludes that countries with abundant fossil fuel and renewable energy resources, including Australia, can potentially become hydrogen-exporting countries. While there is considered to be significant hydrogen production potential within APEC countries, a lack of demand for hydrogen is a major limiting factor at present.

Figure 2: Production Cost Estimates of Carbon Free Hydrogen in the APEC Region in 2030



Note: ROK = Republic of Korea; CT = Chinese Taipei; NZ = New Zealand. Red denotes hydrogen derived from fossil sources, blue from renewable sources. Costs are in US currency.
Source: Asia Pacific Energy Research Centre (2018), Perspectives on Hydrogen in the APEC Region.

2.3 Sectoral developments

Strategies and roadmaps generally identify four broad areas where hydrogen may be deployed to facilitate decarbonisation:

- industry as a feedstock and heat source;
- heat for homes and buildings;
- transport and mobility applications through the development of fuel cell vehicles (FCVs); and
- power generation and storage, particularly in terms of integrating higher levels of variable renewables into the electricity system.

The variations in end-use for hydrogen identified in the strategies are summarised in Figure 3, with more detailed descriptions of the potential end uses following the table.

Figure 3: Key End-uses for Hydrogen Identified in Strategies

	<20% hydrogen in existing gas distribution and transmission pipelines[a]	100% hydrogen in existing gas distribution and transmission pipelines[a]	Long-term store of energy	Industrial heat	Industrial feedstock	Electricity generation	Household heating	Combined heat and power generators	Manufacture of fuel cell vehicles	Use of H2 for heavy vehicle transport	Use of H2 for small passenger vehicles	Hydrogen production for export
Brunei												✓✓
China					✓					✓✓	✓✓	✓✓
European Union (Hydrogen Roadmap Europe)	✓[b]	✓✓[b]	✓	✓✓	✓✓	✓	✓✓	✓✓		✓		
European Union (Decarbonisation strategy)[c]	✓[c]	✓✓[c]	✓	✓✓[c]	✓✓	✓	✓✓[c]			✓✓	✓	
France	✓				✓✓					✓✓	✓	
Germany (power-to-gas)		✓✓[d]					✓✓	✓✓				
Hydrogen Council	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
International Energy Agency	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
Japan	✓	✓	✓			✓	✓	✓✓	✓✓	✓✓	✓✓	
Netherlands	✓✓	✓✓				✓	✓			✓	✓	
Northern Netherlands	✓✓	✓✓	✓	✓	✓✓	✓	✓✓			✓	✓	
Norway										✓✓	✓✓	✓✓
Republic of Korea		✓✓		✓	✓			✓✓	✓✓	✓✓	✓✓	
United Kingdom	✓	✓✓		✓✓	✓		✓✓			✓✓	✓	
UK - Leeds (gas network)	✓	✓✓	✓				✓✓			✓	✓	
UK - London		✓					✓	✓✓		✓✓	✓✓	
UK – Northern England	✓	✓✓	✓	✓		✓	✓✓	✓				
United States of America						✓✓				✓✓	✓✓	
California			✓							✓✓	✓	

Notes: ✓✓ = primary use case assumed in strategy; ✓ = secondary use case assumed in strategy. These assessments of relative focus are necessarily subjective and reflect the focus of policy as outlined in the strategy document(s).

(a) hydrogen concentration by volume rather than by energy.

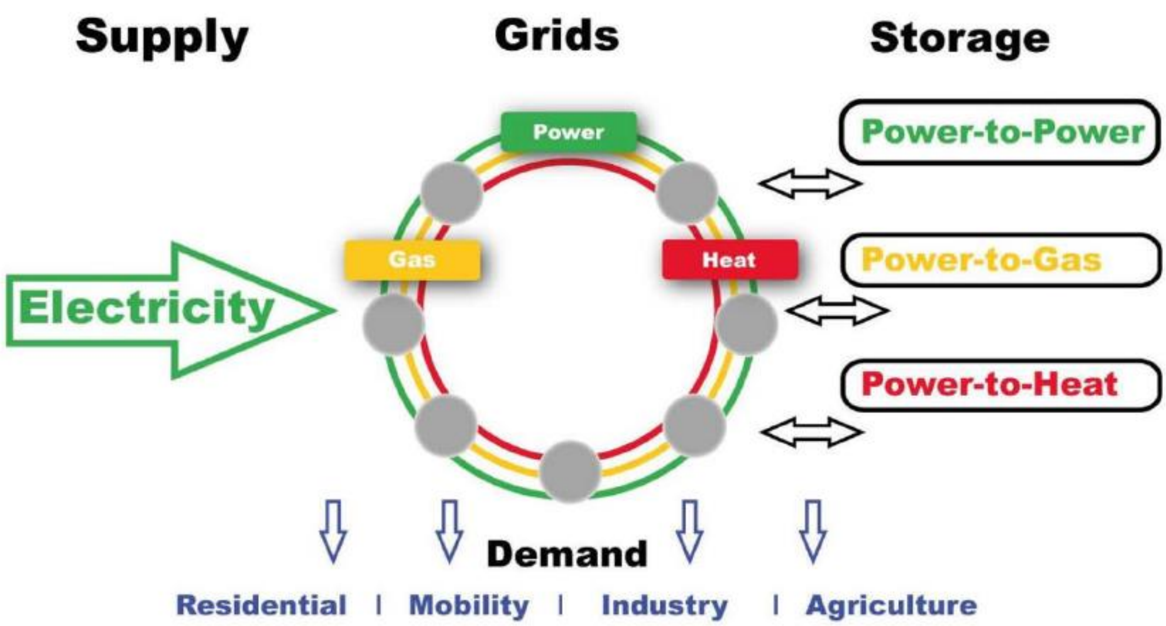
(b) Targeted approach is blended to 5 to 15% by volume up to 2030, with transmission to a full H_2 gas network between 2030 and 2050.

(c) Hydrogen (or 'e-fuels' derived from green hydrogen and 0 net GHG emission sources of carbon) only has a substantial role in 'high hydrogen' and 'e-fuel' scenarios. In other scenarios hydrogen would not be used in the gas distribution network, with the gas distribution network shut down and energy transmission (and localised uses derived from it such as industrial heat and household heating) fully electrified. In these other scenarios, the role for hydrogen would be focussed on industrial feedstock and transportation (particularly heavy transport).

(d) As synthetic methane or other 'e-fuels' derived from green hydrogen and 0 net GHG sources of carbon.

These sectoral applications are discussed briefly in turn below, however, there are also strategies that seek to consider potential sectoral implications jointly to take advantage of synergies. This is an important focus of the European Union's strategy for a climate neutral economy (European Union 2018). This strategy seeks to consider the various approaches that could be taken to supplying, distributing, storing and using energy in a consolidated way in order to develop realistic decarbonisation pathways that could be implemented in the European Union to achieve 2050 greenhouse gas emission reductions consistent with less than 2°C or less than 1.5°C increases in global temperatures compared to pre-industrial levels. Rather than starting from specific technologies or use cases, the strategy seeks to set out how emissions are currently generated in the EU economy and map out, albeit in a very high-level way, the various portfolios of technologies and behavioural changes that could deliver the targeted levels of greenhouse gas reductions whilst maintaining economic growth. So, for example, hydrogen (and other gases created using zero-carbon electricity) are considered as distribution systems, ways of storing energy, and ways of satisfying energy (and feedstock) demands of key sectors, see Figure 4.

Figure 4: Inter-relationship of energy flows in a decarbonised economy



Source: European Union 2018, p. 66.

Industry

Hydrogen is currently used as a feedstock for a number of industrial processes, including but not limited to, the manufacture of ammonia, petroleum refining, and methanol production. There is also limited use of hydrogen in other industrial processes including other chemicals manufacturing, iron and steel making, and glassmaking. Almost all of the hydrogen used in these industrial processes is derived from fossil fuel sources such as steam methane reforming. Substituting low or zero-carbon hydrogen for existing fossil fuel derived hydrogen consequently offers one pathway for achieving carbon abatement in the industry sector.

There are other potential novel uses for hydrogen in industrial processes – e.g. direct reduced iron steelmaking – however, these uses are still at the pilot stage and need feasibility testing.

The other main potential application for hydrogen in industry is as an alternative to natural gas for high and low-temperature heat. Hydrogen may be used as a fuel source for boilers and furnaces, although replacement may be required, especially if high or hydrogen only fuel sources will be used.[4] Carbon dioxide, which is sometimes produced as a by-product of industrial processes (e.g. cement making), could be combined with hydrogen to produce synthetic methane, which can then substitute for natural gas used in existing industrial processes or elsewhere.

The strategies recognise that technological uncertainty and the current cost advantages enjoyed by fossil fuels are currently major barriers to adopting hydrogen in industrial applications. The industrial sector is generally highly exposed to international competitive pressures and is therefore sensitive to any factors that raise input costs. Hydrogen Europe (2019) observes that hydrogen technologies will probably need to reach a price level that is in line with the price of natural gas including carbon externalities in order to facilitate adoption. Given these pressures and the uncertainties associated

4 Toyota has recently developed a general-purpose hydrogen burner for industrial use, which could potentially replace existing natural gas burners.

with implementing new hydrogen technologies, nations are generally taking a cautious approach to exploring potential industrial applications and ways of reducing costs.

Nonetheless, the industrial sector has been selected as the initial focus for France's hydrogen strategy as it is effectively the only source of existing hydrogen demand and therefore has the greatest potential for exploiting economies of scale in the short term. The French plan seeks to overcome existing cost barriers by subsidising the acquisition of electrolysers. It also plans to establish a 'traceability system' so that the carbon abatement achieved by using hydrogen produced from renewables energies can be recognised. Meanwhile, the UK has established an Industrial Fuel Switching program to explore the potential for industries to switch to low carbon fuels such as hydrogen, biomass and clean electricity.

Heating

Heating of homes and buildings (including hot water) is a major source of carbon emissions in many countries. In the UK, for example, nearly 70% of heat for homes, business and industry is derived from natural gas. In order to meet aggressive carbon abatements goals by mid-century, almost all heating in buildings will need to be decarbonised. However, progress to date has been slow due to several factors including the sheer scale of energy demand for heating; large daily and seasonal variations in heat demand which requires flexible heating solutions; and the existing scale, cost and supply flexibility advantages that are currently enjoyed by fossil fuels such as natural gas (Staffell *et al.* 2019).

Beyond reducing demand for heat by increasing energy efficiency, the main options for decarbonising heat include direct electrification, replacing natural gas with low or zero-carbon alternatives, and district heating (heat networks). While direct electrification using heat pumps may be the preferred option in some circumstances – e.g. new buildings and high-density buildings in more temperate climates – partially or completely replacing natural gas with hydrogen in existing gas networks emerging as an attractive option due to its ability to leverage existing infrastructure (including avoiding retrofitting existing buildings where existing appliances can continue to be used with partial hydrogen blending).[5]

As high concentrations or high-pressure transportation of hydrogen can cause embrittlement of metal pipes, the partial blending of hydrogen is generally the preferred approach as it reduces the need to reconvert or replace existing network infrastructure. Existing infrastructure can generally accommodate concentrations of up to 5 to 15% of hydrogen by volume, although Germany hopes to raise the maximum limit to 20% in the long term. The exact allowable threshold will depend on a range of local factors including the technical specifications of existing pipeline infrastructure, connected appliances, and the presence of industrial users who may have lower hydrogen tolerances (Hydrogen Europe, 2019).

Complete conversion of gas networks to 100% hydrogen is also being seriously considered in some jurisdictions. For example, the H21 Leeds Citygate Project in the UK involves converting an existing natural gas network that serves approximately 660,000 people to pure hydrogen. In this case, an existing mains replacement program means that much of the existing distribution network is suitable for hydrogen. The project, which has been found to be feasible, involves producing hydrogen using SMR with CCS under the North Sea, salt cavern storage to meet inter-seasonal and intraday demands; a hydrogen transmission system to connect production, storage and distribution infrastructure; and appliance conversion for domestic, commercial and industrial customers. One current challenge is the need for hydrogen appliances, which is an undeveloped market. Of a total capital cost for the project estimated to be £2,054 million (A$3,692 million), appliance conversion accounted for 51% of the cost.

5 A third option to partial or complete conversion to hydrogen would be to use hydrogen to produce synthetic methane as a substitute for natural gas, but this may be an unnecessary extra step (cost) if hydrogen can be directly injected into the gas network.

Steam methane reforming of natural gas and water electrolysis are the main hydrogen production methods being considered for natural gas substitution, with electrolysis being less economical at present. Nonetheless, the enthusiasm for using hydrogen produced from electrolysis has been encouraged by the development of power-to-gas as a solution to integrating higher levels of renewable energy into the electric power system, particularly in European countries. Existing gas networks are a readymade large scale storage option for hydrogen produced from this source. However, if the availability of curtailed electricity from renewable sources is limited, this will raise the cost of hydrogen production.

A range of feasibility studies and demonstration projects have been commissioned to investigate the technical and economic potential of different approaches for incorporating hydrogen into existing gas networks. The UK has commissioned a Hydrogen to Heat programme to investigate the feasibility of using hydrogen gas for heating homes and buildings, while a detailed engineering solution – H21 North of England – has been developed to convert 3.7 million homes and businesses across the north of England from natural gas to hydrogen. In France, the GRHYD project is demonstrating the injection of hydrogen into the natural gas network of Le Petit village, while Jupiter 1000 is a power-to-gas project with a 1MWe power rating that will use electrolysis to produce hydrogen that will, in turn, be directly injected into the grid, and/or combined with carbon captured from a nearby industrial site to produce synthetic methane.

Finally, existing technical and commercial regulations may need to be modified in order to enable injection of hydrogen into the gas network as hydrogen may not be recognised as an approved fuel. Such regulatory issues may arise across the production, transmission, distribution and storage stages.

Mobility

Transport is a major source of carbon emissions in industrialised economies (e.g. about one third in the EU). Some countries have adopted aggressive plans to phase out fossil fuel cars in order to drive carbon abatement within the sector. Norway plans to ban the sale of new fossil fuel-based cars and light vans by 2025, while France and the United Kingdom plan to follow suit in 2040.

Due to existing capital and operating cost advantages, battery electric vehicles (BEV) are likely to be the preferred choice to replace fossil fuel cars, particularly in the passenger car segment. However, hydrogen-powered fuel cell vehicles (FCVs) have potential advantages in terms of faster refuelling times and greater driving ranges which may make them a preferred option for certain use cases (e.g. vehicles regularly required to travel long). In addition, fuel cells may end up being a better choice for heavy vehicles such as trucks and buses where the weight and bulk of batteries are currently limiting factors to adoption. They have already enjoyed some success in niche segments, primarily forklifts.

The market for FCVs is very small at present. As of 2017 only around 7,800 hydrogen vehicles had been distributed worldwide, with deployment being concentrated in the United States, Japan, the European Union and South Korea (Government of Korea, 2019). Due to small production volumes, FCVs are relatively expensive, with the total cost of ownership estimated to be 20 to 50% higher than internal combustion engine equivalents (MEITF, 2018), while capital costs are roughly double BEV equivalents (Staffell et al, 2019). Adoption is also being curtailed by a lack of hydrogen refuelling infrastructure, which is relatively expensive to construct (and for which the current low numbers of FCVs represents a significant barrier to rollout).

Several countries have ambitious plans to ramp up the production and deployment of FCVs and associated hydrogen refuelling infrastructure in order to reduce capital and operating costs (e.g. hydrogen fuel) for FCVs – see Table 1. South Korea anticipates that increasing annual production to 100,000 vehicles will halve the price of a hydrogen car, helping reach cost parity with internal combustion cars (Government of Korea, 2019). While the FCV roll-out scenarios for South Korea, China and Japan are quite aggressive, they may end up paling in comparison to the deployment of BEVs. For example, California's goal to establish 200 hydrogen refuelling stations by 2025 compares to 250,000 vehicles charging stations by this date.[6] For this reason, some strategies initially focus on developing commercial vehicles such as light vans and taxis which may be more suited to fuel cells (e.g. commercial vehicles comprise 60% of the 5,000 target for China in 2020).

Ambitious roll-out scenarios for some countries – South Korea, China, France and Japan – are in large part driven by industrial strategies to identify new growth opportunities for their local automotive manufacturing sectors. Perhaps most notably, China plans to establish an entire fuel cell vehicle technology and industry chain in order to facilitate large scale domestic production by 2030. This strategy focuses on realising technological progress and cost reduction in a number of key areas including fuel cell stacks, fuel cell systems (engines), fuel cell vehicles, and hydrogen technology (e.g. supply infrastructure and on-board storage). China's strategy goes so far as to provide technical objectives for the development of these technologies, such as the cold start performance, rated power and lifespan for fuel cell stacks. With China throwing its weight behind these technologies there is potential for cost efficiencies being achieved in a similar vein to which the country's earlier focus on solar technologies helped bring about faster than excepted cost reductions for solar panels.

Table 1: Fuel Cell Vehicle and Hydrogen Refuelling Deployment / Production Targets

	Fuel cell vehicles			Refuelling stations		
Country	**2020**	**2025**	**2030**	**2020**	**2025**	**2030**
California				100	200	—
China	5,000	50,000	1,000,000	100	350	1,000
France		5,200[(a)]	20,800-52,000[(b)]		100[(a)]	400-1,000[(b)]
Germany					400	—
Japan	40,000	200,000	800,000	160	320	900
Norway	100% ZEV[(c)] cars and light vans by 2025					
South Korea		81,000[(d)]	1,800,000	86[(e)]	310[(d)]	
UK	100% ZEV cars by 2040			30	150	—

Notes: (a) 2023 target. (b) 2028 target. (c) zero emission vehicle. (d) 2022 target. (e) 2019 target.
Source: Staffell et al (2019), Office of Governor Edmund G. Brown Jr. (2018), Strategy Advisory Committee of the Technology Roadmap for Energy Saving and New Energy Vehicles and Society of Automotive Engineers of China (2016), Ministry for the Ecological and Inclusive Transition of France (2018), and Government of Korea, (2019).

Beyond announcing future restrictions on sales of vehicles with internal combustion engines, countries are supporting the deployment of FCVs by reducing the cost of acquiring hydrogen-powered vehicles, usually by providing direct subsidies and/or waiving existing taxes; subsidising the construction and sometimes even operation of hydrogen refuelling stations; supporting research and development; and funding or commissioning demonstration projects.

The ambitions for fuel cells in transport often extends beyond passenger vehicles to include other forms of heavy transport such as trucks, buses, boats and trains. In some cases, they include novel applications such as drones in the case of South Korea.

Power

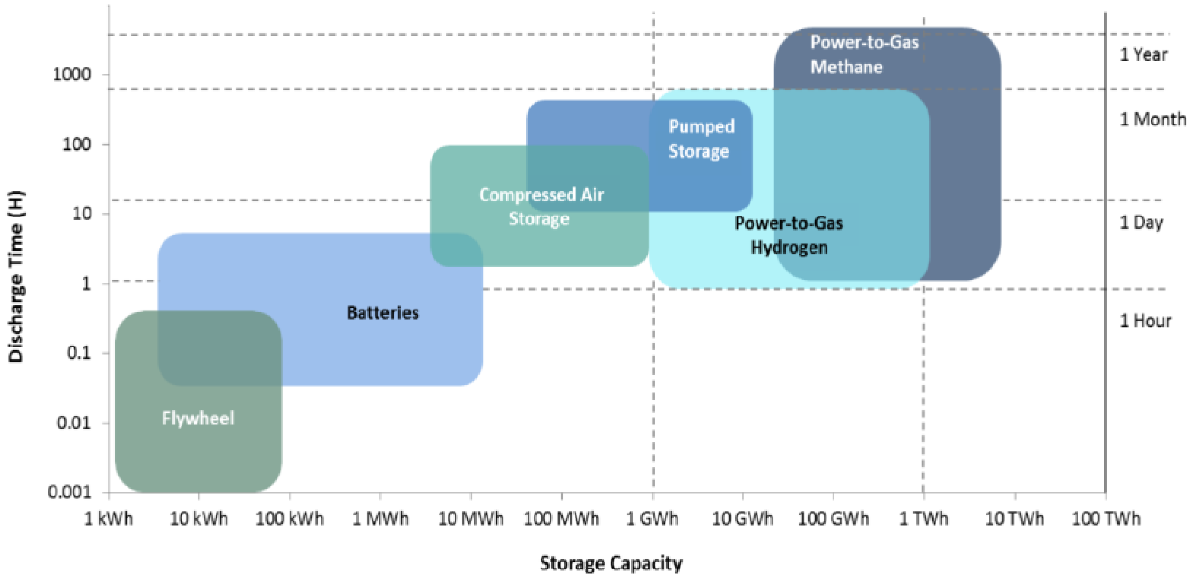
Renewable energies such as wind and solar are now the preferred options for decarbonising the electricity generation sector in many countries. However, the intermittent nature of these energy sources present challenges in terms of balancing the energy system. In some cases, renewable sources are paid to 'turn off' when supply has exceeded demand (e.g. wind farms in the United Kingdom). Such intermittency consequently presents a challenge in terms of integrating higher levels of renewable energy into the electric power system. While batteries provide a solution for short term storage, using surplus or curtailed renewable energy to produce hydrogen using water electrolysis

[6] It should be noted that an individual hydrogen stations will be able to service more vehicles compared to an equivalent sized electric charging station due to faster refuelling/recharging times.

(power-to-gas) has emerged as a potential long-term, large-scale storage option. Given the need to bring more renewable energy online, power-to-gas is a major area of interest for national hydrogen strategies and roadmaps.

The observation that hydrogen and, also, synthetic gas produced using zero-carbon electricity have a role in smoothing demand in a decarbonised grid is well illustrated in the European Union's strategy for a climate-neutral economy (see Figure 5, European Union 2018).

Figure 5: Characteristics of different energy storage technologies



Source: European Union 2018, p. 63

If production costs can be reduced, power-to-gas is particularly attractive as it potentially enables 'sector coupling' whereby the hydrogen produced can be used to decarbonise other sectors such as industry, transportation and heating. Existing gas networks provide a ready means of large scale storage while other storage options such as salt caverns and depleted gas fields can be used for meeting inter-seasonal energy needs.

Furthermore, hydrogen can potentially be transported by pipelines, ships and trucks to transfer energy from regions of high excess renewable energy supply to regions of high energy demand where existing electricity transmission infrastructure does not exist or is insufficient (Hydrogen Europe, 2019). For example, the Northern Netherlands hydrogen strategy (Northern Netherlands Innovation Board, 2017) identifies the local combination of excellent renewable energy resources (on-shore and off-shore wind) combined with significant constraints on electricity transmission infrastructure in the region that would block full exploitation of these resources as a key driver of their hydrogen strategy. Equally, Norway's exploration of a potential role as a hydrogen exporter within Japan's international supply chain is driven by the substantial hydroelectric resources available.

While power-to-gas has yet to prove to be commercially viable, a large number of demonstration projects have been commissioned in order to demonstrate the technical feasibility of this approach, improve cost efficiency and trial different business models. For instance, Germany has more than 30 power-to-gas research and demonstration projects with a combined electrolysis capacity of about 25 MW (German Energy Agency, 2019).

Fuel cells may also be used for distributed electricity generation or combined heat and power (CPH). These systems, however, have high capital costs and so far have had limited adoption to date (almost all of the world's residential fuel cells are located in Japan). Nonetheless, Japan and South Korea hope to bring down costs by scaling up the production and deployment of micro-CHP systems for residential and commercial buildings. South Korea expects that scaling up production will reduce installation and power generation costs by 65 and 50% respectively by 2040 (Government of Korea, 2019). Meanwhile, Japan is looking to promote the introduction of fuel cells for industrial and commercial customers with low heat-to-power requirement and hopes to introduce pure hydrogen fuel-cell systems by 2030 (current systems run on natural gas).

Large stationary fuel cells face similar cost barriers to becoming an economical means of direct power generation. A 2015 European study found that the levelized cost of electricity from large stationary fuel cell was approximately 40% higher compared to grid electricity (Element Energy Ltd., 2016).

The adoption of hydrogen for direct power generation will depend heavily on how competing technologies evolve. For example, a recent study on the potential for hydrogen production in the APEC region assumed there would be "no motivation" for using hydrogen for baseload power generation within a country if CCS becomes available (Asia Pacific Energy Research Centre, 2018). The reasoning here is that CCS would allow existing fossil fuels to continue to be used for power generation without going through the additional step (cost) of converting fossil fuels to hydrogen.

2.4 Role of Government

The IEA (2019) has identified four key short to medium term opportunities to drive adoption of hydrogen, all of which involve government intervention, namely:

1. Make industrial ports, which are currently the centre of much of the existing fossil fuel-based hydrogen production, the focal point of the initial shift to clean hydrogen, utilising existing hydrogen production infrastructure to produce cleaner hydrogen and supply hydrogen to ships and trucks serving the ports.
2. Build on existing natural gas infrastructure, for example introducing initially small quantities of hydrogen (perhaps 5% by volume) to provide economies of scale to clean hydrogen production.
3. Target initial use of hydrogen in the transport sector at high mileage users including fleet customers and freight, in order to deliver economies of scale which can make FCV more cost-competitive.
4. Launch international shipping routes for hydrogen drawing on experience developed in the growth of the LNG market.

National strategies and roadmaps consider various roles for government in facilitating the deployment of hydrogen to achieve carbon abatement. These roles include:

- subsiding hydrogen technologies (e.g. refuelling stations, FCVs, electrolysers), either through direct subsidies and/or exemptions from existing taxes, so that they can better compete with existing fossil fuel technologies and help stimulate demand in order to improve economies of scale.
- supporting demonstration projects in order to verify technological feasibility, reduce costs and assess potential business models.
- providing clear decarbonisation pathways for industry and sectors by setting decarbonisation targets, and mandating the use of low or zero carbon technologies (e.g. phasing out fossil fuel vehicles).
- establishing regulations and certification systems to allow the carbon intensity of hydrogen to be visible to end-users.
- supporting research and development of hydrogen technologies to overcome existing technological barriers and help drive down costs.
- providing a supportive regulatory environment, which would include relaxing any existing regulatory barriers that currently restrict introduction of hydrogen (e.g. restrictions on hydrogen insertion into gas networks, restrictions on hydrogen storage in urban environments) and providing supportive price mechanisms within industry market regulations

(e.g. modifying electricity tariffs to encourage hydrogen use, providing price incentives for storage, and providing renewable energy certificates to recognise hydrogen use).

- modifying existing regulations and guidelines so that issues in relation to the technical, safety and risks of hydrogen are recognised through the whole hydrogen industry chain from production, transport, storage and use.
- helping to promote public awareness regarding the role and safety of hydrogen in order to gain community acceptance and improve safety practices.
- incorporating hydrogen into existing education and training programs and curriculums.
- providing coordination services for project proponents.

It is generally expected that early stage funding support for hydrogen technologies will be withdrawn as the cost efficiency of these technologies improves and approaches cost party with existing technologies.

Although some national strategies are driven by industrial policy considerations in terms of improving the growth prospects of local industries, they also commit to working through international frameworks in order to contribute to international standardisation.

2.5 Scale of investment

Governments are investing significant amounts into testing hydrogen technologies, helping to reduce costs, and seeding supply and demand. However, it can be hard to establish the total funding commitments governments have made toward these efforts. Apart from a lack of published data, including in official strategies, hydrogen support comes in a range of forms including funding for research and development, funding of demonstration projects, subsidies for infrastructure and end-use technologies, tax waivers, and procurement (e.g. hydrogen buses). Sometimes these supports are delivered through general mechanisms rather than specific hydrogen initiatives (e.g. vehicle subsidies may be targeted at zero-emission vehicles including battery electric vehicles, while hydrogen research may receive funding as part of general research and development programs).

Nonetheless, some significant commitments have been made in respect of hydrogen specifically, which include:

- in the United Kingdom, total funding for the Hydrogen Supply Programme, Hydrogen for Support Programme and Hydrogen for Heat Programme amounts to A$122 million;
- California has committed funding of USD100 million annually for ten years to support the establishment of refuelling infrastructure for FCVs;
- as part of its recently announced Hydrogen Development Plan, France has committed A$159 million toward a call for projects, and may provide annual financing equal to this amount if the initial projects prove promising; and
- in Germany, the Federal Ministry of Transport and Digital Infrastructure provided A$794 million in funding support toward the interdepartmental National Innovation Programme Hydrogen and Fuel Cell Technology over the decade to 2016.

As a proportion of gross domestic product (GDP), these annual funding commitments by governments range from 0.0003 to 0.004% of GDP. If applied to Australia's nominal GDP in 2017/18 as estimated by the ABS (2018), these proportions would amount to funding ranging from A$18 to $74 million. This investment appears small relative to the scale of energy system transformation required – perhaps reflecting the relatively early stage of the technology. Total investment requirements would, of course, be larger if one includes the investment that will be needed from the private sector (and indeed has been committed into R&D), and would be larger again if large scale deployment of hydrogen technologies was pursued. For example, the investment that would be required by industry and government for Hydrogen Europe's ambitious hydrogen roll-out scenario for the European Union was estimated to be €8 billion (A$12.7 billion) per annum, which would be equivalent to around 0.05% of GDP.

3 CONCLUSION

The review of overseas strategies and roadmaps reveals strong public sector support for and interest in using hydrogen as a low carbon technology to decarbonise various sectors of the economy and integrate greater levels of renewables into the electricity supply system. This interest is driven by the need to deliver substantial carbon reductions by mid-century as part of the Paris Agreement to limit the increase in global average temperature to well below 2°C above pre-industrial levels. Governments are consequently looking to provide a supportive policy environment and help overcome existing cost barriers across the whole hydrogen economy by providing financial support to help scale up both production and demand. The strategies suggest that these efforts will lead to large scale and rapid deployment of hydrogen technologies from around 2030 onwards.

A surprising omission from many strategies is any explicit consideration toward how potential changes in policy in respect of carbon abatement and the speed of competing technological developments could impact existing hydrogen strategies. For instance, a decision to proceed with carbon abatement more rapidly could push the emphasis towards more mature technologies such as battery electric vehicles and direct electrification powered by renewables, rather than fuel cell vehicles and combined heat and power fuel cell systems. Such developments could lead to the abandonment of certain elements of existing hydrogen strategies. The main concession to this issue made by some strategies is a commitment to monitor developments and update the strategy over time.

In formulating national strategies, countries are often looking to gain a significant comparative advantage by encouraging the development of particular hydrogen technologies or sectors, which typically focus on building on existing areas of comparative advantage. Another major area of focus is how hydrogen technologies can be used to decarbonise heat, industry, transportation and power within the context of local conditions; sources of greenhouse gas emissions that can be difficult to avert with zero-carbon electricity alone. In making such considerations countries must also contemplate how hydrogen will be produced, transported and stored, including the degree to which hydrogen can be sourced from domestic versus foreign sources. The latter will depend on the potential for producing hydrogen from existing industrial sources, excess renewable energy generation, source of existing natural gas and coal resources, and the potential for carbon capture and storage.

Beyond how hydrogen will be used within the country, another major consideration is whether one should produce hydrogen for export. A key deciding factor here is whether the country has comparative advantages in producing hydrogen, which will depend on whether it has fossil fuel endowments such as natural gas and coal (and the CCS capability to enable low or zero carbon hydrogen production from these resources), and/or adequate surplus renewable electricity resources such as solar, wind or hydroelectric power. On this basis, countries with plentiful energy resources have the potential to become hydrogen exporters. In contrast, countries with limited energy resources and aggressive plans to expand hydrogen use within their country will probably need to import hydrogen. Indeed, for countries such as South Korea and Japan with limited domestic resources, developing international supply chains including transport and distribution infrastructure (e.g. liquid hydrogen storage, liquid hydrogen carriers, hydrogen pipelines and import terminals) forms an important element of their strategies. This need reflects that hydrogen technology for international transportation by sea is currently underdeveloped with there being no leading implementation cases at present (APERC, 2018). There is consequently a potential role here for would-be hydrogen producers to participate in these efforts in order to help facilitate the development of international trade in hydrogen.

Potential recipient countries have also set out indicative targets for the carbon intensity of hydrogen imports with zero GHG hydrogen imports favoured. For example, the Republic of Korea has set a target of at least 70% of its hydrogen imports having a zero GHG intensity by 2040.

Some of the strategies reach for, and find, areas where they have a comparative advantage, and make significant investment commitments to develop these strategic areas of focus. To the extent that other countries are starting from behind and lack a similar comparative advantage, they may struggle to out compete these early movers. However, this may create opportunities to free-ride on the early adopters, whereby late movers can implement the resulting technologies without incurring the upfront investment costs and commercial risks (while forgoing the potential economic benefits that could have been derived from developing patented technologies). Potential areas where free-riding may arise include:

- Fuel Cell Vehicles – plans to expand FCV production and/or deployment are in some cases driven by a desire to find potential new growth opportunities for local automotive manufacturing sectors, and at the very least ensure they do not fall behind international competitors in the event FCVs take off. Given the increasing international concentration of automotive manufacturing, it would not be surprising if similar concentrations were observed in the development of FCV technologies.
- Fuel Cells – are an essential component of end-use hydrogen technologies such as FCVs and fuel cell systems for combined heat and power, and are a major area of focus for countries such as China, South Korea and Japan.
- Household appliances that burn hydrogen as part of plans to introduce or completely convert existing gas networks to hydrogen.

To the extent a country does not have existing production capability in these areas they will face major challenges in growing local production capacity. However, this should not preclude supporting any promising local efforts that are targeted at these areas, and in participating in international standard development to ensure the technologies developed to meet local needs.

A final major consideration in formulating a hydrogen strategy is dealing with uncertainty. There are various types of uncertainty which one must potentially consider, including:

- uncertainty about how quickly costs for hydrogen technologies will decline;
- uncertainty regarding whether key technologies will prove reliable or feasible at scale (e.g. carbon capture and storage to enable low or zero carbon production using fossil fuels, new hydrogen production approaches at the early of development including solar thermo-chemical water splitting and biological hydrogen production);
- uncertainty about how the effectiveness and efficiency of competing technologies may evolve; and
- uncertainty about the extent to which greenhouse gas emissions have to be reduced and the speed at which progress has to be made.

Of particular relevance in terms of the uncertainty surrounding competing technologies is direct electrification and lithium-ion batteries. These technologies are more mature and further advances (e.g. faster charging times and greater driving ranges for BEVs) could limit the penetration of hydrogen technologies. One method of dealing with such uncertainty is to take a technology-neutral approach in order to keep all options on the table. An example here would be banning fossil fuel vehicles and letting the market decide which types of zero-emission vehicles – BEVs or FCVs – emerge to fill the space. Another example in terms of hydrogen production is the United Kingdom’s Hydrogen Supply Programme which is trailing various approaches to supplying low carbon hydrogen in bulk. However, not all strategies take neutral approaches due to strategic considerations. For instance, the French Hydrogen Development Program primarily focuses on hydrogen production using electrolysis since this approach can be powered by renewable energy.

The strategies reviewed also suggest that linking regional strategies to national strategies and targets can partially reduce the degree of uncertainty due to the 'richer' information that is typically available.

3.1 Implications and recommendations for industry

The key take-away findings from the review of national hydrogen strategies and roadmaps, which are particularly relevant to those who are involved in developing the National Hydrogen Strategy, include:

- There is considerable international interest in rapidly deploying hydrogen technologies over the next several decades in order to reduce carbon emissions, which could give rise to export opportunities for countries with a comparative advantage in producing hydrogen.
- There is considerable uncertainty regarding how quickly hydrogen and competing technologies will develop in terms of their effectiveness and cost-efficiency. Such uncertainty needs to be taken into account in formulating a strategy, either by taking a technological neutral or flexible approach, or not overcommitting down particular pathways.
- Hydrogen strategies should ideally be built upon areas of comparative advantage in terms of production and use.
- Hydrogen strategies should also reflect the broader international environment, for example by drawing on hydrogen strategies in other countries.
- The logistics of the transition to hydrogen should be a core focus of the strategy.
- The scale of activities should reflect the scale of the transition being targeted.
- Access to low cost, low GHG intensity electricity is likely to be critical to the potential for a hydrogen export trade into the medium term, and for the potential of hydrogen to make a meaningful contribution to domestic GHG reductions. Availability of suitable geological features for CCS is also likely to be an important cost driver.
- International collaboration on standards for technology is potentially important not just for those countries that have comparative advantages in the development of the technology but also for potential users of the technologies developed.
- International collaboration is also likely to be necessary on ways to measure and certify the GHG intensity of hydrogen supplies for end users.

3.2 Next steps and future work

The review of strategies and roadmaps was undertaken in a compressed timeframe in order to inform the development of a National Hydrogen Strategy in Australia.

Due to such time and resource constraints, the review was restricted to the analysis of key policy documents, while the summaries that were developed could not be cross-checked by people who are familiar with each jurisdiction. As such, the summarises could be improved by considering a broader range of materials and consulting with relevant stakeholders in each jurisdiction.

In addition, as hydrogen technologies and policies are developing at a rapid rate, the summaries are likely to need to be updated regularly in order to ensure that they remain current. There is an opportunity, also, to use this document as a means to begin discussions about and determine the best way to develop other strategies and examine the consequences of pursuing different development scenarios.

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APPENDIX A – BRUNEI DARUSSALAM

Caveat – Unofficial synthesis. Readers are advised to check against the source.

Title / Key document(s)

Energy White Paper, Energy Department, Prime Minister’s Office Brunei Darussalam (2014)

Document Type and Author

Energy strategy by a government authority

Abstract

Brunei does not appear to have an overt hydrogen strategy but is seeking to be well-positioned to supply hydrogen initially to Japan.

A white paper issued by the Energy Department in 2014 only makes a small reference to pioneering new carbon technologies including hydrogen:

> *“A variety of efficient end-use technologies and alternative fuels have been proposed to address energy-related environmental or supply security challenges in fuel use. Recently, hydrogen have received increased attention world wide because it offers a long term potential to radically reduce several important societal impacts of fuel.”*

Brunei’s main effort in developing a local hydrogen industry is its role in Japan’s Global Hydrogen Supply Chain Demonstration Project – a world-first project that involves producing hydrogen from natural gas in Brunei, which will then be transported to Japan. In effect, Brunei is one of the initial beneficiaries of Japan’s current hydrogen strategy, a major part of which involves developing international hydrogen supply chains.

Driving Factors

Participation in Japan’s efforts to develop a global hydrogen supply chain.

Hydrogen Supply

The Global Hydrogen Supply Chain Demonstration Project involves the construction of a hydrogenation plant in Brunei. Hydrogen will be produced by steam reforming of liquefied natural gas piped from the Brunei LNG plant in Lumut. The hydrogen will be converted to methylcyclohexane (MCH) for transportation to Japan in liquid form at ambient temperatures and pressures. A dehydrogenation plant in Kawasaki, Japan will then extract the hydrogen, which will then be supplied to customers as hydrogen gas (Mitsui & Co., Ltd. 2017).

The scale of the project involves supplying a maximum of 210 tonnes of hydrogen, which would be enough to fill 40,000 fuel cell vehicles (Mitsui & Co., Ltd. 2017).

The project is an initiative of the Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD), which is comprised of four Japanese companies: Chiyoda Corporation, Mitsubishi Corporation, Mitsui & Co., Ltd, and Nippon Yusen Kabushiki Kaisha.

Power Generation

Transport / Mobility

Industrial Systems

Gas Networks

Residential

Exports

Comparative Advantages

Brunei has a relatively large oil and gas sector which accounted for 58% total gross value added in the first quarter of 2018 (Department of Statistics 2018). Japan is a long-standing major customer of Brunei's oil and gas resources. This existing integration coupled with the country's close proximity to Japan makes it an ideal test bed for hydrogen derived from steam reforming natural gas.

Role of Government

The Global Hydrogen Supply Chain Demonstration Plant is subsidised by the National Research and Development Agency and the New Energy and Industrial Technology Development Organization (Mitsui & Co., Ltd. 2017).

Funding / Costs

Challenges

Existing oil and gas fields are ageing, and there is a need for greater investment and exploration activity to boost oil and gas reserves.

Recommendations (Roadmap)

Public Awareness

Timeframes

The project should be completed by December 2019, enabling operation during the 2020 calendar year.

Regulatory

Update

References

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APPENDIX B – CHINA

Caveat – Unofficial synthesis. Readers are advised to check against the source.

Title / Key document(s)

Hydrogen Fuel Cell Vehicle Technology Roadmap, developed by the Strategy Advisory Committee of the Technology Roadmap for Energy Saving and New Energy Vehicles and Society of Automotive Engineers of China, 2016.

Document Type and Author

Strategy by a national academic organisation (Society of Automotive Engineers) and government authority.

Abstract

China's hydrogen strategy is currently centred on developing an entire fuel cell technology and vehicle industry chain, including supply infrastructure. Government policy in terms of maintaining global competitiveness in automotive manufacturing is the main driving factor, while the need to mitigate climate change and reduce air pollution are also imperatives. It is expected that hydrogen will be sourced from coke oven and industrial by-product gases, and eventually from water electrolysis powered by renewable energies. Although the hydrogen FCV technology roadmap envisions certain technologies becoming commercially viable by particular milestone dates and provides unit cost targets for certain technologies, no specific unit cost estimates are provided for hydrogen production.

China appears to be ignoring opportunities to use hydrogen to manufacture steel, cement, etc., and to decarbonise urban heating.

Driving Factors

In 2015 China published *Made in China 2015* – a 10-year industrial plan designed to modernise China's industrial capability and reduce its reliance on foreign technology imports. The plan is designed to move the country up the manufacturing value chain by focusing on hi-tech industries. Energy-saving and new energy vehicles were identified as one of ten priority sectors by the plan. An *Energy Saving and New Energy Vehicle Technology Roadmap* has been subsequently developed, and hydrogen fuel cell vehicle (FCV) technology forms one element of this roadmap.

In addition to enhancing the automotive industry's international competitiveness, hydrogen FCV technology will help reduce climate change by transitioning to a low-carbon energy system. Under the Paris Agreement, China has pledged that carbon emissions will peak by around 2030 and that carbon dioxide emissions per unit of GDP will be reduced by 60 to 65% below 2005 levels by 2030 (China, 2016).

Development of FCVs and pure electric vehicles will also help "promote national or regional energy security" by diversifying energy sources used for powering vehicles (Strategy Advisory Committee, 2016).

China currently faces environmental pollution issues, due in part to emissions from fossil fuel-based urban vehicle traffic. The adoption of zero-emissions vehicles through FCV development (and pure electric vehicles) is expected to improve urban air quality.

Hydrogen Supply

Hydrogen is currently mainly produced from coke-oven gas and industrial by-product gases, with some production being met from renewable energy sources.

The roadmap anticipates that centralised, large scale hydrogen production will be achieved through the development of reforming technology to extract hydrogen from coke oven gases and industrial by-product gases. Coke oven plants would ideally be connected by a hydrogen supply network. In terms of distributed hydrogen production for transportation (hydrogen refuelling stations), it is expected that "economically viable" production using water electrolysis powered by intermittent renewable energies will be developed by 2020.

In order to meet increasing FCV market demand beyond this date, China plans to "further develop low-cost and high-efficient water electrolysis technology, mainly through solid polymers and solid oxide electrolyzers" (Strategy Advisory Committee, 2016). It is hoped that hydrogen production for transportation will be mainly derived from renewable resources by 2025, while over 50% of hydrogen production will be derived from clean energies by 2030.

Hydrogen production from natural gas is not considered competitive in China (Li, 2018).

Power Generation

Transport / Mobility

The overarching objective of the roadmap is to establish an entire fuel cell vehicle technology and industry chain in order to facilitate large scale domestic production (industrialisation) and deployment of FCVs by 2030. The roadmap identifies four key focus areas where technological progress and priority actions will need to be made in order to meet this overall objective:

- fuel cell stacks including key materials and components;
- fuel cell systems (engines) for commercial and passenger vehicles;
- fuel cell vehicles, including commercial and passenger vehicles; and
- hydrogen technology, particularly in relation to supply infrastructure and on-board storage.

The roadmap provides technical and production objectives for these four technology areas. For instance, key technical objectives for fuel cell stacks include power density, cold start performance, rated power and expected lifespan. Among these objectives include cost reduction targets for fuel cell stacks, fuel cell systems, commercial and passenger FCVs, and on-board hydrogen storage. For instance, the aim is to reduce the materials cost for fuel cell stacks by 75% from RMB 4,000/kW (A$816) in 2015 to RMB 1,000/kW (A$204) by 2020, and to RMB 500/kW (A$102) by 2025. However, no-cost objectives are provided for hydrogen generation.

Table C.1 summarises China's development goals for hydrogen FCVs in terms of deployment of vehicles and refuelling stations, the average cost of commercial and passenger vehicles, and hydrogen generation sources. In 2018 there were over 150 FCVs operating in China (Li, 2018). Under the roadmap, the goal is to demonstrate 5,000 FCVs operating in selected public spaces by 2020 and achieve large scale commercial deployment of one million passenger and commercial vehicles by 2030. Initial FCVs would comprise hybrid fuel cell-battery systems, with pure hydrogen-powered vehicles hopefully being established by 2030. The early focus would also be on commercial vehicles such as buses and heavy-duty vehicles, and would then transition to passenger cars.

In terms of transportation and storage, it is expected that cryogenic liquid hydrogen delivery will be deployed in 2020 and that high density organic liquid hydrogen storage and delivery will be ready for commercialisation by 2025.

Table B.1: China's development goals for hydrogen fuel cell vehicles

	2015	2020	2025	2030
Fuel cell vehicles				
- Number		5,000	50,000	>1 million
- Commercial–passenger		3,000; 2,000	10,000; 40,000	
Fuel cell vehicle cost (RMB)				
- commercial	2m	≤1.5m	≤1.0m	≤600,000
- passenger	>500,000	≤300,000	≤200,000	≤180,000
Hydrogen refuelling stations				
- Number	6	100	350	1,000
- Pressure	35MPa	35/70 MPa	35/70 MPa	35/70 MPa
Hydrogen generation	Coke oven gas, industrial by-product gases	Wind / solar / hydro	Renewable sources	Multiple sources available locally

Source: Hydrogen Fuel Cell Vehicle Technology Roadmap.

Industrial Systems

Gas Networks

Residential

Exports

Comparative Advantages

Strong industrial policy support from the central government.

Role of Government

The government supports hydrogen energy development through a combination of financial incentives and affirmative policies in respect of industrial policy and climate change mitigation, although the latter is much less aggressive compared to most high-income economies.

Funding / Costs

The central government provides significant subsidies for hydrogen fuel cell vehicles. These subsidies amount up to RMB 200,000 (A$40,800) for passenger vehicles, RMB 300,000 (A$61,200) for light buses and trucks, and RMB 500,000 (A$102,000) for large and medium-sized fuel cell vehicles, and medium and heavy trucks (Li, 2018). Some cities and provinces also provide full or partial matching subsidies.

Hydrogen vehicles also enjoy tax breaks, such as exemption from the vehicle and vessel tax.

Significant support is also provided through strategic research and development funding. For instance, in 2018, six projects involving the development of FCV technologies were approved as part of special funding targeting 'new energy vehicles' under the National Key Research and Development Program (IPHE, 2019). The total funding contribution from central government for these projects amounted to RMB $486 million (A$99 million). A subsequent special projects funding round has called for applications in respect of 'renewable energy and hydrogen energy technology' (IPHE, 2019).

Challenges

China currently faces a number of current limitations in relation to fuel cell vehicle development. These limitations include improving fuel cell system operational lifespans; a lack of domestic capability in respect of critical materials and components (e.g. fuel cell electro-catalysts, proton exchange membranes, carbon paper, air compressors, hydrogen reticulation pumps etc.); and hydrogen tanks with higher storage densities / pressure (Strategy Advisory Committee, 2016).

Recommendations (Roadmap)

Public Awareness

Timeframes

The roadmap has milestone objectives for 2020, 2025 and 2030.

Regulatory

New hydrogen transportation and storage technologies (e.g. liquid hydrogen) will require regulatory approvals.

Update

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APPENDIX C – EUROPEAN UNION (HYDROGEN ROADMAP EUROPE)

Caveat – Unofficial synthesis. Readers are advised to check against the source.

Title / Key document(s)

Hydrogen Roadmap Europe – A Sustainable Pathway for the European Energy Transition

Document Type and Author

Roadmap by stakeholder group, Hydrogen Europe, also known as the European Hydrogen and Fuel Cell Association. It represents industry companies across the value supply chain, research organisations and national associations.

Abstract

The roadmap outlines an "ambitious scenario for hydrogen development in the EU" in order to contribute to the Paris Agreement aspirations for limiting global warming. It envisions generating 2,250 TWh of hydrogen within Europe by 2050 (approximately 24% of final energy demand), which compares with a business-as-usual demand scenario of 780 TWh by this date. The ambitious scenario involves deploying hydrogen technologies to decarbonise various sectors, especially the gas grid through blending and limited conversion to 100% hydrogen; transportation through adoption of fuel cells in vehicles and shipping and synthetic fuel in aviation; and in industry as a substitute for natural gas for high-grade process heat and as a feedstock in processes, either directly or with CO_2 as a synfuel or electrofuel. Given its suitability for energy storage, hydrogen is expected to play an important role in facilitating the transition to renewable energy generation, providing power balancing and buffering services, and additional generation capacity.

Driving Factors

As part of the Paris Agreement, the 28 member states of the EU have agreed to keep the increase in global average temperature well below 2 degrees Celsius above pre-industrial levels. Achieving this goal requires reducing carbon emissions from a current level of approximately 3,500 Mt to 770 Mt in 2050. Large scale adoption of hydrogen can be used to bridge the gap between existing emissions reduction commitments and constraints of existing technologies.

Wide-scale deployment of hydrogen would enable EU industry to scale up and reduce costs, enhancing its international competitiveness and therefore export potential. Another benefit of adopting hydrogen and fuel cell technologies would be to reduce air pollution, providing health benefits.

Hydrogen Supply

The final energy demand for hydrogen in the EU was estimated to be 339 TWh in 2015 and composed mostly of industry feedstock demand for refining and chemical production purposes. Most of this hydrogen is produced from natural gas using SMR without CCS or as a by-product.

In terms of the future deployment scenario, it is anticipated that hydrogen will be derived from a mix of ultra-low carbon sources. The pattern of production methods may differ by application and will depend on how technologies and costs evolve. Nonetheless, "both electrolysis and steam methane reforming/auto thermal reforming with carbon capture and storage (SMR/ATR with CCS) will most likely play key roles", while "electrolysis could provide the sector coupling mechanism required for the integration of renewables". While SMR is the more mature technology and available for large scale production, large scale demonstrations of electrolysis of up to 10 MW are underway. The roadmap argues that relying on only one method may be unrealistic and that policy makers and industry should aim to develop and scale-up both methods.

Power Generation

Using excess power generation from renewables to produce hydrogen will enable "sector coupling", whereby hydrogen can be used as a fuel for transport, building heating and industry. It can help balance variabilities in the supply and demand of power over the short and long term, which is expected to become more pronounced over time with the trend toward electrification of energy use and increasing penetration of renewables. While batteries are an efficient short term option for energy storage, hydrogen is better suited for long periods, which means it can help balance large inter-seasonal variations in demand and supply. And via transportation in pipelines, ships and trucks, it can connect regions with excess or high potential for renewable energy production (e.g. southern Europe, northern Africa) with areas of high demand.

In the ambitious hydrogen adoption scenario, power companies are assumed to store approximately 25 TWh of surplus renewable energy as hydrogen by 2030, while approximately 40TWh in power is produced from about 64 TWh of hydrogen.

Transport / Mobility

Transport accounts for 32% of CO_2 emissions in the EU.

The roadmap recognises that battery electric vehicles will be the main choice for certain car segments – e.g. small vehicles, short commuting distances – due to current cost advantages. However, it argues that the higher energy density of hydrogen which enables relatively lightweight storage, coupled with advantages in re-fulling times and long driving ranges, makes hydrogen-powered fuel cells the "most promising decarbonization option" for trucks, buses, trains, ships, large cars and commercial vehicles.

Under the ambitious hydrogen scenario, the European fleet would comprise 45 million passenger cars, 6.5 million light commercial vehicles, 250,000 buses and 1.7 million trucks by 2050. In order to service this fleet, the number of hydrogen refuelling stations would need to increase from around 120 currently to approximately 3,700 by 2030, and around 15,000 by 2050. Simulations for Germany suggest that the costs for deployment of hydrogen refuelling infrastructure amount to approximately EUR $4,000 per vehicle in the initial establishment phase, which compares to a cost of EUR $2,000 for battery electric vehicles. The costs for hydrogen are expected to decline over time as usage improves.

For aviation, using hydrogen and CO_2 to produce synthetic fuels was considered the "only viable direct decarbonization solution" for the sector.

Industrial Systems

Under the ambitious scenario, hydrogen would be used to produce high-grade heat rather than natural ga and would be used as a feedstock in several industrial processes, including steel making and ammonia production. Other potential applications, such as direct reduced iron steel making, require feasibility testing.

As industry is highly exposed to international competitive pressures, it is recognised that cost efficiency will play a major role in whether hydrogen technologies are adopted within the sector. For adoption, a reasonable assumption is that hydrogen would need to match the natural gas price plus the cost of required carbon offsets.

Gas Networks

About 40% of European households have gas heating, with natural gas being the main fuel source.

While electrification with heat pumps can replace gas heating, retrofits of older buildings are more costly and challenging, making this approach more suited for new buildings. The blending of hydrogen into the natural gas leverages existing infrastructure and may be more cost-efficient for older buildings. Existing gas pipelines can typically accommodate blending concentrations of 5 to 15%, with the exact threshold depending on local conditions relating to pipeline infrastructure, connected appliances, and presence of industrial users who may have lower tolerances. A transition to a pure hydrogen grid is also feasible, although this requires retrofitting or replacement of existing steel pipelines and appliances.

In the roadmap, blending would provide 1% of energy demand for heating in residential and commercial buildings by 2030, while pure hydrogen grids would emerge after this date to supplement pilot projects. Energy efficiency would be further improved through the use of fuel cell-based combined heat and power units (i.e. co-generation) in the place of natural gas boilers.

Beyond the existing gas network, salt caverns and depleted gas fields would provide additional storage options for hydrogen.

Residential

See gas networks.

Exports

The net export potential associated with achieving the ambitious scenario is estimated to be EUR $50 billion ($A79 billion) in 2030. The report recommends focusing on the manufacture of electrolysis equipment and associated distribution infrastructure.

Comparative Advantages

The EU is considered to have several advantages when it comes to developing a hydrogen economy. These include the presence of existing leaders across the hydrogen value chain who can facilitate deployment; research strengths in terms of institutions with hydrogen expertise and mature research and development programs at various levels of government; and a strong policy commitment to reducing carbon emissions and increasing renewables.

Role of Government

Meeting the carbon reduction requirements to contain global warming to 2 degrees will require a coordinated response from policy makers, industry and investors. Regulators should work with industry to develop clear decarbonisation pathways for all sectors and segments. This would include targets for renewable content and decarbonization in end applications, and should "consider the requisite infrastructure for energy generation and distribution". Public procurement may also be used to encourage adoption (e.g. buses).

Funding / Costs

It is estimated that annual investments of approximately EUR $8 billion would be required by industry and government to realise the ambitious roll-out scenario. This annual amount is equivalent to 0.05% of Gross Domestic Product for the EU 28 in 2018. The required investments could be funded, in part, by appropriate environmental taxes (e.g. taxes on gasoline and diesel fuel for transportation infrastructure).

Challenges

The ambitious scenario requires a significant policy commitment.

Recommendations (Roadmap)

The roadmap makes the following overarching recommendations:

- *Regulators and industry should jointly set out clear, long-term, realistic, and holistic decarbonisation pathways for all sectors and segments.*
- *The European industry should invest in hydrogen and fuel cell technology to remain competitive and positioned to capture emerging opportunities.*
- *Regulators and gas companies should decarbonize the gas grid.*
- *In the power system, regulators should encourage the use of electrolyzers to balance the grid, e.g., by exempting them from grid fees and ensuring competitive access to renewable power on the market.*
- *In transport, regulators should overcome the chicken-and-egg problem by setting out a clear and credible roadmap, developing policies for zero-emission mobility with corresponding funding and guarantee mechanisms to unlock investment in refuelling infrastructure.*
- *In industry, stakeholders should kick-start the transition from grey to low-carbon hydrogen and further substitution to fossil fuels with new hydrogen uses. Regulators should ensure carbon-free hydrogen production counts towards renewable targets (e.g., as set out by Renewable Energy Directive II for refining) and low carbon targets are set across all major uses of hydrogen (e.g., in ammonia production).*
- *To produce ultra-low-carbon hydrogen on a large scale, companies should enlarge their electrolysis operations to commercial levels and prove CCS can produce hydrogen of very low carbon intensity on a large scale within the next ten years.*
- *Industry and regulatory stakeholders should continue to develop additional hydrogen and fuel cell applications and plans to scale up successfully proven ones* (Hydrogen Europe, 2019, p.12-14).

Public Awareness

Timeframes

In the short term transport and heating are considered to be the most viable applications for achieving decarbonisation through hydrogen, while more widescale adoption of these technologies together with industry feed-stock and power generation representing long-term opportunities.

Regulatory

The regulatory framework should be designed to provide “long-term visibility for market demand for zero-emissions products” to encourage investment in fuel cell and hydrogen technologies. Regulatory changes will be required to accommodate hydrogen technologies (e.g. hydrogen blending into the grid, new uses in industrial feedstock).

Update

References

Hydrogen Europe (2019), Hydrogen Roadmap Europe – A Sustainable Pathway for the European Energy Transition. Available at https://www.fch.europa.eu/sites/default/files/Hydrogen Roadmap Europe_Report.pdf

APPENDIX D – EUROPEAN UNION (A CLEAN PLANET FOR ALL)

Caveat – Unofficial synthesis. Readers are advised to check against the source.

Title / Key document(s)

A Clean Planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy
In-Depth Analysis in Support of the Commission Communication COM(2018) 773

Document Type and Author

Decarbonisation strategy prepared by the European Union

Abstract

This broader strategy is focussed on the set of scenarios that would allow the EU to achieve sufficient decarbonisation by 2050 to be consistent with a less than 2°C (and less than 1.5°C) increase in temperature from pre-industrial averages. The modelled decreases in emissions are 80%, 90% and 100% below 1990 levels. Although the strategy is one of overall emissions reductions, hydrogen and ‘e-gas’ (e.g. gas produced using zero-carbon energy such as synthetic methane) play an important role in many of the scenarios developed given their potential to substitute for greenhouse gas emissions in many sectors where it is considered likely that it will be difficult for electricity to do so cost-effectively.

An important feature of the strategy if the effort to consider energy decarbonisation needs and approaches systemically from energy generation, through potential distribution and storage technologies, to users of the energy (and industrial feedstock).

This summary focuses on those elements of the broader strategy most closely connected with the development of hydrogen industries to contribute to decarbonisation, it does not seek to summarise the full extent of the strategy.

Driving factors

The strategy is driven by the need to achieve a substantial reduction in emissions across the European Union (between 80% to 100%) in order to make an appropriate contribution towards the Paris Agreement mid-century targets of keeping global temperature increases to less than 2°C above pre-industrial levels, and ideally limiting temperature increases to no more than 1.5°C whilst still sustaining economic growth.

Hydrogen Supply

The document examines eight pathways to achieving the required level of decarbonisation; five scenarios aim at achieving an 80% reduction. All eight scenarios assume almost completely decarbonised power generation, substantial increases in energy efficiency and reductions in other waste.

The first three are centred around different carriers of zero carbon emission energy carriers – electricity, hydrogen, and “e-fuels” that is synthetic hydrocarbons produced using renewable energy, with the remaining two 80% scenarios based around the development of a circular economy and deep lifestyle changes respectively. Three more ambitious scenarios are also modelled based on combining the least cost basket of energy carriers with additional measures and lifestyle changes.

In the hydrogen scenario 100% hydrogen is distributed through the gas grid (after the necessary changes to avoid embrittlement are made) and fills all of the roles grid natural gas currently provides including household heating, stationary energy, and acting as an industrial feedstock (in combination with sustainable sources of carbon where necessary). Hydrogen is also the primary fuel source for heavy vehicles and fuels a proportion of light vehicles.

In the e-fuels scenario, 100% e-gas is distributed through the gas grid and it fills all of the roles grid natural gas currently provides including household heating, stationary energy, and acting as an industrial feedstock. E-fuels are also a key fuel source for all transport modes.

Power Generation

Electricity generation is assumed to be almost completely de-carbonised, primarily through renewables (with solar PV taking the most significant role), however nuclear is assumed to still have a role in the power generation system.

'Future fuels' are assumed to have a distinct, albeit limited, role in the power system as a mechanism for long-term, large scale storage either through hydrogen, e-gas, or ammonia which can then be used to fuel power plants in intervals of prolonged low renewable generation.

Transport / Mobility

Different scenarios see different assumed roles for hydrogen and related technologies:

- In the electricity scenario hydrogen or e-fuel have almost no role in the transport system, being used only for maritime transport (and possibly aircraft);
- In the hydrogen scenario, hydrogen is the primary fuel source for heavy vehicles and maritime transport, with some use by passenger vehicles (although BEVs are expected to dominate that market segment);
- In the e-fuel scenario, e-fuels are the primary fuel source for heavy vehicles, maritime transport and air transport, as well as capturing a significant proportion of the passenger vehicle market (with the remainder being BEVs).

Industrial Systems

Those industrial processes where electricity cannot displace gas will be met through on-site of local production of hydrogen or e-gas using electricity.

In the hydrogen scenario,100% hydrogen will be distributed using the gas distribution network, modified to prevent embrittlement or seal leaks.

In the e-fuels scenario, synthetic natural gas will be distributed through the existing gas pipeline network.

Gas networks (and distribution)

In the electricity dominated scenario gas networks and gas distribution are assumed to be displaced entirely or almost entirely by electricity which will capture their current markets including domestic and industrial heat, and most industrial processes.

In the hydrogen and the e-fuel scenarios, the existing gas distribution network is used to transmit the alternative zero net carbon gas (with necessary modifications in the case of hydrogen).

Residential / Commercial

Residential heating is an important consideration in northern and eastern Europe, with these needs currently being primarily met through gas, either directly in building based heating systems, or through neighbourhood-based heat distribution systems, with the heat for the latter typically generated through combined heat and power plants.

Exports

Exports are not a specific objective of the strategy, although it envisions European firms being able to maintain existing market positions, so by implication the strategy is assuming that hydrogen or e-fuel vehicle and industrial plant exports will substitute for existing carbon consuming products in those markets.

Comparative Advantages

This strategy does not assess or target comparative advantages in hydrogen-related industries, but rather it seeks to develop decarbonisation trajectories that will achieve the reductions necessary for the Paris Agreement global temperature targets to be met whilst not eroding the existing comparative advantages of European industry.

Role of Government

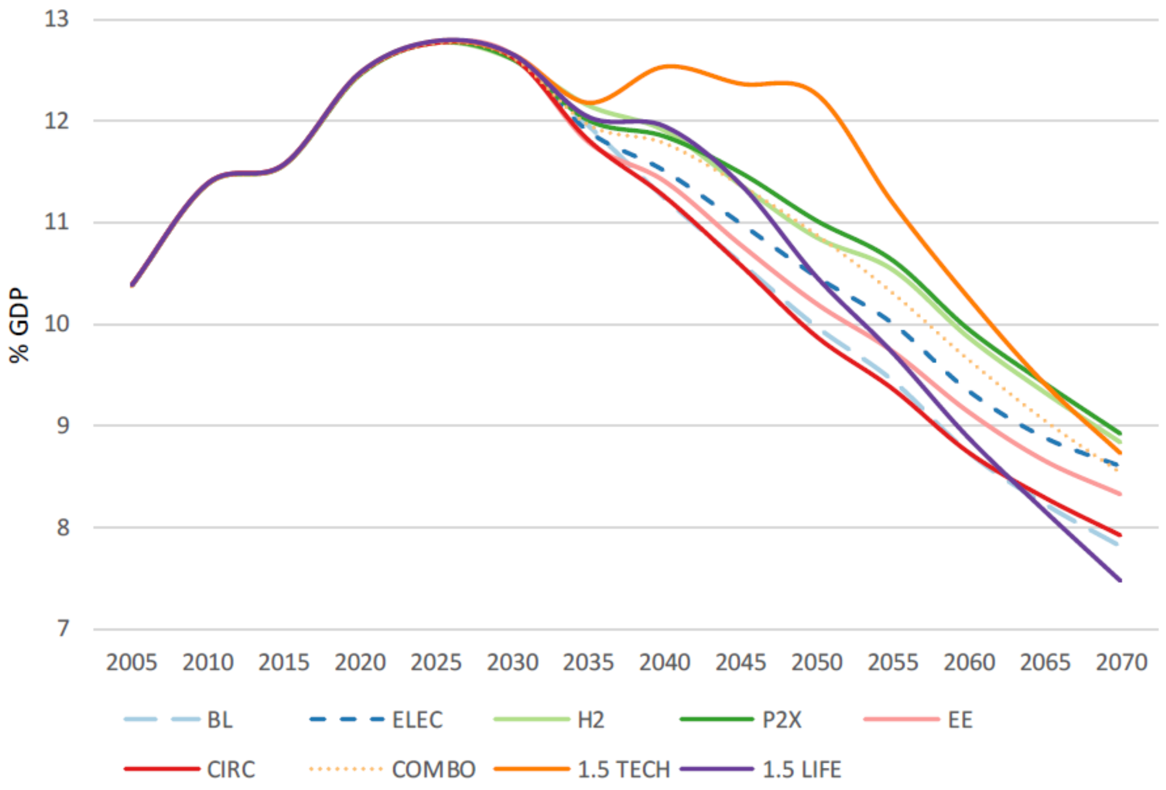
Governments are seen as having a critical role in certain aspects of the decarbonisation strategy, namely ensuring the security of supply of power, ensuring that the network infrastructure required for the decarbonisation is in place, creating the necessary incentives to drive energy efficiency and renewable energy deployment, and in supporting research and innovation.

Funding / Costs

Explicit funding levels are not included in this strategy.

Modelling of energy system transition costs suggest that the hydrogen or e-fuels driven scenarios for decarbonisation are likely to involve higher energy system costs than the other 80% reduction scenarios. However, it is assumed that reduction in costs due to learning by doing, the reduction in input costs for power due to the adoption of renewables, and continued economic growth will see energy system costs decline as a share of GDP after 2030.

Figure D.1: Total energy system costs as a % of EU GDP under various decarbonisation scenarios



Scenarios: BL = baseline (electricity sector almost completely decarbonised, but 80% reductions are not achieved as other sectors of the economy do not substantially decarbonise; ELEC = electricity driven scenario consistent with achieving an 80% reduction in GHG emissions; H2 = hydrogen driven scenario consistent with achieving an 80% reduction in GHG emissions; P2X = e-fuel driven scenario consistent with achieving an 80% reduction in GHG emissions; EE = energy efficiency driven scenario consistent with achieving an 80% reduction in GHG emissions, with substantial efficiencies achieved in household, commercial and industrial energy use, and substantial transport mode shifts towards public transport and cycling for individuals, and trains for freight; CIRC = a 'circular economy' driven scenario consistent with achieving an 80% reduction in GHG emissions with industrial processes optimised to minimise waste and maximise the reuse of waste products; COMBO = adopting the least cost basket of changes from the ELEC, H2, P2X & EE scenarios consistent with achieving a 90% reduction in GHG emissions; 1.5 TECH = adopting the least cost basket of changes from the ELEC, H2, P2X & EE scenarios together with extensive use of biomass energy combined with CCS and moderate use of landuse change to achieve a 100% reduction in GHG emissions; 1.5 LIFE = adopting the least cost basket of changes from the ELEC, H2, P2X & EE together with lifestyle changes, adoption of circular economy measures and land use changes to achieve a 100% reduction in GHG emissions.

Challenges

Challenges explored in the strategy include:

- The need to manage differential regional impacts, particularly on employment;
- The need to ensure low-cost finance is available to support the capital investments required for decarbonisation;
- The need to maintain industrial competitiveness through the transition; and
- Identifying publicly acceptable strategies to drive lifestyle changes.

Recommendations (Roadmap)

Recommendations in the strategy are extensive, detailed, and sector and strategy specific and are beyond the scope of this report to summarise.

Public Awareness

Public awareness is considered important both in sustain support for the decarbonisation and in achieving behavioural changes to support decarbonisation. Civil society has been identified as the key influencer to maintain public awareness and achieve public acceptance of the necessary changes.

Timeframes

The strategy is based around decarbonisation goals for 2050, and the trajectories required to get there from current emissions patterns

Regulatory

Regulation is the key lever that the EU has to influence member states, and there are a number of regulations structured around achieving the necessary reduction in GHG emissions, ensuring the burden of reducing GHG emissions is shared equitably amongst member states and regions, and in managing potential transition costs, for example, there are regulations to ensure the security of natural gas supplies through the transition period.

Competition policy is also seen as having a central role in ensuring that the transition measures adopted by member states and industries are low cost, in the interest of consumers, and do not lead to the exploitation of market power.

Update

References

European Commission (2018) A Clean Planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. In-Depth Analysis in Support of the Commission Communication COM(2018) 773A Clean Planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. Available at https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_en.pdf

APPENDIX E – FRANCE

Caveat – Unofficial synthesis. Readers are advised to check against the source.

Title / Key document(s)

Hydrogen Development Plan for Energy Transition, Ministry for the Ecological and Inclusive Transition of France (2018).[7]

Document Type and Author

National strategy by government authority.

Abstract

The French national hydrogen roadmap is organised around three axes: hydrogen production by electrolysis for industry, in mobility as a complement to battery vehicles, and to assist the stabilisation of energy networks. The initial focus is on subsidising the deployment of hydrogen in industrial uses which currently have greater potential economies of scale and therefore commercial viability. Deployment will then extend to transport and energy network applications. A total of €100 million (A$159 million) in funding has been allocated to support deployments throughout France across the three axes.

Driving Factors

As part of its broader greenhouse gas abatement efforts, France aims to increase the proportion of renewable energy in final energy consumption to 32%, and the share of renewables in electricity supply to 40%, by 2030 respectively. It also hopes to reduce fossil fuel consumption by 30% and decarbonise 10% of gas by this date. (In late 2018 President Emmanuel Macron announced that all coal plants would be closed down by 2022 while 14 nuclear reactors would be shut down by 2035.) Hydrogen can potentially contribute to these objectives but may be an “essential lever” in pursuing the longer-term goal of carbon-neutrality by 2050.

Encouraging the development of a local hydrogen sector is another driving factor. The plan notes that a “global competition” has emerged with respect to hydrogen and that industrial sectors are highly globalised.

Hydrogen Supply

French industry currently produces around 900,000 tonnes of hydrogen per annum, with almost all (94%) being produced from fossil fuels such as gas, coal and hydrocarbons. The main uses are desulphurisation of petroleum fuels, ammonia production and chemistry.

While industry is exploring the potential for large scale hydrogen production using methane combined with carbon capture and storage, the national plan is primarily focused on hydrogen production by electrolysis of water using renewable energy.[8] Electrolysis technologies such as proton exchange membrane (PEM) and alkaline are now well established, with the costs of the former falling significantly over recent years. High-temperature electrolysis is considered the most promising in terms of competitiveness, and accelerating development of this technology could provide France with a competitive advantage.

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[7] An English language version was not available. The following summary is based on a version that was translated using Google Translate.

[8] The plan does not mention a specific role for nuclear energy but France’s considerable nuclear energy resources would seem a natural low carbon energy source for powering water electrolysis.

In terms of deployment, the initial focus will be on decarbonisation of existing industrial uses as only this market has sufficient current demand to realize the economies of scale from deploying larger numbers of electrolysers, and is, therefore, the nearest to commercial viability. Deployment will then extend to transport and then stabilisation of energy networks.

Transport / Mobility

Hydrogen technologies such as fuel cells can be deployed in mobility applications to complement all battery vehicles. It has advantages for mobility applications that require faster recharging times and high autonomy, and in certain forms of heavy transport (e.g. road, rail and shipping) where the weight and bulk of batteries are currently barriers to adoption.

The total costs of ownership of hydrogen vehicles is currently 20 to 50% higher compared to thermal equivalents. It is anticipated that decarbonised hydrogen distribution should reach a price of below €7 per kilogram (A$11.1) by 2030, a level similar to the cost of energy for diesel vehicles.

The Agency for the Environment and Energy Management (ADEME) will provide project leaders with logistical support and direction, particularly in respect of regulatory and financing. Financial support will initially be provided to facilitate deployment of refuelling infrastructure and purchase of commercial and transit passenger vehicles. Future investment support will look to fund the development of locally built heavy-duty hydrogen-powered vehicles such as trucks, buses, boats and trains, extending across the whole supply chain to include components and hydrogen production and storage systems.

The objective of the plan is to construct 100 hydrogen refuelling stations nationwide and deploy 5,000 light commercial vehicles and 200 heavy vehicles (buses, trucks and ships) by 2023. It is hoped that between 400 to 1,000 refuelling stations, 20,000 to 50,000 light commercial vehicles and 800 to 2,000 heavy vehicles will be deployed by 2028.

Industrial Systems

The initial focus of the French hydrogen plan is to replace existing industrial uses of fossil hydrogen with “green” or decarbonised hydrogen. Particular focus areas will be:

- Industries that currently consume hydrogen as inputs to the production process, such as refining, fertiliser production, chemicals, iron and steel making, glassmaking etc.; and
- Industries that produce large quantities of carbon dioxide (e.g. cement manufacturing) which could be combined with hydrogen to produce synthetic methane.

Upfront investment costs and residual technology risks are current barriers to industry adoption of electrolysis. The cost of producing hydrogen from fossil sources such as steam reforming of gas is currently between €1.5 and 2.5 per kg (A$2.4 to 4.0) for large scale industrial customers. For smaller diffuse industrial users these costs may rise to €10 to 20 per kg (A$15.9 to 31.8). In comparison, the costs of producing hydrogen using electrolysis are currently around €4 to 6 per kg (A$6.4 to 9.5) based on a duration of 4,000 to 5,000 hours per year and an electricity cost of €50 per MWh (A$79.4). It is anticipated that this cost could fall to €2 to 3 per kg (A$3.2 to 4.8) by 2028, approaching the competitiveness of large scale industrial users.

The French plan will subsidise the deployment of electrolysers to enable carbon-free hydrogen to replace some existing industrial uses (see funding below). The plan sets the objective of achieving 10% decarbonised hydrogen (about 100,000 tonnes) in industrial hydrogen use by 2023, rising to between 20 and 40% in 2028.

The plan also calls for the establishment of a traceability system in 2020 for the origin of hydrogen so that stakeholders can recognise the use of decarbonised hydrogen or hydrogen derived from renewable energies.

Power Generation / Gas Networks

In the medium to long term, the production of hydrogen by electrolysis is considered a solution for integrating high rates of renewable energies into the electricity system. It is a particularly promising means for providing massive inter-seasonal storage of intermittent renewable energies. A further promising avenue is power-to-gas whereby hydrogen is injected into gas networks, either directly or indirectly through methane synthesis.

The role of hydrogen in stabilising energy networks is at a very early stage of development. Government authorities and electricity system operators/providers have been asked to identify the services that electrolysers can provide to electricity networks, which may include storage, demand management and interconnection. A distinction is made here between the connected metropolis network and non-interconnected zones (e.g. islands and overseas territories) that are not connected to the continental power grid.

Gas carriers and distributors will determine the technical and economic conditions that will enable hydrogen to be integrated into gas networks, including the connected installations and potential uses. Two demonstration projects – GRHYD and Jupiter 1000 – were in operation and would provide evidence to inform the prospects of this approach.

Industry is also currently exploring the potential for decarbonised hydrogen production using carbon capture and storage in the North Sea.

Residential / Commercial

Exports

Fostering a hydrogen sector will improve the “export potential” of French industry.

Comparative Advantages

Considerable policy support including financial support (see below) and carbon abatement targets. France has significant industrial capability and therefore existing hydrogen use, providing a vector for initial hydrogen adoption.

Role of Government

Provision of financial support to enable hydrogen technologies to compete with existing fossil fuel-based technologies; regulatory measures to facilitate deployment of hydrogen; and coordination services for project proponents, including local government.

Funding / Costs

In order to facilitate the first deployment of hydrogen, a call for projects will be made with the government committing €100 million (A$159 million) from 2019. Should these projects prove successful, regular financing of €100 million per annum (equivalent to 0.004% of GDP) may follow. This program complements existing research and development programs.

The initial support will focus on investment aid in terms of subsiding the acquisition of electrolysers for industrial users of hydrogen, with support expected to amount to a maximum of €20 per kg (A$31.8) of avoided carbon dioxide. There will also be financial assistance for end uses to support technologies that compete with fossil fuels. This will include repayable advances for hydrogen charging stations and support for purchasing professional vehicles and large people carriers (e.g. buses), and aid for hybrid energy projects, particularly in non-profit areas that are interconnected to the energy network.

It is anticipated that investment aid may be withdrawn once electrolyser costs approach market competitiveness.

Challenges

Recommendations (Roadmap)

A total of 18 measures were identified that would help facilitate the development of the hydrogen sector. Beyond the provision of investment support, these measures include, among other things, recognising the environmental impact of hydrogen in greenhouse gas emissions depending on the mode of production; implement regulation and risk prevention measures to facilitate deployment; establish a hydrogen research program within the National Agency for Research; incorporate hydrogen into relevant training programs; and explore the potential for hydrogen in rail etc.

Public Awareness

Timeframes

Regulatory

There is a need to clarify regulations in respect of security, safety and risk prevention along the whole hydrogen value chain, including production, storage, transport and use. Regulatory measures will need to be implemented to enable injection of hydrogen into gas infrastructure.

Update

References

Ministre de la Transition écologique et solidaire (2018), Plan hydrogène : un outil d'avenir pour la transition énergétique. Available at *https://www.ecologique-solidaire.gouv.fr/sites/default/files/Plan_deploiement_hydrogene.pdf*

APPENDIX F – GERMANY

Caveat – Unofficial synthesis. Readers are advised to check against the source.

Title / Key document(s)

Power-to-gas system solution. Opportunities, challenges and parameters on the way to marketability. German Energy Agency, 2015.

Document Type and Author

National strategy by government authority.

Abstract

The *Power-to-gas system solution* report outlines the current state of this technology including remaining challenges. The conversion of renewable energy into hydrogen or methane using water electrolysis can connect renewable energy with other sectoral energy uses, including mobility, industry, heat supply and power generation. Considerable funding has been provided to support research and development in order to lower costs, improve energy efficiency and test potential business models.

Driving Factors

The Federal Government has committed to pursuing an accelerated transition to a sustainable energy economy. Underlying this transition is a pledge to reduce greenhouse gas emissions by 80 to 95% by 2050 compared to 1990 levels. In addition, the share of renewables in gross final energy consumption should increase to 60% by 2050. Existing technologies will be insufficient to meet these ambitious objectives meaning innovative technological solutions will be required. Power-to-gas has been identified as a potential "system solution".

Hydrogen Supply

Power-to-gas involves converting renewable electrical power (wind or solar) into hydrogen through water electrolysis. The resulting hydrogen can be used directly in mobility applications or industrial uses or can be fed into the existing gas network either directly or indirectly as methane, where it can be used for various applications including mobility, electricity generation and heat supply. In this sense power-to-gas provides a cross-sectoral system solution whereby renewable energy sources can be integrated with different energy consumptive uses, helping to displace existing fossil fuel usage.

While the underlying technology was considered "mature and ready for use" at the time of the report, it was not yet economical.

In terms of water electrolysis processes, polymer electrolyte membrane (PEM) electrolysers have technical advantages in terms of better responsiveness to power load changes but are relatively more expensive. The investment costs for PEM electrolysis were estimated to range from €2,000 to 6,000 per kW (A$3,175 to 9,525) compared with €800 to 1,500 per kW (A$1,270 to 2,380) for alkaline electrolysis. The goal is to bring down the investment costs of electrolysis to €500 per kW (A$795) by 2022 primarily through increasing economies of scale.

The cost of power-to-gas plant operation depends on numerous factors, including proximity to renewable energy sources, load balancing of the energy system, proximity to the gas network and associated technical parameters (e.g. hydrogen mixing capacity), proximity to potential buyers, and availability of carbon dioxide where methanation will be undertaken.

In August 2015 there were 20 hydrogen plants in operation for research and demonstration purposes with capacities ranging from below 100 kW to 6 MW. This has since increased to 30 pilot projects with a total electrolysis capacity of about 25 MW. In addition to demonstrating technical feasibility, these pilot projects are designed to achieve cost efficiencies and test potential business models and applications.

The efficiency of the electricity to hydrogen and back to electricity conversion process depends on various factors but is typically around 40%, which is comparable to conventional power plants. Improving efficiency is a key objective of current research, particularly if the pathway of using natural gas infrastructure for energy storage is to be realised.

Power Generation

Hydrogen is an attractive long-term electricity storage medium and can compensate for variations in electricity generation from wind and solar energy. The existing gas network and connected gas storage systems provide large storage capacity. The renewable gas could potentially be reconverted in gas power plants or cogeneration plants to provide additional power generation.

Transport / Mobility

Hydrogen and/or methane can be used in the transportation sector (e.g. hydrogen fuel cell vehicles). In terms of non-biogenic fuels, hydrogen or methane can be supplied in greater quantifies and have a smaller impact on land use compared to plant-based fuels.

Industrial Systems

Hydrogen produced with renewable energy can replace fossil fuel-based hydrogen used in various existing industrial uses, including fuel refining, chemicals manufacturing and steel production, while synthetic methane can also substitute for natural gas.

Gas Networks

Under current regulations, existing natural gas infrastructure can accept up to 10% of hydrogen by volume although lower restrictions apply in some areas (e.g. 2% due to compressed natural gas refuelling) (FuelCellsWorks, 2019). The 10% limit will apply across the whole network by 2030, while the long term goal is to increase the maximum limit to 20%. Greater usage of renewable power generation can in effect be achieved by converting hydrogen into methane through the methanation process. Combining methanation with a biogas plant is considered a particularly efficient pathway for maximising methane production.

Residential / Commercial

Approximately 75% of space heating in buildings was derived from gas in 2015 (German Energy Agency, 2019). Hydrogen and synthetic methane can be a substitute for fossil natural gas in the existing natural gas infrastructure for heating purposes and may be utilised in combined heat and power plants.

Exports

Comparative Advantages

A significant policy commitment to reduce carbon emissions, increase renewables share in the energy system, and facilitate research and development into Power-to-gas.

Role of Government

Implement required regulatory changes to facilitate hydrogen adoption (see below). Provision of a stable framework and funding opportunities to support research and development on hydrogen technologies in order to pave the way for market introduction.

Funding / Costs

Research and development funding is provided through the interdepartmental National Innovation Programme Hydrogen and Fuel Cell Technology. The Federal Ministry of Transport and Digital Infrastructure provided €500 million (A$794 million) in funding support between 2007 and 2016 (Project Management Jülich, 2019). On an annualised basis (i.e. €50 million per year) this would be equivalent to 0.001% of GDP in 2018.

Challenges

Fluctuations in electricity generation present technical challenges for water electrolysis. For instance, recurrent load changes can strain mechanical components, shorten operational lifespans, and increase maintenance requirements.

Despite committing over €500 billion on transforming its energy system by 2025, Germany will likely miss its short term target of reducing greenhouse gas emissions by 40% by 2020, having achieved a 28% reduction by 2017 (Bloomberg, 2018).

Recommendations (Roadmap)

Public Awareness

Timeframes

Market launch of renewable hydrogen and methane by 2022, with a specific aim to build a 1,000 MW capacity power-to-gas plant in Germany by this date.

Regulatory

The report identified five regulatory parameters that would need to be modified to facilitate commercialisation of Power-to-gas in a German context:

- recognise hydrogen and methane derived from renewable energy as biofuels;
- provide incentives in the electricity system for the storage of electricity;
- implement political measures to support the market launch of renewable hydrogen and methane by 2022 (e.g. legislative recognition of renewable gases in the fuel market);
- extend the energy tax reduction on natural gas; and
- exempt power-to-gas facilities from end-user taxes.

Update

Dena has published various fact sheets that may provide updated contextual information, including in relation to the performance of various technologies, but these only appear to be available in German.

References

Bloomberg (2018), Germany's Failed Climate Goals. A Wake-up Call for Governments Everywhere. Available: https://www.bloomberg.com/graphics/2018-germany-emissions/

FuelCellWorks (2019), German Association for Gas and Water (DVGW) Develops Rules for Climate-Friendly Hydrogen in the Natural Gas Infrastructure. Available: https://fuelcellsworks.com/news/german-association-for-gas-and-water-dvgw-develops-rules-for-climate-friendly-hydrogen-in-natural-gas-infrastructure/

German Energy Agency (dena) (2019), Integration into the existing infrastructure. Available: https://www.powertogas.info/power-to-gas/nutzung-im-gebaeudebestand/

Project Management Jülich (2019), National Innovation Programme Hydrogen and Fuel Cell Technology (NIP). Available: https://www.ptj.de/en/project-funding/nip

APPENDIX G – HYDROGEN COUNCIL

Country / Region

International

Title / Key document(s)

The Hydrogen Council, “How Hydrogen Empowers the Energy Transition”, January 2017.

Document Type and Author

Roadmap prepared by 13 CEOs from leading energy and industry who launched the Hydrogen Council at Davos in 2017.

Abstract

This report recognises the importance of hydrogen in the attainment of the goals set out in the Paris Agreement. It emphasises the role of hydrogen in power generation (grid balancing, buffering etc.), transport and mobility sector (FCEVs), industrial systems (hydrogen as feedstock) and application of hydrogen in the residential and commercial sectors (heating).

The report recommends the development of

- long-term and stable policy frameworks to guide the energy transition in all sectors
- incentive policies and increased coordination among sectors
- the harmonization of industry standards across regions and sectors to enable hydrogen technologies and take advantage of scale effects and decrease costs.

Driving factors

This report by the Hydrogen Council had its origin in the goals set at the Paris Agreement to keep “*the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit warming to 1.5°C*”. This report states that to achieve the goals set in the Paris Agreement, large scale decarbonisation of the energy system and transportation sector will be mandatory. In particular, emphasis should be placed on:

- improving energy efficiency;
- developing renewable energy sources;
- switching to low/zero carbon energy carriers; and
- implementing carbon capture and storage as well as carbon capture and utilisation.

This report states that hydrogen and fuel cell technologies can play a significant role in transitioning to a clean and low carbon energy system.

Hydrogen Supply

This report identifies the following methods of hydrogen production:

- electrolysis using renewable energy sources;
- steam methane reforming using bio-methane; and
- steam methane reforming with carbon capture, storage and utilisation.

Power Generation

Increased use of renewable energy sources in the future coupled with an increase in demand for energy can create imbalances in the power sector. The report recognises the main challenges in the future of energy generation as issues related to grid capacity, intermittency, low-carbon seasonal energy storage and backing up generation capacity. This report states that hydrogen can help address these challenges.

Hydrogen produced from excess renewable energy through electrolysis can be used to service transport, industry and residential requirement for heat or for storage for future use. Thus, hydrogen has the potential to increase returns on investment in renewable energy, improve the security of power supply and act as carbon-free seasonal storage. For example, in European winters when renewable energy production is low and demand for energy is high, hydrogen can supply zero-carbon energy.

However, the Council foresees the need for major transformation of the local and global infrastructure so that clean energy supply can be secured across borders. Hydrogen can be transported through ships, pipelines or trucks with almost 100% efficiency and distributed among cities and regions. For example, hydrogen can be transported from the Middle East, which has the potential for high renewable power generation, to areas with high energy demand like Europe. The report also acknowledges the plans made by Japan and Leeds in this context.

With increasing electrification over time, fossil fuels which act as a buffer in times of energy shocks will not be adequate for the smooth functioning of the system. In contrast, hydrogen can be used for providing adequate buffer since it can be stored and transported upon requirement. A number of hydrogen-based storage demonstration projects are underway in Denmark, Canada, Japan and the Asia-Pacific region.

The report states that underground storage of large volumes of hydrogen is a well-established industry practice and does not present a major technological barrier. Cost of hydrogen storage is a factor at present. However, as more renewable energy is used in future, the use of hydrogen as a long-term storage solution is also expected to increase with it and the cost of hydrogen storage is projected to decrease to €140/MWh (A$222/MWh)(power to power) in 2030 for hydrogen stored in salt caverns which is less than the projected cost for pumped-hydro storage (about €400/ MWh or A$635) in 2030.

Transport / Mobility

The report states that Fuel cell electric vehicles (FCEVs) have an important role to play in decarbonizing transport. Currently, efficient hybrid vehicles like hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) are being used. However, the transport sector can be fully decarbonized only through the deployment of zero-emission vehicles like hydrogen-powered FCEVs and battery electric vehicles (BEVs), or other hybrid combinations. The Council lists the following benefits of using FCEVs:

- FCEVs can drive long distances without needing to refuel (already more than 500 km);

- FCEVs refuel quickly (3 to 5 minutes);
- The technology used in FCEVs are conducive for use in heavy load capacity and/or long range/heavy use); and
- FCEV infrastructure can be developed along with the existing gas distribution and retail infrastructure thus creating cost advantages and preserving local jobs and capital assets.

FCEVs will be important in decarbonizing passenger cars (e.g., medium to large cars, fleets, and taxis), heavy-duty transportation, buses, and non-electrified trains. Currently, synthetic fuels made from green hydrogen in shipping and aviation is also under consideration. At present, the main constraint in use of FCEVs is the high cost of owning such a vehicle but the Council expects the cost parity can be reached for medium to large passenger cars by 2025 and earlier than that for selected car fleets and buses. FCEV trials have already started with more than a thousand vehicles on road in Japan and the US and a few hundred in Europe. In addition, China has set the goal of having 50,000 FCEVs on the road by 2025 and 1 million by 2030. Japan plans to deploy 200,000 FCEVs by 2025 and 0.8 million by 2030.

FCEVs have already started entering the market for mass and goods transport. For example, Lianyungang Haitong Public Transport (China) plans for 1,500 FCEV buses, Europe has announced to deploy in total 600 to 1,000 FCEV buses by 2020 and South Korea plans to replace 27,000 CNG buses with FCEVs by 2030.

The report observes that Germany has announced that its first hydrogen trains will soon start running and now are running). FCEV trains are already cost-competitive with diesel trains in terms of total cost of ownership.

In addition, there are plans to develop hydrogen infrastructure in leading Western and Asian countries over the coming decade. In Europe, the number of refuelling stations is expected to double biannually, with up to 400 stations in Germany alone by 2023, and California has set the goal of having 100 stations by 2020. Japan already has more than 80 stations operating, and South Korea and China are planning to set up a hydrogen network, together aiming to establish 830 hydrogen refuelling stations by 2025. The total targeted number of more than 3,000 stations in 2025 will be sufficient to provide hydrogen for about 2 million FCEVs. The report states that after this initial development phase, refuelling infrastructure will be self-sustaining.

Industrial Systems

The report identifies the need for industries to improve energy efficiency which includes the recovery of waste heat and thus reduce the need for energy. One of the methods of transforming waste heat into hydrogen is steam electrolysis.

Hydrogen can also be used to decarbonize the conventional sources of producing low- and high-grade heat. In terms of low-grade heat, since hydrogen can be combusted in hydrogen burners or used in fuel cells, it can be used asa zero-emission alternative for heating. While high-grade heat is harder to decarbonise, the report observes that hydrogen burners can be used to complement electric heating to generate high-grade heat. The Council believes that, in the future, the mixed-use of hydrogen burners and fuel cells may used by the industry to meet the demand for both low and high temperature requirements. While the use of former still requires significant investment in new infrastructure, the latter will only require the adjustment of existing equipment.

Hydrogen can have wide application in the chemical industry as feedstock. Currently, crude oil is used as a feed stock. However, if carbon capture and utilisation can be used widely then green hydrogen will be required by the industry to convert the captured carbon into usable chemicals like methanol, methane, formic acid and urea. While this type of technology is still in the research and development stage with a few pilot-concepts being trial, opportunities are starting to emerge. For example, Iceland has an operational geothermal plant that produces green hydrogen and then use it to produce methanol which is claimed to be cost-competitive with an electricity price of €30/MWh (A$48/MWh).

Gas networks

Residential / Commercial

The report identifies that, in Japan, hydrogen technologies such as fuel cell micro-combined heat and power systems can act as energy converters that provide more than 90 percent efficiency in terms of heat or power generation. In this country, where more than 170,000 buildings already have a system installed, by 2030, it is planned for about 5.3 million Japanese households to use such a combined system as their prime source of heat and power. Economies of scale have already cut prices more than 50%, from 2.4 USD/W installed in 2009 to 1 USD/W installed in 2014.

Besides, hydrogen can be used as fuel in itself or in combination with gas. This can be easily achieved through small modification and investments towards the existing gas grid. However, a full decarbonisation would require a total switch to hydrogen, e.g. Leeds.

Exports

Comparative Advantages

Role of Government

Funding / Costs

The report states that more investment is needed to deploy hydrogen-related products. Investments planned over the next five years by Council members alone are approximately €10 billion (A$16 billion).

Challenges

The report identifies the following challenges for hydrogen deployment:

- "insufficient recognition of its importance for the energy transition;
- the absence of mechanisms to mitigate and share the long-term risks of the initial large-scale investments;
- a lack of coordinated action across stakeholders;
- a lack of fair economic treatment of a developing technology; and
- limited technology standards to drive economies of scale."

Recommendations (Roadmap)

The report recommends the following actions:

> "*1. Provide long-term and stable policy frameworks to guide the energy transition in all sectors (energy, transport, industry, and residential). We will bring in our expertise on the feasibility of decarbonisation solutions in each sector.*
>
> *2.* ***Develop coordination and incentive policies*** *to encourage early deployment of hydrogen solutions and sufficient private-sector investments. These policies should complement sector policies and provide tools to capture the benefits of hydrogen.*

- *In the transport sector, ensure strong coordination among governments (to give direction), car manufacturers (to produce and commercialize FCEVs), infrastructure providers (to invest in supply and distribution infrastructure), and consumers (to purchase FCEVs).*

- *Ensure the energy market reforms effectively in terms of feed-in tariffs, curtailment management, seasonal balancing capacity remuneration and taxation, while taking into account the benefits hydrogen can deliver to the energy system.*

- *Provide financial instruments to leverage private investment with the support of public guarantees, to mitigate risk for early movers.*

3. ***Facilitate harmonization of industry standards** across regions and sectors to enable hydrogen technologies and take advantage of scale effects and decrease costs.*"

Public Awareness

Timeframes

Regulatory

Update

References

Hydrogen Council (2017) How Hydrogen Empowers the Energy Transition, January 2017. Available at http://hydrogencouncil.com/how-hydrogen-empowers-the-energy-transition/

APPENDIX H – INTERNATIONAL ENERGY AGENCY

Caveat – Unofficial synthesis. Readers are advised to check against the source.

Country / Region

France, Germany, Italy, UK, Japan, United States.

Title / Key document(s)

Technology Roadmap, Hydrogen and Fuel Cells, International Energy Agency (IEA), June 2015.

Document Type and Author

Roadmap prepared by an international agency.

Abstract

This roadmap and its 2019 update provides an exhaustive discussion of the nature, function and cost of key hydrogen technologies. It also identifies applications where hydrogen can offer maximum value added. The road map takes a short term and long term perspective on actions that are required to develop and deploy hydrogen technologies while taking into consideration global energy and climate goals. The roadmap also intends to promote stakeholder understanding of the business opportunities offered by hydrogen and the synergies they offer in existing energy systems.

This roadmap covers hydrogen-based solutions for both energy supply and energy demand. Within energy demand sectors, the roadmap covers transport, fuel cell micro co-generation in the residential sector and selected applications in the refining, steel and chemical industries. Within the supply sector, the roadmap covers variable renewable energy (VRE) integration and energy storage, comprising power to power, power-to-gas and power to fuel. The roadmap also covers hydrogen infrastructure such as transmission and distribution, storage and retail technologies. In addition, the roadmap also takes into consideration the main hydrogen generation and conversion technologies such as electrolysers and fuel cells. Recommendations in the update stress the importance of making the most of existing industrial ports to turn them into hubs for lower-cost; lower-carbon hydrogen; use existing gas infrastructure to spur new clean hydrogen supplies; support transport fleets, freight and corridors to make fuel-cell vehicles more competitive; and establish the first shipping routes to kick-start the international hydrogen trade.

Driving factors

The 2015 edition of the International Energy Agency's (2015) Energy Technology Perspectives 2DS (ETP 2DS) examines a carbon emission trajectory that limits global warming to 2°C. According to the ETP 2DS, total global energy-related carbon emissions need to be reduced by 60% compared to current levels by 2050 to meet the global warming limit objective. This will be possible only if all energy sectors contribute. In particular, energy supply, including the power generation and fuel transformation sectors will need to provide approximately half of the emission reductions.

Low-carbon energy systems largely rely on the deep decarbonisation of the power sector. The increased deployment of renewable energy such as wind, solar, biomass and hydropower is a key element of delivering low-carbon electricity and will play a major role in meeting the 2050 emissions reduction target. The remaining half of the required emissions reduction will need to come from energy demand sectors, especially transport, buildings and industry. This will largely depend on the deployment of highly efficient end-use technologies, switching to low-carbon fuels such as hydrogen or advanced biofuels, and avoiding the use of energy through reduced activity levels, e.g. in the transport sector.

Hydrogen Supply

The roadmap states that the cost of producing hydrogen at a large scale using steam methane reforming depends mainly on natural gas prices. The cost of producing hydrogen using this method is currently estimated to be US$0.9 per kg (A$1.2 per kg) in the United States, US$2.2 per kg (A$3.0 per kg) in Europe, and US$3.2 per kg (A$4.4 per kg) in Japan.

Another means of hydrogen production is electrolysis. The cost of producing hydrogen using this method is largely determined by the cost of electricity and the investment costs associated with the electrolyser. The cost of non-renewable electricity used in the electrolyser can be lowered by increasing the annual utilisation of renewable electricity. However, the supply of very low-cost, surplus renewable electricity is only available for a limited amount of time per year, which in turn has an impact on the ability to recoup investment costs. The roadmap, therefore, argues that it is important to find the right balance between reducing investment costs and achieving efficiency improvements.

Power Generation

Electricity that is not needed at the time or the place of generation can be transformed and stored as hydrogen such that it can be used in another sector of the energy system. Hydrogen-based technologies which can convert power to fuel, power-to-gas and power to feedstock are available but at a demonstration stage only. The roadmap points out that hydrogen-based electricity provides both large scale and long term storage solutions.

In an electricity system with high levels of variable renewable energy, supply will be greater than demand at certain times of the day as well as certain days in a year. Due to its intermittent nature using this excess energy to generate hydrogen may not be economically viable. Firstly, electrolysers have significant investment costs, which means that they will only be cost-effective if they are operated for a significant amount of time during the year. This relying solely on intermittent excess energy may not be able to cover the cost of electrolysers. Secondly, conversion of electricity to hydrogen and vice versa incurs losses which may be higher than if surplus electricity is stored via thermal storage. Hence the roadmap points to two areas for technology improvement: increasing efficiencies and reducing investment costs. However, focussing solely on improving the technology may not be sufficient, and new and more integrated approaches may need to be applied to create feasible business cases.

Transport / Mobility

The roadmap focuses on the use of fuel cell vehicles and the use of pure hydrogen in the transportation and mobility sector. Both FCVs and hydrogen refuelling stations are at an early stage of market introduction whereas technology for delivering hydrogen such as tube trailers and liquid tankers have matured in the meantime. FCVs require the least amount of investment in terms of transport solutions and liquid tankers require the least amount of investment in terms of delivery solutions. The roadmap identifies a total of 550 FCVs running in several demonstration projects around the world today. However, the main barriers to increased use of FCVs are their high cost owing to the high cost of fuel cells and high-pressure tanks. Even though the former is expected to fall due to economies of scale the later may not see a rapid decline due to the high cost of composite materials used in such tanks.

The next challenge is establishing hydrogen refuelling stations which can offer affordable refuelling options. Currently, there are 79 refuelling stations documented in the roadmap. Hydrogen can either be produced at the station using small scale technologies or supplied using hydrogen delivery methods. The development of refuelling stations depends on the demand for hydrogen and high fixed and operational costs. They currently suffer from the risk of being underutilised. If hydrogen is produced onsite then this can lower costs by eliminating delivery and transportation costs. The cost of producing hydrogen off-site then delivering it can vary. For example, gaseous tube trailers have a low fixed cost and high variable cost and are being deployed in the short term. However, economies of scale can be reaped from hydrogen pipelines but they involve high fixed costs and can only be deployed in the medium to long term. However, if technological and cost barriers can be removed then FCEVs will produce very low carbon emissions compared to conventional vehicles.

Industrial Systems

Hydrogen that is used in industrial systems is mostly generated and used on site. Hydrogen is used by the petroleum industry and is also generated by the steel industry as part of by-product gases during the coke, iron and steelmaking processes. These off-gases are mainly used to contribute to on-site thermal requirements.

Gas networks

Residential / Commercial

The waste heat that is produced during the co-generation of power and heat can be used for heating purposes. This technology can increase the energy efficiency of buildings and micro co-generation systems can also offer efficient heating systems in the absence of district heating networks. While natural gas-powered co-generation systems using internal combustion engines (ICE) are already available on the market, fuel cell micro co-generation systems powered by natural gas are an alternative to conventional ICE systems. The roadmap points out that along with higher efficiency, annual availability and government incentives, the difference between electricity prices and natural gas prices forms the economic basis for selecting a micro co-generation system over grid electricity and conventional domestic hot water boilers for heating and hot water supply.

Exports

Comparative Advantages

Role of Government

Funding / Costs

Challenges

Recommendations (Roadmap)

The roadmap recommends the following actions with respect to opportunities offered by hydrogen and fuel cells as well as utilising hydrogen in energy storage, transport, industry and buildings over a period of ten years:

- Developing the following opportunities offered by hydrogen and fuel cells:
    - *"Encourage fuel efficiency and low greenhouse gas emission technologies across all energy sectors through market-driven, technology- and fuel-neutral policies. A stable policy and regulatory framework – including for example carbon pricing, feed-in tariffs, fuel economy standards, renewable fuel standards or zero-emission vehicle mandates – is important for raising market certainty for investors and entrepreneurs.*
    - *Stimulate investment and early market deployment of hydrogen and fuel cell technologies and their infrastructure through effective policy support to bring down costs. National and regional priorities should determine the value chains and the market barriers to be targeted.*
    - *Continue to strengthen and harmonise international codes and standards necessary for safe and reliable handling and metering of hydrogen in end-use applications.*
    - *Keep up supporting technology progress and innovation by unlocking public and private funds for RD&D for key hydrogen technologies, such as fuel cells and*

electrolysers. Enhance the focus on cross-cutting research areas, such as materials, that could play a transformative role in improving performance. Where possible, promote projects with international cooperation to maximise the efficiency of funding.
    - *Improve understanding of regionally specific interactions between different energy sectors through integrated modelling approaches to quantify benefits of energy system integration.*
    - *Where regionally relevant, accelerate activities directed at developing the capture and storage of CO_2 from fossil-derived hydrogen production into mature business activities."* (IEA, 2015a).

- Utilising hydrogen in energy storage, transport sector, industry and buildings:
    - *"Prove on-road practicality and economics across the supply chain of FCEVs by putting the first tens of thousands of vehicles on the road, along with hydrogen generation, T&D and refuelling infrastructure, including at least 500 to 1000 stations in suitable regions around the world, and cross-border projects. Build upon deployment programmes in Europe, Japan, Korea and California as well as the use of captive fleets.*
    - *Engage international stakeholders from relevant industries as well as regional, national and local authorities in developing risk-mitigation strategies, including the development of financial instruments and innovative business models that de-risk hydrogen T&D and retail infrastructure development for FCEV market introduction.*
    - *Increase the number of hydrogen-based energy storage systems suitable for integrating VRE and collect and analyse performance data under real-life conditions.*
    - *Establish regulatory frameworks that remove barriers to grid access for electricity storage systems including power-to-fuel and power-to-gas applications. Where regionally relevant, establish a regulatory framework for the blending of hydrogen into the natural gas grid.*
    - *Increase data on resource availability and costs for hydrogen generation at national and regional levels. Analyse the potential future availability of curtailed electricity for hydrogen production as a function of VRE integration, other power system flexibility options and competing demands for any surplus renewable electricity.*
    - *Address potential market barriers where opportunities exist for the use of low-carbon hydrogen in industry (e.g. in refineries).*
    - *Extend information campaigns and educational programs to increase awareness-raising."* (IEA, 2015a).

Public Awareness

Timeframes

Regulatory

Update

IEA's recent 2019 report on hydrogen identifies four key areas that governments, industries and various stakeholders should focus on for the near-term development and deployment of hydrogen. IEA observes that interest in the use of hydrogen is gaining momentum. Focusing on the following four key areas would act as a real world "*spring board*" through further development of current policies, infrastructure and skills. This, in turn, is predicted to upscale the development of hydrogen infrastructure, enhance investor confidence and lower costs of hydrogen production and consumption:

- Currently, most of the demand for hydrogen is in hydrocarbon refining and chemical production typically located in coastal industrial zones around the world, e.g. the North Sea in Europe, the Gulf Coast in North America and South-Eastern China. Providing adequate incentives to these plants to move to cleaner hydrogen production would scale up hydrogen production and drive down costs. Hydrogen produced by these industrial zones can also be used as fuel in ships and trucks that provide service to these ports and as an industrial feedstock (for example in steel plants) for manufacturing located in the vicinity.

- Utilise the already existing natural gas pipelines to drive demand for hydrogen. For example, if clean hydrogen were to replace only 5% of the volume of natural gas supplies for all countries taken together then this would increase the demand for hydrogen and to the extent necessary to drive down costs and achieve economies of scale.
- Even though fuel cell vehicles are currently being trialled in various countries they currently have significant disadvantages in terms of cost. However, targeting initial take-up of FCV in high mileage cars, trucks and buses to carry passengers and goods along popular routes can make fuel-cell vehicles more competitive.
- International trade in hydrogen is vital if hydrogen has to make its mark on the global energy system. As such, it is essential to set up hydrogen trade's first international shipping routes. Learnings from the success of global LNG market can be utilised in this context. In particular, the report mentions that "h*ydrogen and hydrogen-based fuels can transport energy from renewables over long distances – from regions with abundant solar and wind resources, such as Australia or Latin America, to energy-hungry cities thousands of kilometres away.*"

The IEA also identified four key barriers that may result in hydrogen being unable to establish itself as a significant energy technology despite the current spike in interest:

- Producing hydrogen from low-carbon energy is current much more costly that using natural gas, or even using hydrogen derived from fossil fuels.
- The development of hydrogen infrastructure, such as refuelling stations and distribution and transmission networks, is slow, and can be expected to hold back widespread of hydrogen end-uses such as household heating and FCVs. The IEA believes that this may require coordination between governments (national and local) and industry to resolve.
- Currently, almost all hydrogen is sourced from fossil fuel feedstocks, and as such is responsible for substantial GHG emissions (equivalent to those of Indonesia and the United Kingdom combined). If hydrogen is to play its hoped-for role in decarbonisation, there will need to be widespread use of CCS in hydrogen production or production of hydrogen from electrolysis using zero GHG electricity.
- Current regulations are an impediment to the development of a clean hydrogen industry, for example, there are currently no common international standards for safe transportation and storage of large volumes of hydrogen. Nor are there systems in place that would allow the GHG intensity of different hydrogen supplies to be measured and certified in a way that gives confidence to potential end-users.

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International Energy Agency (IEA) (2015a), *Technology Roadmap, Hydrogen and Fuel Cells*. Available at http://ieahydrogen.org/pdfs/TechnologyRoadmapHydrogenandFuelCells-(1).aspx

IEA (2019), "The Future of Hydrogen: Seizing Today's Opportunities." Report prepared by IEA for G20, Japan.

APPENDIX I – JAPAN

Caveat – Unofficial synthesis. Readers are advised to check against the source.

Title / Key document(s)

Basic Hydrogen Strategy and Basic Hydrogen Strategy (key points), Ministerial Council on Renewable Energy, Hydrogen and Related Issues (2017).

Document Type and Author

National strategy prepared by government authority.

Abstract

Japan has developed a comprehensive strategy to guide the public and private sectors, with the ultimate goal being to "become the first country in the world to realize a hydrogen-based society" (MCREHRI 2017). The national strategy is multifaceted, involving strategies to develop international hydrogen supply chains, promote hydrogen adoption in power generation, transportation, heating and industrial processes, promote hydrogen technologies overseas, with the effect of promoting and enhancing the competitiveness of Japanese hydrogen and fuel cell technologies. The main thrust is to increase the cost competitiveness of hydrogen with existing energy sources by increasing economies of scale and overcoming technological barriers.

Driving Factors

Japan has an overwhelming reliance on overseas fossil fuels for primary energy and is committed to reducing GHG emissions as part of the Paris Agreement (26% reduction by financial year (FY) 2030 from FY2013 levels; 80% by 2050).

In order to improve its energy self-sufficiency and meet its GHG reduction targets, hydrogen has been identified as a potential solution given it emits no carbon dioxide when burned, and has flexibility as an energy carrier to store, carry and use various renewable energy sources.

Hydrogen Supply

A primary goal is to reduce hydrogen procurement and supply costs by making use of existing low cost, overseas fossil fuel resources (e.g. coal gasification) through hydrogen production and carbon capture and storage, and developing hydrogen from cheap overseas renewable energy through electrolysis.

To support the above, Japan will develop international hydrogen supply chains, including the development of carrier technologies to enable efficient and safe transportation and storage of hydrogen. The development and demonstration of various carrier technologies are being pursued, including:

- a liquefied hydrogen supply chain by the mid-2020s;
- an organic hydride supply chain by FY2020, with commercialisation in or after 2025;
- overcoming existing technical challenges to introduce CO_2-free ammonia by the mid-2020s, which can be used directly in existing commercial sectors;
- dissemination of methanation technology that employs CO_2-free hydrogen, which can be used directly in existing gas and LNG infrastructure, and as a source of low carbon heating.

A target has been set to increase procurement of hydrogen from a current level of 200 tonnes to 300,000 tonnes per annum by 2030, and reduce the plant delivery cost from around 100 yen to 30 yen per Nm^3 ($A1.2 to 0.4). Beyond 2030, further demand and supply-side measures will be pursued to reduce the cost to 20 yen per Nm^3 ($A0.2) in order to achieve cost competitiveness with traditional energy sources (after allowing for environmental externalities).

Power Generation

Power-to-gas systems are expected to play a key role as a regulated power supply and backup storage to accommodate the rapid expansion of renewable energy, which is expected to lead to periods of oversupply.

Japan hopes to cut the cost of water electrolysis equipment for power-to-gas equipment to around 50,000 yen per kW (A$619) by 2020.

In the short-term, hydrogen will be largely used in existing natural gas plants and for small cogeneration systems. In the longer term, Japan will seek to commercialise hydrogen combustion technologies by trying to address technical challenges related to generation efficiency whilst reducing NOx emissions.

The country aims to reduce hydrogen power generation costs to 17 yen per kWh ($A0.2) by 2030, which may require hydrogen procurement to reach 300,000 tons per annum. In order to achieve cost parity with LNG power generation, hydrogen procurement may have to reach 5 to 10 million tonnes per annum.

Transport / Mobility

The strategy for the transport sector involves expanding the number of renewable energy-based hydrogen stations and increasing fuel cell usage across various modes of transport.

The current aim is to increase the number of hydrogen station to 160 by FY2020 and 320 by FY2025 and make these stations independent soon thereafter.

Targets for other forms of fuel cell vehicles include:

- 200,000 fuel cell vehicles by 2025, and 800,000 by 2030;
- 1,200 fuel cell buses by 2030; and
- 10,000 fuel cell forklifts by 2030.

Japan will also look to develop and commercialise fuel cell usage in trucks and small ships.

Industrial Systems

CO_2-free hydrogen may be used as a fuel for industrial uses where electrification is difficult and may substitute for hydrogen derived from fossil fuel sources that are used in existing industrial processes such as steel making and oil refining. However, it is acknowledged that substitution may be difficult given the greater economic efficiencies currently enjoyed by fossil fuels. While potential industrial applications will be considered, the national strategy does seek to "promote the introduction of commercial and industrial fuel cells for users with low heat-to-power ratios and step up technological development to reduce initial costs to allow fuel cell costs to fall below the grid parity as early as possible" (MCREHRI, 2017).

Gas Networks

The existing strategy notes that existing city gas pipelines may be used for methanation.

In terms of power-to-gas strategies, limitations associated with the existing natural gas pipeline network, including poor interconnection and lower technical specifications compared to European pipelines, mean that new infrastructure may be needed in the long term to accommodate hydrogen or synthetic natural gas (Shibata, 2016).

Existing laws requiring hydrogen to be odorized in order to monitor gas leaks may need to be revised given potential for odorants to damage fuel cells.

Residential / Commercial

Ene-Farm residential fuel cells are currently used to extract hot water and electricity from gas. The government aims to increase adoption by making existing systems cheaper and smaller and hopes to eventually introduce pure hydrogen fuel cell co-generation systems from 2030 onwards. However, the government is likely to miss its short term targets given a combination of still high costs, compounded by the withdrawal of Toshiba as a supplier, and competition from rooftop solar (BloombergNEF, 2017).

Exports

Japan is looking to expand its hydrogen and fuel cell technologies, including supply chain technology package, overseas. Development of many of these technologies has been publicly subsidised to date.

As Japan is looking to develop international supply chains, there are export opportunities for other countries, including Australia. For instance, a pilot coal to hydrogen plant will be established shortly in Latrobe Valley (Hydrogen Energy Supply Chain Pilot Project) in order to test the hydrogen supply chain from Australia to Japan.

Comparative Advantages

Considers itself a leader in hydrogen and fuel cell technologies, including fuel cell vehicles. Scientific and technological capacity, and highly educated workforce.

Role of Government

The national strategy directs the "whole of government to implement relevant measures". The central government is expected to play a leading role in reducing costs in the hydrogen supply chain, and "must (1) cooperate with local governments and enterprises in expanding regional hydrogen demand and optimizing regional supply and demand (contributing to raising capacity utilization rates), (2) reduce costs of various hydrogen facilities, and (3) cut running costs (including power generation and raw material procurement costs)" (MCREHRI, 2017).

Funding / Costs

According to Nagashima (2018), $1.5 billion over the past six years in technology R&D and subsidies has been provided in support of:

- hydrogen production from overseas fossil fuels using carbon capture and storage and renewable energy electrolysis;
- developing hydrogen supply chain infrastructure; and
- scaling up hydrogen across various sectors, including transportation, power generation and combined heat and power.

Challenges

Technological, safety and environmental problems associated with different forms of hydrogen storage and transportation will need to be solved. Port facilities will need to be developed to accommodate international supply chains.

Recommendations (Roadmap)

Public Awareness

Central government committed to working with local government and businesses to promote understanding of the safety of hydrogen and its significance.

Timeframes

The strategy identifies short, medium and long term goals and actions. Most goals, including the development of global liquefied hydrogen supply chains, are expected to be realised by around 2030, but the strategy is developed with a view towards major achievements being realised by 2050.

Regulatory

Japan will look to lead international standardization through international frameworks.

Aligning domestic regulations with international standards that facilitate market access.

Update

The strategy will be updated over time.

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Ministerial Council on Renewable Energy, Hydrogen and Related Issues (MCREHRI) (2017), Basic Hydrogen Strategy, December 26. Available at https://japan.kantei.go.jp/98_abe/actions/201712/26article5.html

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APPENDIX J – NETHERLANDS

Caveat – Unofficial synthesis. Readers are advised to check against the source.

Title / Key document(s)

Outlines of a Hydrogen Map, TKI NIEUW Gas, Topsector Energie, 2018.

Document Type and Author

Roadmap prepared by an energy company.

Abstract

A need to reduce carbon emissions as part of the Paris Agreement and the adoption of hydrogen initiatives at the regional and international levels has encouraged the Netherlands to develop a national hydrogen strategy. The Netherlands has the potential to use its large wind energy to produce hydrogen. Much work needs to be done in respect of the development of technology, regulations, the market for hydrogen and government policies to enable the Netherlands to transition to a hydrogen economy.

Driving factors

Netherlands' interest in having a well-defined hydrogen strategy stemmed from the Paris Agreement and its goal to reduce carbon emissions and global warming. The Netherlands government aims to achieve a 49% reduction in greenhouse gas emissions by 2030 and an 80 to 95% reduction by 2050 compared to 1990 levels.

In addition, the adoption of hydrogen strategies at a regional and international level has prompted the Netherlands to develop a formal roadmap for hydrogen. For example, H2 Platform, the members of the National Hydrogen and Fuel Cell Association and WaterstofNet have been developing and launching hydrogen initiatives at the regional level in the north of the Netherlands, the Rotterdam region and in Goeree-Overflakkee. The national government was also influenced by overseas developments, such as the H2 Mobility project in Germany, the development of hydrogen cars in Japan and South Korea, the launch of the 'Hydrogen Council' and the signing of a hydrogen manifesto by international companies in Switzerland in 2017.

The Netherlands realised that sustainable or zero-emission hydrogen could play an important role in supplying energy and raw materials as part of the transition to a cleaner energy system. In particular, consideration was being given to partially convert Netherland's large wind potential to produce hydrogen. The incorporation of hydrogen into the energy system can be achieved through the suitable provision of storing hydrogen and building up suitable infrastructure.

Hydrogen Supply

The roadmap looks at various technologies for producing hydrogen and also estimates the cost of producing hydrogen using those technologies. Large scale production of hydrogen from natural gas by using steam methane reforming is one such option. With this type of production method, however, costs are determined mostly by natural gas prices since natural gas accounts for 70 to 80% of production costs. The production costs are estimated between €1 to 1.50 per kg (A$1.6 to 2.4 per kg) of hydrogen using natural gas. However, transporting hydrogen over large distances can be expensive. The road map estimated a cost of €1.50 to 2.50 per kilometre (A$2.4 to 4.0 per km) for delivery by truck. In addition, the total price of compressed hydrogen delivered to the refuelling station was estimated at €5 per kg (A$7.9 per kg). However, increasing economies of scale should bring this cost down to below €4 per kg (A$6.3 per kg).

Small scale or onsite production of hydrogen using SMR can be quite cost-effective in comparison to a combination of large scale production and transport. Several companies have started developing small scale SMR units which can generate approximately 200 to 600 kg of hydrogen per day. The efficiency of this approach is between 60 to 65%. It was estimated that by 2020, the production cost of hydrogen could fall to €4 to 5 per kg (A$6.3 to 7.9), and fall further to €3 to 4 per kg (A$4.8 to 6.3 per kg) by 2030. This process can also use locally available biogas or green gas.

Production of hydrogen using various types of electrolysis was estimated to currently cost between €5 to 5.5 per kg (A$7.9 to 8.7 per kg) for alkaline electrolysis and €6 to 6.5 per kg (A$9.5 to 10.3 per kg) for PEM electrolysis. The costs were projected to drop to around €3 to 3.5 per kg (A$4.8 to 5.6 per kg) for on-site production at MW scale by 2030. Larger electrolysis units can bring costs to as low as €2 per kg (A$3.2 per kg). However, hydrogen produced from electrolysis depends on electricity prices and hence movements in electricity prices will have a major impact on production costs.

The roadmap identified five alternatives other than electrolysis that could be potentially worth exploring:

- Biomass pyrolysis and gasification (cost €4.5 to 6.5 per kg or A$7.1 to 10.3 per kg);
- Fermentation of biomass flows to biogas, combined with biogas reforming (cost €3.5 to 5.5 per kg or A$5.6 to 8.7 per kg);
- Thermochemical water splitting (cost €6 to 6.50 per kg or A$9.5 to 10.3 per kg);
- Photo-catalysis using photo-electrochemical cells (cost €4.5 to 5 per kg or A$7.1 to 7.9 per kg);
- Supercritical water gasification of biomass (cost €3 to 3.50 per kg or A$4.8 to 5.6 per kg).

2030 production costs were estimated for these processes. Among these five processes, production of hydrogen using fermentation of biomass flows to biogas reforming was projected to be the most cost-effective method of producing hydrogen, costing about €3.5 to 5.5 per kg (A$5.6 to 8.7 per kg) with a small onsite production of 0.2 to 4 tonnes per day.

Power Generation

Transport / Mobility

The road map considers the supply of hydrogen to refuelling stations for FCVs. The report states that for a start hydrogen will be supplied to refuelling stations via road by tube trailers. Hydrogen can also be supplied through pipelines as in the Rhoon refuelling station. Onsite production can also take place through electrolysis or small-scale SMR. The success of hydrogen in the mobility sector will also require the availability of adequate and cost-effective refuelling points. Since FCVs can run for 500 km and upwards and refuelling options are expensive, the location of refuelling stations should be based strategically taking into consideration locational demand for hydrogen. If this can be combined with onsite production then the cost of refuelling can be further brought down making FCVs more attractive.

In the case of large vehicles such as buses and goods transport vehicles, most of the refuelling time takes place at the point of return. Hence, if refuelling points are located in those areas then other fuel cell vehicles can also be serviced in these areas, maximising the use of refuelling stations. The roadmap also points out that reliability and robust arrangements regarding supply security will also be key points of consideration for the future transition to hydrogen.

Among the various applications of hydrogen, business cases are most popular for the mobility sector since hydrogen can contribute most to this sector in terms of decarbonisation. Specific plans have been laid out for increasing the number of refuelling stations from 3 to 10-12 by 2020 and to increase the number of hydrogen-powered buses to 60 over the same period. There is work in progress to establish a small fleet of refuse collection lorries and lorry prototypes in the 27 to 40-tonne class.

Industrial Systems

Initiatives are in place that focus on producing hydrogen in bulk for use in gas-fired power plants and generation of high-temperature heat and feedstock for the petrochemical industry by combining natural gas and CCS. The initiative relating to the Magnum power plant in Eemshaven led by Nuon, Statoil and Gasunie represents the most concrete application at present with implementation scheduled for 2023.

Gas networks (and distribution)

If hydrogen is used in large quantities then it will be required to adopt large scale technologies and this, in turn, would require a proper transport and distribution network that can link up production sites with consumers. This can also reap the cost advantages of large scale production and distribution networks. The road map states that existing high-pressure natural gas infrastructure could be used for this, based on the timing and locations of producers and consumers. However, objects like compressors, monitoring stations and gas storage facilities will require modification to make it adaptable for hydrogen. In addition, further investigation of external security and integrity would be required. Investigation is needed to determine which sections of the network could be made available for hydrogen. This, in turn, will depend on demand for natural gas, gas quality and the speed of hydrogen production. All of these factors will jointly determine how the transition from natural gas infrastructure to hydrogen infrastructure will take place. Other options that are being considered include inserting a small proportion of hydrogen in with the gas network, and dual-use of existing natural gas pipeline corridors by installing pipelines for transporting hydrogen alongside existing pipelines.

Alternatively, hydrogen could be produced offshore using renewable electricity generated through wind power. In that case existing gas assets, including infrastructure, compressors and platforms can be used. Sustainable hydrogen can also be produced on an energy island and transported on land to locations such as the Rotterdam region (chemical and manufacturing industry) and IJmuiden (steel production) which have a high demand for hydrogen.

Residential / Commercial

Exports

Comparative Advantages

Role of Government

Policies in the Netherlands to promote the use of hydrogen are currently limited to hydrogen as an energy carrier with a focus on cars and buses only. Policies for hydrogen are appended to other green policies rather than being a stand-alone policy. For instance, electric cars are exempt from excise duties, which includes FCVs. Hence, there is no all-encompassing and structural policy in the Netherlands that could promote the development of hydrogen to its full potential.

In terms of statutory and regulatory provisions, a substantial proportion of safety regulations and the associated safety requirements are based on the large-scale use of hydrogen as an industrial gas and as a feedstock in the chemical industry. These rules and regulations may not be appropriate for hydrogen used as an energy source. Hence the road map points out that a review into the requirement of developing new standards and guidelines for new applications of hydrogen should be considered. The existing framework of the Dutch Gas Act offers little scope for grid operators to take significant action in the transport and distribution of hydrogen. Hence there is scope for reviewing and amending this act taking into account the use of hydrogen in the context of transport networks.

The development of hydrogen will require new skills and competencies in the labour market particularly in areas of mechanical engineering, electrical engineering, chemistry and physics. Hence the roadmap recommends including hydrogen in the curriculum of basic education programmes.

Funding / Costs

Various European and national schemes are available for the introduction of fuel cell electric buses and the roll-out of hydrogen refuelling points. Innovation subsidies for hydrogen are available through Topsector Energy and early phase research is funded by the Netherlands Organisation for Scientific Research. However, no structural support is available for hydrogen within the Netherlands. Support for demonstration projects is available at the European level through a range of large-scale programmes.

Challenges

The main technologies for end-use applications of hydrogen are fuel cells and burners. Netherlands faces innovation challenges in relation to development, implementation and testing of systems, in particular, fuel cell systems for practical applications such as in buses, lorries, mobile machinery and ships. In terms of the generation of hydrogen, Netherlands faces the challenge of how to decarbonise current production and how to replace current production with hydrogen produced from sustainable energy sources. Finally, the key innovation challenge faced by the Netherlands in terms of storage, transport and distribution relates to the use of existing natural gas infrastructure for hydrogen.

Recommendations (Roadmap)

The roadmap proposes a “three-pronged approach” in order to develop a hydrogen strategy in the Netherlands:

- **Integrated plan and vision building for hydrogen**: On the supply side, the roadmap stresses that it is important to focus on the role of hydrogen as an energy carrier while on the demand side plans for increasing the sustainability of the industrial sector are important. It is important to consider the following as a building block for hydrogen strategy:
    - expected position of CCS,
    - timeframe within which the large-scale import of wind and solar energy in the form of hydrogen could be feasible,
    - future of the natural gas infrastructure,
    - role of biomass in the production of renewable gases,
    - degree of electrification in the transport sector,
    - role of controllable gas-fired power stations if the share of solar and wind is large, and
    - nature and scale of the need for renewable gas in the built environment.

  The roadmap suggests that good quantitative substantiations are required for this and considers 2030 and 2050 as good time reference points. In relation to the importance of the new Dutch Climate and Energy Agreement, the roadmap proposes to incorporate the plan and vision into the coordination committee.

- **Putting hydrogen into practice over the next 3-5 years:** To develop knowledge and experience and to generate stakeholder interest in pilot projects with readily available applications are required. Examples of this are industrial applications on a larger scale for the production of hydrogen as a raw material and for high-temperature heat, and in the transport sector (such as logistics, buses, refuse collection vehicles). The roadmap considers that demonstration projects provide the option to test the social, institutional and economic aspects in addition to technical implementation. In addition, the roadmap suggests that industrial clusters, logistics centres and regions are suitable locations for such an approach.

- **Research, development and demonstration for hydrogen:** The roadmap suggests that the key R&D questions regarding hydrogen should be addressed and tackled to lower the costs of hydrogen production and use, to increase the efficiency of the technology, to develop new processes, to develop the application of more widely available materials and to show these in pilots with the ultimate goal of developing a sustainable, reliable and affordable supply of hydrogen. A mission-driven long-term innovation programme would be suitable for that purpose. The Top Sector Energy will take the initiative for such a programme in collaboration with other top sectors, such as Chemistry and Logistics.

Public Awareness

The roadmap identifies the need for public support and awareness for during the roll-out of new hydrogen production sites, infrastructure, refuelling points and any other aspects which will involve direct consumer interaction. Past CCS projects have shown that people can be critical of such projects and hence it is crucial to provide information and encourage public engagement as part of the hydrogen strategy. The roadmap also considers it necessary to engage environmental organisations as has been done in the context of the CCS roadmap and to distinguish it from discussions on CCS.

Timeframes

The roadmap has considered various projects that are currently underway or recently concluded or for which a follow up is being considered on a five-year basis. These include a significant number of R&D projects through EU programmes.

The following regions in the Netherlands are working on hydrogen initiatives:

- Northern Netherlands
- Rotterdam/Goeree
- Southern Netherlands
- Arnhem/Gelderland
- Zeeland

The roadmap also provides examples of promising projects in industry, transport and mobility, climate-neutral electricity generation, and projects in the built environment in the short term (3 to 5 years).

Regulatory

There is work in progress to address issues such as the harmonisation of regulations, the development of certification for sustainable hydrogen and the development of standards for measuring the quantity and quality of hydrogen delivered at a refuelling station. A group of stakeholders led by the Netherlands Standardisation Institute has introduced a hydrogen safety programme. The primary focus of this programme is to conduct systematic reviews to identify all safety aspects, determine the existence of adequate measures and whether or not regulatory aspects have been addressed appropriately or not. It also considers safety aspects within built environments such as parking of hydrogen-powered cars in underground car parks or homes. The safety program does not include guidelines if hydrogen is to be used for heating purposes in homes. Even though a program specification is available and safety has been identified as an important aspect, it is yet to be implemented and will only be so when sufficient funding becomes available and industry participation increases. The roadmap points out that this issue should be clearly addressed in an action plan for hydrogen.

If hydrogen were to develop into a widely used energy carrier then the next issue that would arise is how to organise trade in hydrogen. The roadmap identifies that the Dutch gas market, which is organised around the Title Transfer Facility (TTF), can be used as a template for such a trading platform. However, unlike natural gas, in the case of hydrogen, the purity of the product must be predetermined and agreed upon between buyers and sellers.

Update

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APPENDIX K – NORTHERN NETHERLANDS

Country / Region

Northern Netherlands

Title / Key document(s)

The Green Hydrogen Economy in the Northern Netherlands, report by Northern Netherlands Innovation Board, Oct 2017.

Document Type and Author

Roadmap by a government authority (The Northern Netherlands Innovation Board).

Summary

This roadmap sets out the Northern Netherlands vision to develop into a green hydrogen hub within the Netherlands. Its existing gas fields, current challenges regarding gas production, extensive gas network, abundant onshore and offshore wind energy, a large chemical industry that consumes hydrogen (non-green) and existing know-how is believed to create a comparative advantage for the Northern Netherlands in transforming itself into a green hydrogen economy. The roadmap plans to develop the use of green hydrogen in its chemical industry, transportation sector, grid balancing and for heating homes and buildings. Three main potential sources of hydrogen production identified in the roadmap are electrolysis, biomass gasification and smart cities using solar energy.

Driving factors

The Northern Netherlands is well placed strategically for energy production. The Groningen/ Slochteren gas field situated in the Northern Netherlands is one of the largest gas fields in Europe. This has contributed to significant economic growth and employment for the region. However, natural gas production will be reduced in the future due to the following reasons:

- gas fields in the Northern Netherlands are becoming depleted;
- goals set at the Paris Agreement to reduce greenhouse gas emissions;
- subsidence caused at Groningen for years which impacted the groundwater levels; and
- earthquakes caused by gas production.

A reduction in gas production in the near future also means that fossil fuel based power plants need to start planning for their longer-term future, including approaches to reduce their carbon footprint. Under these circumstances and following a significant stakeholder consultation process, the Northern Netherlands formed the idea that transitioning from gas economy to green hydrogen economy will be the best option for the development of the Northern Netherlands in the energy arena.

In addition, the strategy argues that the geographical position of the Northern Netherlands also makes it conducive for the development of one of the first green hydrogen economies in Europe. The prominent features of the Northern Netherlands which place it at an advantageous position are large-scale green electricity production and importation, a large-scale chemical industry, gas expertise, constrained electricity transmission infrastructure leading to periods of very low-cost electricity, and, above all, a gas pipeline infrastructure that enables transmission of energy from the Northern Netherlands to the rest of Europe, and which has the potential for being efficiently converted to transport hydrogen.

Hydrogen Supply

The Northern Netherlands intends to produce hydrogen from:

- biogas or natural gas from steam reforming; and
- renewable sources such as on shore and off shore wind farms through electrolysis.

The existing electricity transmission infrastructure creates a potential barrier to the Northern Netherlands making full use of its potential renewable energy resource (particularly the ability to export surplus generation). However, this creates an opportunity for the Northern Netherlands to access this low-cost, surplus power together with imports of low-cost renewable electricity from Norway and Denmark, to produce hydrogen for export (also avoiding the cost of electricity grid enhancement). The strategy estimates that local surplus renewable generation together with the offshore cable connections with Norway and Denmark has the potential to run an electrolyser plant for more than 8,000 hours a year. The roadmap estimates that such an electrolyser can produce 160,000 tons of green hydrogen which will cost €2 to 3 per kg (A$3.2-4.8 per kg). This cost estimate is also similar to hydrogen produced from natural gas by steam reforming. The roadmap is hopeful that:

"*Once the green nature of the hydrogen is valued properly, a market for green hydrogen as a feedstock in industry and (eventually) for mobility could certainly be developed."*

The roadmap also explores the idea of installing a 1,000 MW biomass gasification plant next to the electrolysis plant. The oxygen released by the electrolysis plant can be used as an input in the biomass gasification plant. The price of hydrogen produced at a biomass gasification plant is estimated at €1.5 to 2.5 per kg (A$2.4-4 per kg).

The roadmap estimates that by 2025 or 2030, the calculated economic costs of producing green hydrogen, under the assumptions that the future economic conditions for offshore production and transportation of green hydrogen remain the same, will be between €3.4 and 4.2 per kg (A$5.4 to 6.7 per kg).

The roadmap believes that green hydrogen and green syngas production, along with the existing agricultural and chemical sectors in the Northern Netherlands, will attract new companies from sectors such as chemical, energy, agricultural, equipment and services and hence lead to growth in the Northern Netherlands.

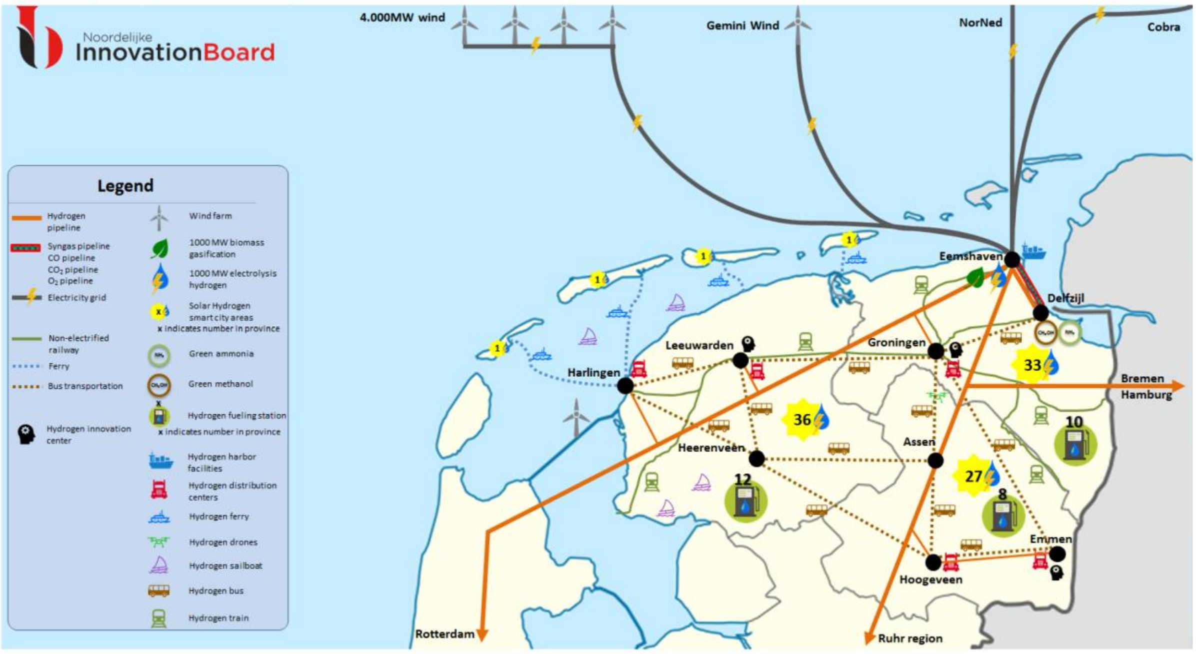
The roadmap envisions the production of 270,000 tons of hydrogen by 2030, including:

- production of 160,000 tons of hydrogen through 1,000 Mw electrolysis plant;
- production of 100,000 tons of hydrogen through 1,000 Mw biomass gasification plant; and
- production of 10,000 tons of hydrogen by 100 solar-hydrogen smart areas.

Major consumer of this hydrogen will be the chemical industry (Delfzijl). In particular, plants that produce ammonia and methanol will each consume 60,000 tons of hydrogen in order to produce 300,000 tons of ammonia and methanol respectively. Besides, other consumers of hydrogen will be:

- 12,000 tons demanded by 100,000 cars;
- 10,000 tons demanded by 1,300 buses;
- 5000 tons demanded by 50 trains; and
- 3000 tons demanded by other mobility sectors.

Figure J.1: Indicative schema for Green hydrogen economy in the Northern Netherlands



An additional 20,000 tons of hydrogen will be used for grid balancing and, finally, 100,000 tons of hydrogen can be fed into pipelines connecting Delfzijl and Rotterdam and Limburg and Germany.

Power Generation

The roadmap mentions that hydrogen as a fuel for power generation for energy-intensive industries needs research and development as part of the latter stage of market development.

Transport / Mobility

The development of hydrogen fuel cells for transportation is at an early stage in the Northern Netherlands. However, the roadmap foresees the need for a fuel cell hydrogen mobility infrastructure and intends to apply Germany's model to transition to a greener transportation sector in the Northern Netherlands.

Currently, there is sufficient interest from relevant companies to install hydrogen fuelling stations with the first one being under construction and announcements of a further eight stations to be constructed in the near future. The roadmap estimates that the Northern Netherlands will need at least 100 hydrogen fuelling stations to ensure that there is a station either within 20 minutes driving distance or every 30 km (maximum). At present, the minimum hydrogen supply is about 200 kg per day (40 to 60 cars), but it is forecast to grow to 1,000 kg per day (200 to 300 cars).

Industrial Systems

Presently, hydrogen is mostly produced from methane through Steam Methane Reforming (SMR) for industrial purposes. This hydrogen is extensively used in the chemical and petrochemical industries, but it is not green hydrogen. The roadmap states that one way to produce low-carbon hydrogen from methane is to capture and store the CO_2 in offshore geological features, such as an empty oil or gas field. The roadmap notes that since the Northern Netherlands is trying to reduce natural gas production, underground onshore storage of CO_2 is not viable in the Netherlands.

Gas networks

The roadmap states that both the onshore and offshore gas networks at Eemshaven are conducive for transitioning to a hydrogen economy. The onshore gas network can be initially used to blend hydrogen into the natural gas stream and once sufficient hydrogen is available, one of the gas pipelines can be transformed to transport hydrogen to places like Delfzijl, Zuidwending, Rotterdam, Limburg and Germany.

Renewable energy can be transported in the form of hydrogen through existing gas pipelines, thus eliminating the need for building additional transmission infrastructure. This strategy can be applied to off-shore wind farms.

With the depletion of natural gas as well as the goal of reducing greenhouse gas emissions, there is a risk that the existing natural gas pipeline infrastructure will become redundant unless an alternative use can be found for them. Converting them to transport hydrogen would not only increase the life of the gas pipelines but also save costs of demolishing them. In addition, the Northern Netherlands has an already established gas industry which includes knowledge base and infrastructure to easily transition from natural gas to hydrogen. The roadmap explains how various stakeholders who are currently operating in the natural gas industry can have similar roles in a green hydrogen industry. In addition, the existing companies have the potential to attract other industries who in turn could develop new and innovative products, systems or services in a green hydrogen economy.

Residential / Commercial

The roadmap states that it is important that homes and buildings become zero-emission structures in the future. As such, there is need to provide alternative zero-carbon energy sources to them. For example, in city areas with high-density homes and buildings, a heat grid could supply heat produced centrally. In other areas, homes can be better insulated and low-temperature heating system with an electric heat pump along with a heating and cooling underground storage can be used. In small villages and older sections of cities, it is worth considering whether green hydrogen or biogas could be delivered to homes and buildings in these areas through retrofitting the existing gas infrastructure. In which case, the burners in the boiler and stove can be changed easily and cheaply.

The roadmap talks about building “future smart areas” in which villages, farms, data centres, islands, industrial sites and everything in them needs to be fully sustainable which includes sustainable energy provision as well. The roadmap discusses further that an average city area or village in Europe with a population of 4,500 people contains 2,000 homes, one shopping centre, one gas station, schools, offices, 2,300 cars and several buses and trucks. To make such an area sustainable about 20 MWp of solar is required to be installed on roofs. In addition, a 5 MW electrolyser can be used to convert the excess electricity into hydrogen.

Smart areas like these will need an estimated investment of 25 million euros in solar and electrolyser capacity, hydrogen compression and storage. The problem with solar energy is excess production in summer and inadequate production in winter. Hence the electrolysers can bridge the seasonal gap by converting the excess solar electricity into hydrogen. Hydrogen fuel cells can then be used to produce enough energy to meet energy demand in winter.

Exports

Comparative Advantages

The roadmap cites the following reasons as to why the Northern Netherlands has a comparative advantage in developing a green hydrogen economy:

“*Abundant availability of low-cost green electricity from offshore wind and offshore electrical cables;*

Large and very sophisticated gas infrastructure, both onshore and offshore;

A well-established gas industry and knowledge network;

The presence of relevant chemical and agricultural industries; and

Neighbouring Germany is rapidly developing hydrogen fuelling infrastructure for cars."

The above combination of industrial activities, assets and infrastructure along with the need for transitioning to a green economy places the Northern Netherlands in a unique position to develop one of the first green hydrogen economies in Europe.

The Northern Netherlands is well placed to play a prominent role in the critical innovations for the green hydrogen economy. The region has already got well-established infrastructure for research, education, innovation and start-ups. The roadmap explains that the existing strong knowledge and education infrastructure in the region can be easily extended to hydrogen.

The roadmap lists the following institutions and industries that can be the foundation for a green hydrogen economy that the region aspires to be:

Academic institutions: Energy Academy Europe, the University of Groningen, several universities of applied sciences (Van Hall Larenstein in Leeuwarden and the Hanze University of Applied Sciences in Groningen) and secondary education centres.

Research and innovation centres: EnTranCe in Groningen could be one of the main contributors of innovation in green hydrogen production, conversion, storage, transportation and distribution. Wetsus in Leeuwarden could take the lead in membrane technology application. Senbis Polymer Innovations in Emmen can contribute to developing new and better chemical processes and applications for green hydrogen.

Innovative industries: Groningen Airport Eelde, will be redeveloped into a drone airport with hydrogen fuel cell technologies playing a role in sustaining longer drone flights in future. A maritime industry cluster in Friesland can use fuel cell and hydrogen technology for propulsion in the maritime sector, sailing, yachts, ferries, ships, etc. And a manufacturing industry cluster - High-Tech Systems and Materials can manufacture sensors, products and materials for the hydrogen industry, as well as using fuel cells and hydrogen technology in products such as buses, drones, robots and planes.

Role of Government

Funding / Costs

The total investment cost required for the development of a green hydrogen economy in the Northern Netherlands is estimated to be 17.5 to 25 billion euros up until 2025.

Challenges

The roadmap states that large scale production of hydrogen is required in order to reach competitive hydrogen prices of €2-3 per kg (A$3.2-4.8 per kg). In other words, unless a sufficient amount of hydrogen can be produced, it won't justify modifying an existing gas network to hydrogen network.

Recommendations (Roadmap)

Accenture concluded that "*a green hydrogen economy can only be realized by a well-coordinated and tightly directed approach by companies and governments working together. Companies need to make investments, but governments need to create the right conditions. To realize this large-scale green* *hydrogen economy, Accenture proposes the following phased approach, consisting of: I) the current phase, which is focused on ideation and mobilization; II) masterplan phase; III) backbone realization; IV) scale-up phase; and V) maturation phase.*

To realize the shift to the green hydrogen economy, a range of initiatives need to be agreed upon and executed in tandem. Accenture, therefore, proposes developing a master plan within a strong governance structure and in alignment with multiple stakeholders. This master plan needs to be developed from mid-2017 to mid-2018 and should be led by a Green Hydrogen Ambassador in combination with strong program coordination. The main elements of this master plan are as follows (in order):

A plan with business cases for the realization of initial projects: the creation of large-scale production facilities, hydrogen transport infrastructure and the development of industrial offtake markets for hydrogen feedstock;

The plan and the projects need to be developed in the context of a wider green hydrogen economy. Many aspects, such as a regulatory framework, research, education and training about hydrogen also needs to be developed. Other initiatives, projects and developments should be considered that focus on the transition to a sustainable energy system and a green economy; and

A covenant signed by stakeholders from industry, politics, civil society and knowledge centres."

Public Awareness

The roadmap suggested that an international green hydrogen trade fair and exhibition for businesses, professionals and an interested public should be held in the Northern Netherlands to increase public awareness, increase stakeholder engagement, provide information to interested parties (companies, organizations, politicians, civil servants and the public) and encourage society to embrace and get involved in green hydrogen. The roadmap further suggests that every year, a large trade fair and exhibition should be organized in a city in the Northern Netherlands. And between these events, a mobile green hydrogen exhibition could travel around the Northern Netherlands to inform the public.

Timeframes

The roadmap has been designed to achieve its goals by 2030.

Regulatory

The roadmap states that hydrogen is not included in the current regulatory framework (standards, regulations, permitting procedures, safety, environmental regulations and spatial planning) other than those prescribed for use in large-scale industrial production. In this case, reviewing and replicating regulatory frameworks and procedures from other countries, namely Germany and the US, can be used as a good starting point.

Update

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The Green Hydrogen Economy in the Northern Netherlands, report by Northern Netherlands Innovation Board, Oct 2017. Available at https://www.deingenieur.nl/uploads/media/5880bffadd9af/Green%20Hydrogen%20Economy%20in%20Northern%20Netherlands.pdf

APPENDIX L – NORWAY

Caveat – Unofficial synthesis. Readers are advised to check against the source.

Title / Key document(s)

No current hydrogen specific strategy document.

Norway's Climate Strategy for 2030: a transformational approach within a European cooperation framework, Norwegian Ministry of Climate and Environment.

Document Type and Author

National climate strategy by a government authority.

Abstract

Norway does not presently have an explicit, comprehensive strategy for developing hydrogen infrastructure and related industries. Although an advisory body – the Norwegian Hydrogen Council – was established by the Ministry of Petroleum and Energy in the early 2000s and delivered two hydrogen action plans (the most recent being for 2012-2015), it appears there was not complete follow-through by authorities. Nonetheless, policy development appears to be more advanced than most other countries, with early efforts to demonstrate hydrogen technologies in automotive vehicles and shipping. More recently, policy measures to promote adoption of zero-emission vehicles and a new programme to support the deployment of hydrogen stations have been introduced to promote the use of hydrogen-powered vehicles, while funding support has been provided to develop hydrogen-powered shipping. Norway's considerable natural gas and renewable energy resources can be utilised to produce hydrogen on a large scale, and the country is currently participating in a Japanese pilot project that will produce hydrogen using renewable energy.

Driving Factors

As part of the Paris Agreement, Norway pledged to reduce domestic greenhouse gas emissions by at least 40% below the 1990 level by 2030.

Norway has introduced a number of ambitious targets which are designed to promote adoption of zero-emissions technologies, especially in transportation. For example, the National Transport Plan calls for phasing out the sale of new fossil fuel-based cars and light vans by 2025, while all new urban buses will be required to either have zero emissions or use biogas by this date. Other targets apply for heavy vehicles (refer below). Meanwhile, the use of oil and paraffin for heating both new and old buildings will be prohibited from 2020.

The Norwegian Hydrogen Council published two Action plans for the periods 2007-2010 and 2012-2015. Notable outcomes from these plans respectively include the establishment of Transnova (now merged to form Envoa – see below) to support low and zero-emission transport and the provision of incentives for hydrogen refuelling infrastructure. The recommendations from the second action plan include:

- *"Business Development for Increased Value Creation, including measures to involve Norwegian SMEs in the emerging hydrogen technology market;*
- *'Research and Development, Network and Infrastructure', including extending and focusing R&D in hydrogen production, storage, distribution and use, as well as the creation of a national network of test laboratories;*
- *'National Facilitation', involving: the strengthening of Transnova to reflect the challenges it is handling, funded through a gradual increase in the fuel tax; the creation of a national plan for fuel supply for future vehicles, including incentives and support for hydrogen refuelling*

stations; and the investigation of the potential for large-scale export of sustainable hydrogen from Norway based on Norwegian energy resources;

- *'Effective Tools for Early Introduction of Hydrogen Vehicles', including incentives for zero-emission vehicles, with a required proportion of these vehicles in public fleets, subsidies for hydrogen cars until they are competitive, and coordinated procurement of FCEV with a focus on hydrogen in urban transport or fleet vehicles."* (Fuel Cell Today 2012, p.18).

However, the Council's recommendations across both Action Plans "were not similarly embraced by the Government" (Norwegian Hydrogen Forum, 2017).

Hydrogen Supply

Production of hydrogen from natural gas with carbon capture for European consumption was identified as one of four overarching goals when a government-appointed committee first considered the formation of a national hydrogen program in 2004 (Fuel Cell Today 2013).

Kawasaki Heavy Industries (KWI) and Nel Hydrogen are undertaking a pilot project in Norway as part of Japan's strategy of developing a global hydrogen supply chain. The project involves producing hydrogen using hydropower and is effectively competing with KWI's Australian pilot project that will use brown coal gasification and carbon sequestration. In 2017, Nel Hydrogen advised that it was aiming to eventually deliver liquefied hydrogen at a minimum cost of ¥24 (A$0.30) per Nm^3. In comparison, the cost of sourcing hydrogen from Australia was estimated to be ¥29.8 (A$0.37) per Nm^3 (Reuters, 2017).

In terms of production costs, Nel Hydrogen (not dated) observes that current renewable power at a cost of less than ¥6 (A$0.1) per kWh enables the production of hydrogen using electrolysers (50MW capacity) at less than ¥400 (A$4.95) per kilogram at the plant.

Power Generation

Hydropower accounts for more than 90% of the installed capacity of Norway's electricity system. Such high penetration reduces the imperative of hydrogen as a source of low emissions power generation, and decarbonisation efforts have consequently focused on the transportation sector.

Transport / Mobility

In addition to its goal of banning the sale of all fossil-fuel-powered cars and light vans by 2025, Norway has set zero-emission vehicle sales targets for new heavy-duty vehicles (100%), long-distance coaches (75%) and new trucks (50%), although these are not scheduled until 2030 (Norwegian Ministry of Transport and Communications, 2017). The economic cost of achieving the 100% zero-emission target for passenger vehicles by 2025 is estimated to be NOK 500 to 1500 (A$82 to 246) per tonne reduction in carbon equivalent emissions averaged over the period 2016 to 2030 (Norwegian Ministry of Climate and Environment, 2017).

Norway provides preferential tax treatment for hydrogen and electric cars including, among other things, exemptions from value-added tax and motor vehicle registration tax, and lower annual motor vehicle tax.

Enova – a Norwegian public enterprise dedicated to investing in innovation and technology to reduce greenhouse gas emissions – has established a support scheme for public hydrogen transportation infrastructure. The organisation provides subsidies for the establishment of hydrogen fuelling stations up to 40% of approved project costs (Enova, 2019).

Norway is leading efforts to adopt hydrogen in shipping through a combination of government support and industry cooperation. Through its PILOT-E environmental innovation program, the Norwegian Government has provided funding for a hydrogen-powered high-speed ferry and a short-sea containership and has mandated that at least 50% of energy for an existing ferry service be derived from hydrogen upon future conversion to an electrically powered service (Lipsith, 2019).

Industrial Systems

Enova has funded various hydrogen-based projects, including a new smelting technology process that utilises hydrogen instead of coal.

Gas networks

Residential

Exports

Comparative Advantages

Aggressive policy targets for the adoption of zero-emissions technologies.

Role of Government

The public sector plays a leading role in setting targets and developing policy instruments, including incentives, to promote adoption of low-emission technologies. It provides early-stage funding support for infrastructure and research and development in new technologies through grant funding rounds (e.g. hydrogen stations, PILOT-E program). However, the development of transport infrastructure should ideally become market driven as soon as possible, enabling public sector withdrawal (Norwegian Ministry of Climate and Environment, 2017).

Funding / Costs

Norway provides support to the hydrogen economy through various measures including preferential tax treatment, investment support, subsidies and general technology grant programs, which makes it difficult to identify specific funding commitments for hydrogen. The value of supports for promoting low-emissions technologies more generally are significant. For instance, the value of tax advantages and other preferential treatment for zero-emissions vehicles, which would accrue overwhelmingly to battery electric vehicles rather than hydrogen fuel cell cars given their greater adoption, was estimated to be NOK 2.9 billion (A$476 million) in 2016 (Norwegian Ministry of Climate and Environment, 2017).

In terms of hydrogen more specifically, in late 2018 Enova awarded a grant of NOK 24 million (A$3.9 million) to establish four additional hydrogen fuelling stations in Norway.

Challenges

Targets for zero-emission vehicle adoption are predicated on technological progress enabling price competitiveness with conventional vehicles being achieved.

Recommendations (Roadmap)

Public Awareness

Timeframes

Regulatory

Update

The government is in the process of establishing a new national hydrogen strategy.

A study of Kawasaki Heavy Industries' pilot hydrogen project is expected to be released in 2019.

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APPENDIX M – REPUBLIC OF KOREA

Caveat – Unofficial synthesis. Readers are advised to check against the source.

Title / Key document(s)

Hydrogen Economy, Roadmap of Korea, Ministry of Trade, Industry and Energy, 2019

Hydrogen Economy Roadmap of Korea, Government of Korea, 2019.

Remarks by President Moon Jae-in at Presentation for Hydrogen Economy Roadmap and Ulsan's Future Energy Strategy

Document Type and Author

National strategy announcement and national government documents.

Abstract

On 17th January 2019 South Korean President Moon Jae-in outlined a vision for developing a hydrogen-based economy. The core elements of the plan include:

- increasing production and adoption of hydrogen fuel cell vehicles;
- increasing production of fuel cells for power generation and home consumption (electricity and heat); and
- building a hydrogen production and distribution system.

The strategy involves providing incentives and subsidies to increase economies of scale on both the supply and demand sides in order to lower production costs, accelerate the self-proliferation of hydrogen technologies, and increase exports.

Driving Factors

The hydrogen economy has been identified as a core component of South Korea's current industrial strategy and a potential new growth engine. The potential for hydrogen to displace oil and coal as an energy source, and the development of hydrogen technologies and infrastructure in respect of production, storage and transportation may form new industries and sources of economic growth. As the hydrogen economy is still in its infancy and global competition is intensifying within this space, South Korea sees an early mover advantage in fostering the development of a local hydrogen economy.

The strategy envisions that moving to a hydrogen economy will help South Korea improve its energy self-sufficiency. More than 97% of fossil fuels used by South Korea is met through imports, which in addition to presenting a security of supply risk, makes the country vulnerable to fluctuations in global resource prices (Government of Korea, 2019).

Reducing air pollution is another motive for encouraging hydrogen adoption. Producing energy using carbon-based sources, particularly in automobiles, produces particulate emissions. The government estimates that the volume of particulate emissions could be reduced by 10% compared to current levels by 2030 if its targets for hydrogen-powered cars are met.

Hydrogen is seen as one method of helping South Korea transition to a low carbon economy. The country's current target is to reduce greenhouse gas emissions by 37% from business-as-usual levels by 2030.

Hydrogen Supply

The recently announced strategy aims to build a system for producing and supplying hydrogen. President Moon Jae-in (2019) noted that existing petrochemical plants have the capability to produce hydrogen as a by-product and that hydrogen production using renewable solar, wind and bioenergy will become more widely spread in the future. In the early stage, it is anticipated that hydrogen will be produced from natural gas with production being based near existing LNG gas networks and major sources of demand. In order to reduce production costs and develop eco-friendly sources of hydrogen production, large-scale research and development and demonstrations of electrolysis using excess renewable energy will commence by 2022. However, domestic eco-friendly production will not be sufficient to meet future demand, so Korea expects that by 2030 it will need to import hydrogen that is produced using renewable energy and "brown coal in an eco-friendly way", with 70% of hydrogen demand by 2040 comprising CO_2 free hydrogen (MTIE, 2019).

The production price for hydrogen is estimated to be KRW 1,500 to 2,000 per kg (A$1.9 to 2.5) for by-product hydrogen, KRW 2,700 to 5,100 per kg (A$3.3 to 6.3) for hydrogen extraction, and KRW 9,000 to 10,000 per kg (A$11.1 to 12.4) for water electrolysis (Government of Korea, 2019).

It is anticipated that lifting hydrogen production from 130,000 tons in 2018 to 5.26 million tons by 2040 will reduce the unit price of hydrogen from 8,000 won per kg (A$9.9) to around 3,000 won per kg (A$3.7) over this period (Government of Korea, 2019). In the medium term, raising production to 470,000 tons a year by 2022 is expected to bring the price down to 6,000 won per kg (A$7.4).

In addition to production, South Korea is looking to boost its industrial capability in respect of developing large scale transportation and storage infrastructure. It aims to demonstrate large scale high-pressure gaseous storage and transportation over the next few years, and then localise liquid hydrogen storage technologies such as plants, tanks and pumps by 2030. In terms of hydrogen refuelling, it hopes to develop hi-pressure (700 bar or more) tube trailers and to increase capacity further by introducing trucks with liquid and liquefied hydrogen storage by 2030. It will also look to develop materials that will enable the construction of durable pipelines that can transport hydrogen exclusively at high pressure (50 bar or more). And to facilitate the importation of hydrogen from 2030, it will "develop related infrastructure including liquefaction and liquid technology, hydrogen transport vessel, and liquefaction plants in 2022, as well as the construction of receiving bases for overseas hydrogen" (MTIE, 2019)

Power Generation

The current strategy envisions using fuel cells to provide power for homes and commercial buildings as part of a distributed energy system. It is hoped that by 2040 fuel cell production capacity will reach 15GW, with 8GW going toward domestic use and 7GW for exports. Of the domestic use target, 2.1 gigawatts will be for households and buildings (Government of Korea, 2019).

It is anticipated that scaling up production and deployment of fuel cells will reduce the installation and power generation costs by 65% and 50% respectively, by 2040. More specifically, installation costs are projected to fall from KRW 4.5 million to KRW 1.57 million per kW (A$5,560 to $1,940 per kW), while power generation costs are projected to fall from KRW 250 to 131 per kWh (A$0.3 to $0.2 per kWh). The unit power costs of fuel cells are expected to "reach" small and medium-sized gas turbines by 2025.

In order to encourage the deployment of fuel cells for power generation, a supportive price mechanism will be established by introducing specific gas tariffs for fuel cells, supported by weighted renewable supply certificates for fuel cells (Government of Korea, 2019).

The plan also commits to reviewing and developing hydrogen gas turbines as an additional potential energy source.

Transport / Mobility

Less than 2,000 hydrogen fuel cell vehicles have been produced in South Korea to date. The government plans to increase production to 4,000 vehicles in 2019, 81,000 by 2022, 1.8 million by 2030, and 6.2 million by 2040. It is anticipated that increasing annual production to 100,000 vehicles will halve the retail price of a hydrogen car to approximately 30 million won or A$37,000 (Pulse, 2019). The affordability of hydrogen-powered cars is currently facilitated by a subsidy of approximately 30 million won or A$43,250 per car (Moon Jae-in, 2019).

The central government plans to work with local government to try to increase the number of hydrogen-powered buses to 2,000 by 2022 and replace 820 police buses with hydrogen-powered versions. Meanwhile, existing subsidies for cars and buses will be extended to taxis and trucks in order to further promote fuel cell vehicle adoption. It is anticipated that the number of fuel cell taxis and trucks will increase from zero presently, to 80,000 and 30,000 respectively, by 2040 (MTIE, 2019).

In order to support the growth in FCVs, the government plans to increase the number of hydrogen fuel stations across the country to 1,200 by 2040 (Pulse, 2019). The short-term goals are more modest, with the government planning to increase the number of stations from its recent level of just 14 stations to 86 by the end of 2019, and to 310 by 2022. The government will subsidise the construction of refuelling stations, provide business partners with long-term, low-interest policy loans, subsidies the cost of fuel for commercial vehicles such as taxis and buses, and support demonstration projects (Government of Korea, 2019).

The current strategy also seeks to develop other forms of hydrogen mobility applications including ships, trains and drones, which is a notable departure from the previous 2005 hydrogen energy master plan.

Industrial Systems

Beyond developing a local hydrogen industrial economy, fuel cells will be used as an energy source for commercial buildings.

Gas Networks

The nation’s 5,000km of natural gas pipelines “can be utilized to extract hydrogen economically and supply it to a variety of regions” (Moon Jae-in, 2019). In the short to medium term, the country plans to establish hydrogen specific pipelines near industrial sources of by-product hydrogen and cities with high demand, while by 2030 it will consider installing hydrogen pipelines nationwide (MTIE, 2019).

Residential

Under the current roadmap, fuel cells will be used as an energy source for homes. Provision of hydrogen fuel cells for homes and building is expected to rise from a current level of 7MW to 50 MW in 2022, and to 2.1GW by 2040, when approximately 940,000 homes will be supplied with fuel cells (MTIE, 2019).

Fuel cell installation costs for homes and buildings are currently estimated to be KRW 27 million per kW (A$33,400) (Government of Korea, 2019). It is expected that adoption of fuel cells will be supported by subsidies, financial incentives under the electricity tariff specialisation system, and provisions for mandatory installation of fuel cells in new private buildings and public institutions (MTIE, 2019).

Exports

Development of a hydrogen economy is a core element of South Korea's current industrial strategy. The country has significant export capabilities in industries such as automobile manufacturing, shipbuilding and petrochemicals, which could form the basis of hydrogen-based export activities. While the global market for hydrogen fuel cell vehicles is currently small, South Korea has a 50% share of the global market (Moon Jae-in, 2019).

Comparative Advantages

Ability to leverage existing industry capabilities in automobile manufacturing, shipbuilding and petrochemicals.

A strong policy commitment to support the development of an infant domestic hydrogen industry.

Role of Government

In order to stimulate demand, the government currently provides subsidies for hydrogen-powered cars and buses, which will be extended to taxis and trucks. The government will provide subsidies for the construction and operation of hydrogen stations during the initial phase of deployment. It will modify electricity tariffs to encourage the adoption of fuel cells for power generation and mandate their installation in certain circumstances.

The government will provide a legal and institutional basis to support the development of the hydrogen economy and ensure safety through the entire hydrogen chain from production to use. For example, it will modify existing laws to make it easier to establish hydrogen infrastructure (see Regulatory section below).

Funding / Costs

The government will provide support through a combination of subsidies, tax incentives, demonstration projects, mandatory usage requirements, and research and development support. The exact nature and scale of support are still being determined.

Challenges

The target for future adoption of vehicles and fuel cells may be optimistic given cost advantages enjoyed by lithium-ion batteries, electric vehicles and existing renewable energy technologies in terms of wind and solar power. The adoption of fuel cell vehicles has challenges in terms of high costs and a lack of existing refuelling infrastructure, while fuel cells also have high installation and hydrogen fuel costs (MTIE, 2019).

Policy continuity – the focus of South Korea's energy policy and research focus has shifted in the past (e.g. from hydrogen to nuclear in the late 2000s) with the change of administrations (Strangarone, 2019).

Recommendations (Roadmap)

Public Awareness

Developing a positive public perception of hydrogen safety is one of the roles for government. This will be achieved through the development of 'hydrogen safety guidebooks', designating a 'Hydrogen Day' to promote awareness of new technologies and significant contributions, and the establishment of Hydrogen Safety Experience Centres to promote a hydrogen safety education and culture (Government of Korea, 2019).

Timeframes

The current strategy establishes various time frames, but short to medium terms goals generally reference 2022, while longer terms goals reference 2040.

Regulatory

Existing laws will be modified to accommodate an industrial hydrogen ecosystem. For example, to facilitate the expansion of hydrogen fuel stations the government plans to relax regulations by building a “regulatory sandbox” for constructing hydrogen fuel stations in metropolitan areas. Safety management regulations for hydrogen-related products and facilities will also need to be established.

Update

It is anticipated that a Hydrogen Economy Act will be enacted in the second half of 2019. The Act will formalise South Korea’s strategy for cultivating a hydrogen-based economy.

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APPENDIX N – UNITED KINGDOM

Caveat – Unofficial synthesis. Readers are advised to check against the source.

Title / Key document(s)

The Clean Growth Strategy, Leading to way to a low carbon future, Her Majesty's Government, 2017.

Industrial Strategy, Building a Britain fit for the Future, Her Majesty's Government, 2017.

Document Type and Author

Strategies by prepared by the national government.

Abstract

The United Kingdom industrial and clean growth strategies seek to maximise the economic and social benefits to the UK from transitioning to a clean energy economy and to achieve this transition at the lowest possible net cost to UK society. "Low carbon" hydrogen has been identified as a potential clean technology that can decarbonise the industry, heat and transport sectors. Research and demonstration projects are being funded under a range of programs covering these sectors in order to enable learning and development and overcome cost disadvantages relative to existing carbon-intensive technologies. It is currently expected that the main form of hydrogen production will be steam methane reforming of natural gas with carbon capture, usage and storage.

Driving Factors

Maximising "the advantages for UK industry from the global shift to clean growth" has been identified as one of four grand challenges by the UK's *Industrial Strategy* (HM Government, 2017). This strategy envisions Britain taking a leading role in the development, manufacture and application of low carbon technologies and systems, with the long-term goal of making these technologies cost less than high carbon alternatives. The strategy briefly notes that Britain will continue to explore the potential applications of low carbon hydrogen.

Under the Climate Change Act, the UK has committed to reducing greenhouse gas emissions by at least 80% by 2050 relative to 1990 levels. The *Clean Growth Strategy* identifies three illustrative pathways to meeting this long term abatement goal: an electricity pathway, hydrogen pathway and emissions removal pathway (i.e. biomass power using carbon capture, usage and storage (CCUS)). Under the hydrogen pathway, by 2050 hydrogen would provide a majority of heating for heating homes (62%) and commercial and public buildings (56%), power all cars and vans, and play a significant role in firing industrial processes. These pathways are only illustrative and a combination of these solutions, especially electrification, may well be deployed depending on how the relative cost and effectiveness of the various technologies evolve.

Hydrogen Supply

Under the illustrative hydrogen pathway outlined in the *Clean Growth Strategy*, total hydrogen production would reach approximately 700 TWh in 2050. The main form of production would be steam methane reforming with carbon capture, usage and storage.

A £20 million (A$36 million) Hydrogen Supply Programme has been established to identify and trial various approaches to supplying low carbon hydrogen in bulk. Target uses include supplying the gas network, industry, power, transport and import terminals. The programme is technologically neutral but takes a portfolio approach to funding to ensure that various technologies are given due consideration.

A key aim of the Hydrogen Supply Programme is to overcome the cost differential between low carbon hydrogen and natural gas. The wholesale price of natural gas in the UK was recently 1 to 2 pence (p) per kWh. In comparison, the cost of producing hydrogen using steam methane reformation of natural gas with carbon capture and storage is estimated to range from 2 to 5 p/kWh, while the cost for electrolysis is in the order of 4 to 9 p/kWh (BEIS, 2018). Other potential zero-carbon hydrogen production methods include using nuclear energy and biomass with CCS.

Power Generation

Transport / Mobility

The transport sector was responsible for 24% of UK carbon emissions in 2014 (HM Government 2017a). The UK government has set a target for all new cars and vans to be zero-emission by 2040. In order to accelerate the take up of ultra-low emission vehicles the government provides subsidies for the purchase of eligible new low emission vehicles (up to £3,500) and installing chargers at home, and operates various other schemes that support the deployment of low emission vehicles and infrastructure, including hydrogen solutions.

The Hydrogen for Transport Programme provides up to £23 million (A$41.3 million) in grant funding to accelerate the uptake of hydrogen vehicles and deployment of refuelling stations. Stage one awarded £8.8 million to construct four new refuelling stations, upgrade several existing stations and deploy over 290 FCVs. Stage two awarded £14 million to five projects in early 2019 that together will establish five new hydrogen refuelling stations, and deploy 73 FCVs and 33 fuel cell electric buses (Ricardo 2019).

The government has funded a £20 million Low Emission Freight and Logistics Trail that is designed to demonstrate new technologies and facilitate the deployment of low and zero-emission vehicles. Among the successful applicants include a project that will trial hydrogen dual-fuel technology in a range of vehicles and a project that will trial an on-vehicle system for using hydrogen to enrich hydrocarbon fuels (HM Government, 2017b).

Industrial Systems

Switching to the use of low carbon fuels such as hydrogen in industrial processes is “currently viewed as expensive and disruptive” (HM Government, 2017a). Support is consequently being provided to identify and test potential industrial applications. As mentioned above, the UK has established a competitive Hydrogen Supply Programme to find and test options for producing low cost, low carbon hydrogen at scale to supply various sectors including industry. A £20 million Industrial Fuel Switching Programme has also been established to help industry transition to low carbon fuels such as hydrogen, biomass and clean electricity. A report which identifies the potential for industries to switch to these technologies was commissioned as part of Phase 1 of this programme, while applications for feasibility studies into “developing technologies to enable the use of a low carbon fuel for a particular industrial process or across an entire site” recently closed as part of Phase 2.

Gas Networks

In order to meet the 2050 carbon abatement goal, almost all heat in buildings will need to be decarbonised, which presents the most difficult policy and technology challenge (HM Government, 2017a). Nearly 70% of heat for homes, businesses and industry is produced from natural gas. While switching to electric heat pumps represents one likely solution for residential heating, replacing natural gas in the gas grid with low carbon gases such as hydrogen is another option that is being explored.[9]

[9] Town gas, which used to be widely used in the UK prior, consists of around 50% hydrogen.

Government and industry are currently undertaking research and developing demonstration projects in order to understand how hydrogen can be used in existing gas networks and associated domestic appliances. For instance, the Department of Business, Energy and Industrial Strategy has commissioned a £25 million Hydrogen for Heat programme that is exploring the feasibility of using hydrogen gas for heating homes and businesses. Key focus areas of the programme include the safety of using hydrogen in buildings and the development of appliances that burn hydrogen rather than methane. In terms of industry, Northern Gas Works, Cadent and Equinor have developed the H21 North of England concept – a detailed engineering solution for converting 3.7 million homes and businesses across the north of England from natural gas to hydrogen between 2028 and 2034 (Sadler et al 2018).[10]

Meanwhile, Cadent, the largest gas distribution network in the UK, is developing its HyNet project in the North West of England which aims to demonstrate an end to end hydrogen energy system. This project involves producing hydrogen from natural gas with CCUS, blending up to 20% of hydrogen by volume into the existing natural gas network, and constructing new hydrogen pipeline infrastructure which could also enable hydrogen transport refuelling. The main end-uses would be homes (2 million) and small businesses connected to the existing gas network and industrial users. Over one million tonnes of carbon dioxide emissions would be avoided per annum, while the total required infrastructure investment being estimated to be £900 million (A$1,620 million) (Cadent, 2019). Funding options to move the project forward are currently being explored.

Residential / Commercial

See gas networks.

Exports

A goal of the industrial strategy of developing low-cost clean technologies if "for UK businesses to take the lead in supplying them to global markets" (HM Government, 2017).

Comparative Advantages

Considerable work on exploring the potential for using hydrogen in heating, industrial and automotive applications has commenced.

Role of Government

Funding research and demonstration projects in order to reduce the cost of hydrogen and other clean technologies and identify challenges with integrating hydrogen into existing gas networks, industrial uses and automotive applications. Provide a supportive regulatory environment for low carbon technologies. More generally, government plays an important role in funding education and training, infrastructure (especially transportation) and scientific research which are important sources of productivity, and supports exporters through the identification of overseas opportunities, providing industry briefings, overseas missions etc. (HM Government, 2017).

Funding / Costs

The UK government has committed to invest significant amounts as part of its industrial and clean growth strategies. For example, the clean growth strategy invests over £2.5 billion (A$4.5 billion) between 2015 and 2021 to support low carbon innovation across a range of technologies. Funding for notable hydrogen specific programs including the Hydrogen Supply Programme, Hydrogen for Transport Programme and Hydrogen for Heat Programme, amount to A$122 million in total, which is equivalent to 0.003% of GDP in 2018. Hydrogen projects can also potentially receive funding under

[10] Refer to The H21 Leeds Citygate Project summary for more detail regarding a specific H21 project.

various general schemes such as the Clean Growth Fund, Carbon Capture and Utilisation Demonstration Programme, Industrial Fuel Switching competition, Industrial Energy Efficiency Accelerator, Low Emission Freight and Logistics Trail etc.

Challenges

Reducing the cost of hydrogen solutions to reach parity with existing carbon-intensive technologies.

Recommendations (Roadmap)

Public Awareness

Timeframes

Hydrogen is seen as one of several potential solutions (along with electrification, bio-mass and CCUS) that could be deployed to achieve the 2050 80% carbon abatement reduction target. Current research and development projects are generally focused on enabling these technologies to be deployed on a large scale after 2030 to facilitate carbon abatement, with the exact mix depending on cost competitiveness and technical challenges.

Regulatory

See ‘role of government’.

Update

Various demonstration projects are or will be funded which will provide evidence on the feasibility and costs associated with switching to hydrogen solutions. For example, a report on the Low Emission Freight and Logistics Trial should be released in January 2020, while the deadline for applications for feasibility studies under the Industrial Fuel Switching Programme recently closed.

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APPENDIX O – LEEDS, UNITED KINGDOM

Caveat – Unofficial synthesis. Readers are advised to check against the source.

Title / Key document(s)

The H21 Leeds Citygate Project

Document Type and Author

Government-funded report prepared by a project team led by Northern Gas Networks (private company).

Abstract

The H21 Leeds Citygate Project is a proposal to convert the existing natural gas network in Leeds to 100% hydrogen.

A detailed technical and economic study has determined that the project is feasible.

The finalised conversion area comprises 264,000 meter points, representing approximately 660,000 people.

The strategy involves producing hydrogen using Steam Methane Reformers using natural gas; sequestration of carbon emissions under the North Sea; salt cavern hydrogen storage to meet inter-seasonal and intraday demands; a hydrogen transmission system to connect the SMRs and salt caverns to the distribution network; and appliance conversion for the domestic, commercial and industrial sectors.

The combination of SMRs and carbon capture and storage (CCS) would provide a 73% reduction in carbon emissions.

Driving Factors

The UK has a target to reduce carbon emissions by 80% of 1990 levels.

Conversion of the existing gas grid from natural gas to hydrogen has the potential to achieve significant carbon reductions but has been given little attention in the past.

Hydrogen Supply

Of the three industrial-scale hydrogen production methods - electrolysis, by-product hydrogen from industrial processes (chlor alkali plants or ore refineries) and steam methane reforming (SMR) - only electrolysis and SMR were considered capable of producing the required volumes.

Production using electrolysis was not considered practical due to various factors, including limited availability of curtailed electricity; cost of existing bulk grid electricity leading to “expensive” hydrogen production cost; substantial land requirements for dedicated renewable energy supply (i.e. wind) and electrolysers (400 x 2.6 MW units); additional storage requirements to accommodate variability of wind power; and additional costs of associated electrical infrastructure. Assuming a bulk electricity cost of 6 p/kWh, the cost of producing hydrogen at the electrolyser was estimated to be 10 p/kWh, excluding transmission and storage costs.

SMR (4 x 256 MW capacity) was chosen as it is a proven technology, has a relatively smaller footprint, and can be integrated into the existing natural gas supply chain. As this approach involves the production of carbon emissions, carbon capture technology would be included to capture 90% of emissions for subsequent sequestration (1.5 million tonnes per annum).

Intraday and inter-seasonal storage are included in the form of salt cavern storage. The use of hydrogen storage accommodates large changes in inter-seasonal energy demand, and the smoother production profile reduces the need for natural gas purchases during periods of high demand.

Power Generation

Transport / Mobility

Conversion of the grid to hydrogen could provide a feedstock for automotive use.

Industrial Systems

Gas Networks

Metals pipes are susceptible to embrittlement under high-pressure hydrogen transfer. The existing high pressure national and local transmission systems, which are composed of metal piping, are thus not suitable for 100% hydrogen. A hydrogen transmission system would be required to connect production and storage to the low-pressure local distribution network.

A national Irons Mains Replacement Programme, which involves upgrading the existing gas network to polyethylene, means substantial parts of the local distribution network are suitable for transporting 100% hydrogen. Remaining metallic mains may need to be replaced, and could be fast-tracked into the existing replacement program, but may still be capable of transporting 100% hydrogen given the lower pressure environment.

The existing gas network would be converted in a staged fashion over a three year period.

Residential / Commercial

A benefit of this approach is that households would not need to install other forms of low carbon infrastructure, which can be problematic given space limitations.

Complete conversion of the gas grid could enable heat and power using fuel cell technologies. However, hydrogen clean-up units would need to be developed to achieve the hydrogen purity levels that fuel cells require.

Exports

Intended for domestic consumption purposes only, although the development of hydrogen-based appliances may create export opportunities for local appliance manufacturers.

Comparative Advantages

Leeds was selected due to its proximity to carbon capture projects, local geology which is suitable for salt cavern gas storage, and nature of its gas grid in terms of being representative of other UK cities.

Able to leverage existing gas pipeline infrastructure. The UK has a demonstrated ability to achieve large-scale gas network and appliance conversions given the migration from town gas to natural gas in the 1960s and 70s.

An Existing Iron Mains Replacement Programme has resulted in the development of a distribution system that is suitable for the transmission of hydrogen.

Role of Government

The technical and economic study was funded by the UK government.

The H21 project received £10 million (A$18.0 million) in funding from Ofgem - the government regulator for gas and electricity markets - to test the potential for city-wide transition (BusinessGreen 2017).

Some government funding may be appropriate to stimulate basic hydrogen appliance development.

Funding / Costs

The total capital costs of the project are estimated to be £2,054 million (A$3,692 million).

The largest single cost relates to appliance conversion, which accounts for approximately half (£1,053 million) of the total cost. Other major costs include the Steam Methane Reformer Costs (£395 million), inter-season salt caverns (£289 million), and hydrogen transmission system (£230 million). Network capacity and preparatory works are relatively small (£10 million).

It is anticipated that the project, including potentially appliance conversion, would be funded through regulated price control, and is expected to have limited impact on customer bills (maximum of 2.9% in 2026/27).

Challenges

Although hydrogen appliances are available, the market is underdeveloped, and some form of incentive plan (e.g. national heat policy) would be needed to encourage the development of the wide range of appliances that are required.

Conversion of a city gas network to hydrogen requires careful planning and comprehensive strategy development, including sequencing of works.

Recommendations (Roadmap)

Public Awareness

Timeframes

Conversion takes considerable time. Major stages include several years of preliminary design work, construction of the SMRs, salt cavern storage and hydrogen transmission system over four years, while the gas network and appliance conversion would take place in stages over three years. Assuming the government approves the project in 2021, conversion would not be completed until 2028.

Regulatory

Some existing legislation would need to be modified to accommodate hydrogen supply. For example, the existing Uniform Network Code is restricted to natural gas.

Update

Pilot testing was being carried out (see Role of Government).

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APPENDIX P – LONDON, UNITED KINGDOM

Caveat – Unofficial synthesis. Readers are advised to check against the source.

Title / Key document(s)

London: a capital for hydrogen and fuel cell technologies, report prepared Hydrogen London by Element Energy Ltd, Apr 2016.

Document Type and Author

Report prepared by Advisory Body, Hydrogen London established by the Mayor's Office in 2002.

Abstract

The three main objectives of the report are to:

- show how hydrogen and fuel cell technologies can help solve London's challenges in terms of population growth and environment;
- provide evidence to support the case for continued investment in hydrogen fuel cell (HFC) technology by public and private sector organisations in the transport, transportable and stationary sectors; and
- to spread awareness about these hydrogen technologies to persons and stakeholders who are not familiar with the sector.

London considers itself a leader in deploying zero-emission hydrogen and fuel cell technologies in urban operation. London has achieved a presence in harnessing benefits using hydrogen technology as demonstrated by establishing 3 hydrogen refilling stations; operation of multiple fuel cell vehicles (8 buses, 15 vehicles from global OEMs, and 10 hydrogen-diesel vans); 3 large-scale fuel cell combined heat & power plants (largest number in one European city with a combined total capacity of 1MW); and the sale of hundreds of unsubsidised portable power units.

Driving Factors

Hydrogen London's objective is to stay ahead of other economies such that it remains at the forefront of innovation. This will help London to develop a specialised and skilled industry which will, in turn, attract investment as well as demonstrate to stakeholders its intention to bring positive change.

Two major issues faced by London are decarbonisation (15% CO_2 emissions in London come from the transport sector) and poor air quality (47% NOx emissions in London comes from road transport).

In terms of overall GHG emissions, London has a reduction target of 60% below the 1990 level by 2025.

Hydrogen Supply

The report discusses how hydrogen and fuel cell technologies can help address London's infrastructure and environmental issues in the short and long term. The focus of this report is on natural gas-fuelled fuel cells and foresees the period until 2025 as a transitioning period.

Hydrogen London considers two sources of obtaining Hydrogen:

- Low carbon-hydrogen from conventional fuels such as nuclear power and fossil fuels with carbon capture and storage and then distribution through 100% hydrogen pipelines; and
- Low carbon-hydrogen from power-to-gas where excess renewable energy is converted into hydrogen and injected into existing gas networks. This can establish a link between natural gas and electricity grids. However, the economic viability of this technology will require very

low (possibly negative) electricity prices at times of high generation and low demand, technology cost reductions and efficiency improvements, etc.

The report considers various carbon-hydrogen production processes such as steam methane reforming (SMR), electrolysis, biogas and CCS. Hydrogen production using SMR has a large production capacity in the UK, while hydrogen produced through electrolysis has several suppliers based in the UK. Hydrogen produced through biogas and CCS is at various stages of development in the UK. Production costs for hydrogen in 2030 are estimated to converge to approximately £4 per kg (A$7.2) for natural gas SMR, electrolysis using renewable energies and centralised SMR and CCS respectively. In comparison, the estimated production cost for hydrogen using biogas reforming in 2030 is projected to be £5 per kg (A$9.0).

Power Generation

The report states that hydrogen and fuel cells can address some of the biggest energy system challenges for London. A crucial part of London's plan for decarbonisation and energy security is increasing the use of decentralised heat and power generation. Fuel cells can be a key element of this since it can generate electricity and provide heating and cooling solutions with minimal CO_2 production. Fuel cell technologies can be compatible with decarbonised gas grids in the future as well, leading to further reductions in CO_2 emissions. Some of the other arguments in favour of power generation through hydrogen and fuel cells include:

- Stationary fuel cells produce negligible air pollutant emissions and hence are suitable for London where air quality is a major issue.
- Unlike other prime mover technologies, fuel cells suffer no loss in efficiency between 100% and 50% load.
- Stationary fuel cells have proven reliability and can operate with the availability of >98%.
- Other advantages of fuel cells over alternative large engines include vibration-free, relatively low noise, long life, and low maintenance requirements which makes them *urban-friendly* solutions.
- Large stationary fuel cell generators are already available from a number of suppliers, using robust, reliable, proven technology.
- Even though current costs for fuel cell CHP are higher than for conventional engines, further research and development and economies of scale will pave the way for cost reductions over time.

While energy from stationary fuel cells is more expensive than grid power (and gas boiler), increasing production volumes will lead to cost savings over time and reap the benefits of economies of scale. Levelized cost of electricity from large stationary fuel cell was estimated to be £120 per MWh in 2015 compared to £85 per MWh from grid electricity. This scenario is expected to reverse whereby the levelized cost of electricity from large stationary fuel cells will be £104 per MWh in 2025 compared to £135 per MWh for grid electricity.

Transport / Mobility

London has positioned itself as a key early market for hydrogen vehicles, including passenger cars, buses, and commercial vehicles. A number of models are available now and more are coming to market. Fuel cell vehicles can directly replace diesel and petrol vehicles in London across a range of applications and vehicle types. Feedback from early adopters of FCVs has been positive. The cost premium for FCVs is forecast to fall significantly over the next five to ten years. At the same time, a greater choice of FCVs is expected to become available as more OEMs bring vehicles to market.

It is anticipated that future refuelling stations in London will include on-site hydrogen production using water electrolysis.

Hydrogen London has a strategy for expanding coverage of the publicly accessible hydrogen refuelling station as part of a national network. A separate hydrogen transport strategy for London was prepared within the HyTEC project. This plan involved establishing 20 hydrogen refuelling stations as an initial network to provide fuel to drivers. The net investment required was estimated to be approximately £15m, with the private sector potentially providing the bulk of funding. The aspiration of the UK H2 Mobility project is to establish 65 hydrogen refuelling stations across the nation by 2020.

The report has developed a business case for developing hydrogen refuelling infrastructure with 20 to 400 vehicles per station. Cost of supplying hydrogen based on an assumption of fixed delivery cost and fixed selling price was estimated at £4.5/kg whereas the hydrogen selling price was estimated at £7.5/kg based on offering fuel cost parity for FCEV compared to diesel.

Industrial Systems

Gas networks

Decarbonising gas grids and preventing them from being redundant are additional concepts considered in the report. Hydrogen produced from low carbon hydrogen technologies can be pumped through 100% hydrogen pipelines making available a new genre of fuel for London. This will also help prolong the life span of gas networks in a low carbon future. For example, the H21 Leeds City Gate project being led by Northern Gas Networks is investigating the feasibility of redesigning existing gas networks to accommodate injection of hydrogen.

Conversion of excess renewable energy into hydrogen and injecting it into gas networks is another concept that is being considered. This links up the two main energy providing solutions, natural gas and electricity grid. However, a number of factors must be in place for this to work efficiently: very low (possibly negative) electricity prices at times of high generation and low demand, technology cost reductions and efficiency improvements, etc.

Residential

Fuel cell micro combined heat and power (CHP) systems powered by natural gas provide an option for significantly reducing carbon emissions in dwellings, particularly in old stock where micro CHP systems can replace conventional boilers. However, these systems are relatively expensive compared to conventional options. Based on a 2015 European study, the total system costs (including maintenance and stack replacement costs) of a micro CHP system were estimated to be €31,150 (A$49,460) compared to up to €2,800 (A$4,450) for a condensing gas boiler (Roland Berger Strategy Consultants, 2015). But system costs are expected to fall significantly as production volumes increase, dropping to €7,250 (A$11,510) at an original equipment manufacturer production volume of 10,000 units, and down to €6,225 (A$9,880) at a production volume of 100,000 units.

Exports

Comparative Advantages

Significant industry investment, innovation and funding for R&D has already brought hydrogen and fuel cell technologies to the market entry stage in London.

Role of government

Funding / Costs

As of early 2016, funding was in place for an additional five hydrogen refuelling stations (HRS) in and around London which will produce hydrogen from renewable electricity. These additional refuelling stations will bring the total number of publicly accessible stations in the London area to at least ten within the next couple of years. Funding is also in place for two mobile hydrogen refuelling stations, which could further support the development of the hydrogen transport sector in London over the coming years. This is consistent with the vision of the hydrogen production mix at the national level developed in the UK H2Mobility project, which would lead to FCEV emissions below around 50g CO_2/km from 2020, compared to a fleet average for conventional cars in excess of 100g CO_2/km at that point.

Challenges

London's growing population is putting pressure on London's infrastructure in terms of electricity supply, heating and transport. Currently, the majority of London's energy needs are met by gas networks. Electrifying transport, heat and power in order to decarbonise places pressure on strained electricity networks. In addition, London will need to convert its fleet of 2.6 million cars to low carbon fuels to achieve London's climate goals. If London is to meet its decarbonisation targets then it must adopt greener technologies to meet its increasing demand for energy.

Recommendations (Roadmap)

Public Awareness

Timeframes

Regulatory

Even though London and the broader UK have been at the forefront of using hydrogen and fuel cell technologies (HFC), use of hydrogen as a fuel puts the HFC sector in the context of utilising a legally classified hazardous product which is dangerous to transport (Category 1 'Extremely Flammable Gas' dangerous / hazardous product), dangerous to store (above 5barg) and dangerous to decant / fuel / refuel – or in the case of power-to-gas, to inject and blend into a gas stream. Hence, regulatory frameworks have considered HFC activities as a category to be treated as a high-risk concern. In addition, there is a degree of uncertainty or misconception regarding the exact nature of the hazards involved in generating, storing, transporting and using hydrogen, while existing legal and administrative controls and limitations are considered unreasonable and constraining. The Hydrogen Law (HyLaw) was thus adopted to enforce relevant laws regarding the use of hydrogen and removal of legal barriers to the deployment of fuel cells and hydrogen applications. It was aimed at boosting the market uptake of hydrogen and fuel cell technologies by providing market developers with a clear view of the applicable regulations whilst calling the attention of policy makers to existing legal barriers.

Update

London Hydrogen Network Expansion Project: project summary report, Innovate UK Project Number: 101278. Separate project update released in Sept 2016.

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UK National Policy Paper (2018), *HyLAW - Hydrogen Law and removal of legal barriers to the deployment of fuel cells and hydrogen applications.* Available: https://www.hylaw.eu/sites/default/files/2019 01/HyLaw%20UK%20Policy%20Paper_Final_December%202018.pdf

APPENDIX Q – NORTH OF ENGLAND, UNITED KINGDOM

Caveat – Unofficial synthesis. Readers are advised to check against the source.

Country / Region
North of England, UK

Title / Key document(s)
H21: North of England, report commissioned by Northern Gas Networks, Equinor and Cadent, 2018.

Document Type and Author
Roadmap prepared for stakeholders.

Abstract

The H21 North of England (NoE) strategy is in many ways a large-scale extension of the Leeds specific strategy summarised above. The H21 NoE Project is 13 times larger in terms of energy and 14 times larger in terms of meter points than the H21 Leeds project. The H21 NoE focuses on the development of the engineering solutions necessary to enable conversion of the existing gas networks across the North of England to hydrogen between 2028 and 2034. In so doing, the project would decarbonise 14% of the UK heat and 17% of all domestic gas meter connections in the UK. The project also has the potential to be the world's (to date) largest Greenhouse Gas Reduction reduction project. Fully implemented, a reduction of 12.5 Mtpa in CO_2 emissions would be achieved. H21 NoE also lays down the blueprint for decarbonising 70% of all UK meter points by 2050 via a six-phase hydrogen roll out strategy. H21 NoE's goal is to transition to a 100% sustainable and global hydrogen economy by 2100.

Driving factors
The H21 NoE stems from the overarching global concern about challenges posed by climate change. According to the legal obligations under the UK Climate Change Act 2008, the UK has committed to reducing 1990 greenhouse gas emissions by 80% by 2050. In 2017, the UK used 2,350 Terawatt hours (TWh) of energy for heat, transport and electricity generation. This had a greenhouse gas emissions value of 456Mt CO_2e. To meet the legal obligations of the Climate Change Act the UK has to reduce its greenhouse gas emissions by 65% of the 2017 levels. That is and in order to meet its commitments, the UK needs to reduce its annual greenhouse gas emissions by 300 million tonnes.

Almost half of the UK's energy is used to produce heat which far surpasses the energy production required for generating electricity or in the transport sector. The UK also boasts an extensive gas grid which supplies heat to 80% of its buildings and almost all commercial and industrial heat. The H21 Leeds City Gate Project concludes that the UK gas networks can be "repurposed" for transporting 100% hydrogen. This will not only further utilise an existing asset but also prevent the disruptive and expensive changes associated with a transition to an all-electric energy supply system.

Hydrogen Supply (storage, transportation and commissioning)

Production technology and least-cost source of hydrogen

The H21 NoE considered production technologies such as water electrolysis, natural gas reforming, coal gasification, ammonia production and cracking. After considering factors such as energy requirements, need for guaranteed deep decarbonisation, CAPEX and OPEX cost, status of supply chains, evidence of proven (and referenced) technology, ability to meet construction deadlines and reliability of supply for customers, natural gas reforming through Auto Thermal Reforming (ATR) technology coupled with carbon capture and storage (CCS) is considered the most appropriate option. ATR has the lowest carbon footprint compared to other hydrogen production technologies. Estimates of future prices suggest that the proposed natural gas hydrogen pathway offers the lowest cost to UK gas customers at £30-50/MWh (A$53.6-89.3/MWh, estimated from graph). This cost estimate is 40% lower than those that rely upon coal with CCS and 60 to 70% lower than those that assume hydrogen production via electrolysis.

The strategy considers the option of importing ammonia as a longer-term source of hydrogen to the market for heat in the UK. The analysis was conducted assuming a country like the US which has abundant cheap gas and access to Co2 storage sites. Again the natural gas pathway was the lowest cost alternative with the price of ammonia at £45-50/MWh (A$80.4-89.3/MWh) including transport to UK. In the long term, green ammonia can be produced from solar at £70-120/MWh (A$125-214.3/MWh).

The report also estimated the cost of hydrogen produced from ammonia obtained from alternative sources (natural gas, coal, solar). The estimated hydrogen prices included a transport cost of £5/MWh (A$9/MWh). The cost of hydrogen produced from natural gas-based ammonia was £55-60/MWh (A$98.2-107.1/MWh), which was lower than both coal and solar. Overall, cost of hydrogen produced from natural gas-based ammonia was about 40% higher than hydrogen produced in the UK using ATR and CCS.

The hydrogen production facility consists of nine ATR units operating in parallel, with a capacity of 1.35 GW each. The H21 NoE choose a production capacity that would be able to meet 125% of the peak year average hourly demand. As such, H21 NoE is a 12.15 GW natural gas-based hydrogen production facility which will supply low carbon heat for Tyneside (Newcastle, Gateshead), Teesside, York, Hull, West Yorkshire (Leeds, Bradford, Halifax, Huddersfield, Wakefield), Manchester and Liverpool.

Storage of hydrogen

The report considered different options for storage of hydrogen which included salt caverns, depleted hydrocarbon fields, ammonia and liquid hydrogen. After careful consideration, the project team chose inter-seasonal hydrogen storage using a deep salt strata in the Yorkshire at Aldbrough as the place where hydrogen produced during summer would be stored. This source is predicted to be able to provide the necessary 8052 GWh of storage and is equivalent to 62,000 the mega battery that was recently installed in Australia. In technical terms, the proposed storage system would involve 56 caverns operating between 275 and 85 bar and 8 surface facilities. In addition, the salt cavern would require 0.073% of the total hydrogen produced per annum for its operation.

Hydrogen Transportation system

The report also proposes and maps out a thorough hydrogen distribution system that connects the hydrogen production facility with a hydrogen storage facility and end-users. The overall capacity of this system is far greater than the heat required in the H21 NoE project. The three main components of the hydrogen distribution system are:

- A hydrogen transmission system of 125 GW capacity;
- A local hydrogen transmission system to distribute hydrogen to strategic points to individual urban centres; and
- A hydrogen intermediate pressure system comprising of 605 km of below 7 bar gas distribution networks which allows conversion of gas.

In addition, the NoE project aims at converting 3.7 million meter points (equivalent to 85 TWh of annual demand) within a period of seven years from 2028-2035 and is well-positioned in terms of resources to do so. Meticulous planning has been undertaken to match the successive increasing demand for hydrogen with the progressive increase in the supply of hydrogen as well as storage capacities.

Carbon capture and storage

As this strategy assumes that hydrogen will be produced using ATR with CCS, it is important to understand the feasibility of this technology. The strategy finds that the UK Continental Shelf has one of the largest capacities for underground carbon storage in Europe and can store up to 78 thousand million tonnes of CO_2. The three major regions for storage in the UK are: the Central and the Northern-North Sea; the Southern North Sea; and the East Irish Sea. It is stated that the Southern North Sea is the most suitable place to build the first CCS infrastructure due to its proximity of the proposed storage structures to the shore and also to large emission sources. Further, H21 NoE has the potential to offer a carbon capture, utilisation and storage solution in line with 2018 recommendations from the Committee for Climate Change.

Power Generation

The H21 NoE project not only has the potential for supplying decarbonised heat to the UK but also has the capacity to produce clean power which, as demand for heat in the UK is low in summer could be used to supply energy to other parts of the nation as the optimal amount to store is around a one-third of the expected capacity to produce hydrogen. If this can be done then underutilisation of the hydrogen facilities can be avoided via the use of hydrogen-powered Combined Cycle Gas Turbine power stations (CCGT) to produce electricity.

The strategy also considers the possibility of developing synergies with the renewable offshore wind sector in the North of England. It is observed also that CCGT already exists in the form of Integrated Gasification Combined Cycle (IGCC). Suppliers such as Siemens, GE and Mitsubishi Hitachi Power Systems have extensive experience in this area. For example, gas power plant, Magnum in the Netherlands is a CCGT which has the features to convert to IGCC.

Similar possibilities were considered for the North of England. Since, the hydrogen transmission system passes several potential power plants with either existing CCGT or former coal-powered plant sites planning for conversion. The H21 NoE hence considers the development of a UK CCGT project which could use excess hydrogen to produce clean power in summer months.

Transport / Mobility

Industrial Systems

Gas networks

Residential / Commercial

Exports

Comparative Advantages

The UK has the world-class gas networks and via its Continental Shelf has one of the largest potential CO_2 storage sites in Europe.

Role of Government

Funding / Costs

The H21 NoE Project is 13 times larger in terms of energy and 14 times larger in terms of meter points than the H21 Leeds project. The estimated costs for this project are £22,778 (A$40,675 million)

million in terms of CAPEX and £955 million (A$1,705 million) OPEX per annum after 2035 once the conversion and commissioning of the hydrogen network is complete. The additional unit cost to UK gas customers for using the hydrogen regulated asset is estimated at £3.8/MWh (A$6.8/MWh). Further, based on an asset finance model, the H21 NoE project provides CCS at a price of £5.54 (A$10) per tonne.

Challenges

Recommendations (Roadmap)

Vision

The report also provides a vision of how hydrogen will be rolled out for deep decarbonisation of the UK heat not just in North of England but rest of the UK by 2050 by the gradual conversion of the underground gas networks. The six phases of hydrogen conversion envisioned by this report are:

- Phase 1 (2028-34): H21 NoE;
- Phase 2 (2033-38): H21 South Yorkshire and East/West Midlands;
- Phase 3 (2030-32): H21 Scotland;
- Phase 4 (2036-37): H21 South Wales and South West;
- Phase 5 (2040-45): H21 East Anglia and Home Countries;
- Phase 6 (2045-50): H21 London;

Besides decarbonising UK heat, two other scenarios were also modelled in the report:

H21 XL: This project intends to decarbonise 31% of the UK's power and 61% of the UK's heat and power including 'high-pressure industrial clusters'. This would achieve a 28.5% of the required reduction of the UK Climate Change Act.

H21 Max: This project intends to decarbonise all sectors of energy use including the transport sector under the assumption that hydrogen fuel cell vehicle is twice as efficient compared to a diesel petrol vehicle. This would achieve an 83.5% of the required reduction of the UK Climate Change Act.

Public Awareness

Timeframes

As of 2018, the UK needs to reduce 300 million tonnes per year (Mtpa) before 2050. In addition, the NoE project aims at converting 3.7 million meter points within a period of seven years from 2028-2035.

Regulatory

Update

References

APPENDIX R – UNITED STATES OF AMERICA (HYDROGEN AND FUEL CELLS PROGRAM PLAN)

Caveat – Unofficial synthesis. Readers are advised to check against the source.

Title / Key document(s)

Department of Energy Hydrogen and Fuel Cells Program Plan: An integrated and strategic plan for the research, development and demonstration of hydrogen and fuel cell technologies, U.S. Department of Energy, Sept 2011.

Document Type and Author

Strategy prepared by a government authority.
Officially a plan prepared by the U.S. Department of Energy.

Abstract

The U.S. hydrogen strategy is formulated on the basis of reducing greenhouse gas emissions through increased use of hydrogen and fuel cells. The U.S. has identified stationary power and transportation as the two most important sectors where the use of fuel cells and hydrogen can be applied. It has a long-running hydrogen and fuel cells program which seeks to improve the cost efficiency and effectiveness of fuel cell and hydrogen production technologies.

Driving factors

At the time of the roadmap's preparation, the U.S. had the intention of reducing greenhouse gas emissions by 80% by 2050 compared to its pre-2010 levels, and lower its dependence on imported fuels. This can be achieved through the utilization of diverse domestic energy sources and the use of advanced fuels and technologies in all sectors of the economy. The U.S. Department of Energy (DOE) believes that fuel cells (which can convert various fuels directly into electricity without combustion) and hydrogen (which can be produced from renewable sources without leaving a carbon footprint) are two key elements for building a competitive, secure and sustainable green economy. If these two elements are coupled with a robust, comprehensive research and development (R&D) portfolio which balances short-term objectives with long-term needs then it will help the U.S. achieve its goal of a clean and sustainable economy. The DOE identified that major benefits can be reaped from using fuel cells in the stationary power and transportation sectors. The markets for these two sectors are very large and a significant amount of energy is consumed by these sectors.

Hydrogen Supply/Cost of Fuel Cells and Hydrogen

The program focuses mainly on achieving efficiencies related to fuel cell and hydrogen production. For example, stationary fuel cells such as combined heat and power systems can provide very large efficiency improvements with the potential to use more than 80% of the fuel energy, compared with the 45% to 50% overall efficiency of using electricity from coal or natural gas plants and thermal energy from on-site natural-gas combustion. The levelized cost of energy from combined heat and power (CHP) fuel cells is projected to decrease steadily between 2010 and 2030. The 2040 projections suggest that the levelized cost of energy from CHP fuel cells will be well below the levelized cost of energy from coal. It is assumed that fixed and variable operations and maintenance costs of CHP fuel cells will decrease by about 78% and 87% respectively between 2010 and 2040, whereas capital costs will decrease by 87%.[11]

The program conducts periodic assessments of the high-volume manufacturing cost of 80-kW PEM fuel cell systems for transportation applications. It was estimated that a range of $60 to 80 per kW

[11] SACES calculations from Fig. 1.3 of U.S. DOE's Program Plan.

(A$82.2 to 109.6 per kW) is a valid estimation of the potential manufacturing cost for an 80-kWnet fuel cell system, based on 2008 technology, and assuming a manufacturing volume of 500,000 systems per year.

The focus of the program is on the production of hydrogen from renewable or low-carbon resources through either distributed hydrogen production or centralised hydrogen production. Distributed hydrogen production involves developing small scale technologies to produce hydrogen from renewable liquids to achieve higher energy efficiency and a lower cost of production. Methods of central hydrogen production include electrolysis using power from wind and solar, conversion of biomass, and near-zero atmospheric emission coal plant producing hydrogen and power with carbon sequestration.

In terms of the cost of producing hydrogen in 2006, the total cost of delivered and dispensed hydrogen was estimated to be approximately $2.75 to 3.50 per kg (A$3.8 to 4.8 per kg)—using 2005 technology and assuming an installation rate of 500 new forecourt units per year and a capacity of 1,500 kg per day.

In 2009, the levelized cost range for state-of-the-art forecourt electrolysis was estimated at $4.9 to 5.7 per kg (A$6.7 to 7.8 per kg) of hydrogen for compression, storage, and dispersion of 1,500 kg per day. In comparison, the 2009 levelized cost for state-of-the-art centralized electrolysis was estimated at $2.7 to 3.5 per kg (A$3.7 to 4.8 per kg) for production of 50,000 kg per day.

In 2010, as part of the Program, a rigorous hydrogen "competitive threshold analysis" was conducted to determine the cost at which hydrogen would be competitive with gasoline. The resulting "hydrogen competitive threshold cost," which is independent of the production and delivery pathway, was determined to be $2.0 to 4.0 per gallon gasoline equivalent (gge) (A$2.7 to 5.5 per gge).

The program is also committed to research and development to facilitate safe and low-cost hydrogen delivery through the development of:

- more reliable, lower-cost, higher-efficiency compression technology;
- more energy-efficient and lower-cost liquefaction technology;
- low-cost high-pressure gas and liquid dispensing technologies that ensure safe, reliable, and complete tank fills;
- better pipeline materials to resolve hydrogen embrittlement concerns and to reduce capital costs; and
- lower-cost gaseous hydrogen tank technology and systems for stationary storage and tube trailers.

In addition, the program is developing technologies to enable the lightweight, compact, and inexpensive storage of hydrogen which in turn will help lower delivery costs, allow for smaller footprints of fuelling sites and fuel cell installations, and enable achievement of performance and cost targets for a wide range of early market and transportation applications.

Power Generation

Transport / Mobility

Industrial Systems

Gas networks

Residential / Commercial

Exports

Comparative Advantages

Role of Government

The program's strategic vision is to achieve major developments in pre-competitive R&D which in turn will lead to development at an industrial level and thus commercialisation of hydrogen and fuel cells. To this end, the program incorporates an array of research, development and demonstration (RD&D) activities such as basic research efforts, applied research and technology development efforts and demonstration and validation of new technologies.

The U.S. government invested approximately $1.5 billion (A$2.1 billion) for fuel cell technology RD&D activities between 2004 and 2009. The program argues that to achieve such growth and enable U.S. competitiveness, continued funding is required for RD&D to build and strengthen core competencies in areas such as catalysis, advanced materials, and manufacturing technologies. The government will also need to invest at the university level, to develop human capital, and in industry, to stimulate early markets in order to further develop manufacturing capabilities and help achieve economies of scale.

Funding / Costs

Challenges

Two main challenges identified by the program are reductions in manufacturing cost and advances in technologies for producing, delivering and storing hydrogen. This is because even though fuel cells are becoming competitive in a few markets, the range of these markets can be greatly expanded with improvements in durability and performance and reductions in manufacturing cost, as well as advances in technologies for producing, delivering, and storing hydrogen.

In addition, the program acknowledges that successful entry into new markets will also require overcoming certain institutional and economic barriers, such as the need for codes and standards, the lack of public awareness and understanding of the technologies, and the high initial costs and lack of a supply base that many new technologies face in their critical early stages. The program conducts activities to address the full range of technical and non-technical barriers facing hydrogen and fuel cells. It conducts a comprehensive Systems Analysis effort to guide R&D priorities and set program goals, and to clarify where hydrogen and fuel cells can be most beneficial.

Recommendations/Strategic Vision

Public Awareness

The program has an education and outreach activity which aims to increase public awareness and understanding of the technologies which in turn will facilitate the implementation of near-term demonstration projects and early market fuel cell installations. Higher levels of public awareness will pave the way for long-term market adoption of fuel cell and hydrogen technologies.

Timeframes

Various technology development targets were set to be achieved between 2010 and 2020 in the Program Plan. Such targets include:

- Fuel cell R&D: Targets were set to develop fuel cell systems of varied capacity and applications such as portable power applications, transportation applications etc. using hydrogen, natural gas and other fuels.
- Hydrogen Production: To develop technologies for producing hydrogen through electrolysis (at a cost of less than A$4.1 per gge) and conversion of solar energy to hydrogen (at a cost of less than A$6.8 per gge). To demonstrate the production of hydrogen through photobiological and photoelectrochemical water splitting systems at efficiency levels of 5% to greater than

equal to 15%. Also, demonstrate the production of hydrogen and power from coal with complete carbon capture at less than equal to A$2.7 per gge.

- Hydrogen Delivery: To reduce the cost of delivered hydrogen (production and delivery) to less than A$5.5 per gge and to reduce the cost of delivering hydrogen from centralised production to the point of use to less than A$2.7 per gge.
- Hydrogen storage: To develop and verify on-board storage systems achieving a capacity of 5.5% by weight and an energy density of 1,300 Wh/L. To verify the performance of at least one materials-based hydrogen storage technology under real-world conditions by 2020.
- Manufacturing R&D: To develop as well as reduce the cost of various machinery used in the production of hydrogen.
- Technology validation: To validate stationary fuel cell systems that co-produces hydrogen and electricity, fuel cell vehicles and fuel cell systems for auxiliary power units.
- Education, safety, codes and standards: To develop analysis tools to estimate economic and employment impacts of early market fuel cells on regional, state and national levels. To complete critical hydrogen impurities R&D and publish an international hydrogen fuel specification draft standard by 2015. And conduct quantitative risk assessments and develop hydrogen materials qualification guidelines by 2020.
- Market Transformation: To first include the deployment of 1,000 fuel cells through cost-shared Recovery Act awards. Then enable greater than 8 MW of fuel cell deployments in emerging markets and finally enable economies of scale to achieve cost competitiveness.
- Systems Analysis: First, to complete supply chain analysis and quantify reductions in petroleum use, greenhouse gas emissions, and criteria pollutant emissions. Second, to evaluate fuelling station costs for early vehicle penetration to determine the cost of fuelling pathways for low and moderate fuelling demand rates. Third, to provide analysis of Program milestones and technology readiness goals-including risk analysis, independent reviews, financial evaluations, and environmental analysis – to identify technology and risk mitigation strategies. And finally, complete analysis of the status of program technologies (in terms of cost and performance) and the potential to enable the use of fuel cells for a portfolio of commercial applications.

Regulatory

Update

2017 Annual Merit Review and Peer Evaluation Report, U.S. Department of Energy, Hydrogen and Fuel Cells Program, June 2017.

Annual progress reports are published as part of the Hydrogen and Fuel Cells Program.

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APPENDIX S – CALIFORNIA, USA

Caveat – Unofficial synthesis. Readers are advised to check against the source.

Title / Key document(s)

Renewable Hydrogen Roadmap, report prepared by Energy Independence Now for California Hydrogen Business Council, May 2018.

Document Type and Author

Roadmap by stakeholder group.

Abstract

California has a strong policy commitment towards climate change issues and intends to source 100% of its energy from renewable sources by 2045. Transportation is the largest source of greenhouse gas emissions in California. Excess energy from the state's abundant wind and solar energy resources can be used to produce hydrogen, which can, in turn, be used to power fuel-cell vehicles. This approach to decarbonising transport can help California reach its clean energy targets without leaving a carbon footprint.

Driving Factors

The transportation sector is the largest source of greenhouse gas emissions in California (37%), and the government has committed to an aggressive greenhouse gas reduction target.

In terms of its electricity supply, California intends to run on 50% renewable energy by 2030, rising to 100% by 2045, and have 5 million zero-emission vehicles on its roads by 2030. Even though hydrogen used by the FCVs are very little in comparison to overall hydrogen production in California, the state currently produces very little renewable hydrogen without the use of offsetting renewable energy certificates (RECs).

In terms of overall GHG emissions, California has a reduction target of 40% below the 1990 level by 2030.

California has an abundance of wind and solar energy. It experiences periods of high energy demand when enough renewable energy is not available and periods when there is an oversupply of renewable energy, leading to curtailed renewable energy production. Hence there is a need for energy storage mediums that can store unused renewable energy and provide supply flexibility. Since fuel cell vehicles are an essential part of California's zero-emission target, hydrogen produced from renewable sources and stored economically presents an opportunity for zero-emission vehicles without leaving a carbon footprint. Renewable hydrogen will also help reach California's 100% clean energy target.

The current 33% renewable requirement for all hydrogen used for transportation, along with Low Carbon Fuel Standard credits and emerging consumer demand for hydrogen fuel are the main revenue drivers for renewable hydrogen. However, the roadmap identifies that the demand for hydrogen fuel in the short-term will not be enough to make a business case for investing in renewable infrastructure.

Hydrogen Supply

The roadmap analyses the cost of producing hydrogen using different production methods and various degrees of renewable resources usage based on studies conducted by the US Department of Energy – see Table B.1. The two most cost-effective methods involve using steam methane reformation (SMR) to convert natural gas or biogas to hydrogen. Although natural gas to hydrogen has the lowest levelized cost (A$3.0 per kg), it involves zero renewable energy usage. Bio gas to hydrogen uses landfill, wastewater or dairy biogas – i.e. renewable energy sources – as an input, and has a current levelized cost of production of A$4.0 per kg. A tri-generation system (i.e. combined cooling, heating and power generation technologies) that uses bio-gas to produce hydrogen is the next most cost-effective approach with a levelized cost of A$8.2 per kg. In comparison, water electrolysis using 100% solar photovoltaic generation has the highest levelized cost (A$21.2 per kg). Although water electrolysis using a combination of solar and grid electricity is more affordable (A$11.0 per kg), it is still relatively expensive and has a lower degree of renewable energy usage. These costs do not include compression, storage and delivery (CSD) costs which are a significant part of end-user costs. CSD costs are higher if gaseous hydrogen is delivered through trucks in comparison to a pipeline. Delivery of liquid nitrogen would be a more efficient approach but the costs of liquefaction and storage of liquid hydrogen are relatively high at present.

Table B.1: Costs of Production for Renewable Hydrogen Technologies Excluding Compression, Storage and Delivery Costs

Pathway	Renewable Level (%)	Technology	Input	Plant Capacity (kg/day)	Levelized Cost of Production (US$/kg)
Solar PV and Grid Electricity to H2 (1MW)	32	PEM Electrolysis	Grid and Solar Electricity, Water	398	8.02 (A$11.0)
100% Solar PV Generation to H2 (1MW)	100	PEM Electrolysis	Grid Electricity, Water	126	15.43 (A$21.2)
Biogas to H2	100	SMR	Landfill, Wastewater or Dairy Biogas	1,500	2.94 (A$4.0)
Tri-Generation Biogas to H2	100	Tri-Generation	Biogas	1,500	5.99 (A$8.2)
Natural Gas to Hydrogen	0	SMR	Natural Gas	398	2.17 ($A3.0)

Source: Energy Independence Now (2018), *Renewable Hydrogen Roadmap.*

In early 2016, over 2 million kg per day of hydrogen was being produced in California (using SMR technology) to supply oil refineries. The food and metal industries were the other main consumers of local production capacity.

With the rollout of hydrogen stations and infrastructure development to support FCVs, transportation demand for hydrogen is expected to increase significantly. FCV drivers will consume 6 million kg of hydrogen per annum within a few years.

Comparative Advantages

California has an abundance of wind and solar energy and policy commitment to reduce greenhouse gases.

Role of Government

California is a world leader in adopting hydrogen as an alternative source of fuel for transportation. State leaders have committed to building 200 hydrogen fuelling stations as part of the "California Hydrogen Highway". Policy makers are collaborating with auto manufacturers to bring zero-emission FCVs to the market. Mandates are in place requiring that 33.3% of the hydrogen used in transportation (for stations receiving state funds) must be produced from renewable sources.

Funding

The California Energy Commission committed US$20 million per year for 10 years to build the initial network of 100 hydrogen fuelling stations and recently committed about US$4 million in additional funding to support the development of renewable hydrogen production. In January 2018 Governor Brown increased the State's commitment to 200 hydrogen stations by 2025, although this pales in comparison to a target of 250,000 charging vehicle stations by this date (Executive Order No. B-48-18). These infrastructure investments and a continuation of clean vehicle rebates form part of a US$2.5 billion commitment over eight years.

Challenges

Steam methane reformation (SMR) and *electrolysis* are the two main processes used to produce hydrogen. SMR uses natural gas as one of its inputs to produce hydrogen which leaves behind a carbon footprint. Bio gas can be used as an alternative but this switch may not be attractive for producers due to discrepancies in the Renewable Fuel Standard Program regarding receipt of renewable credits. Transportation cost is another factor. Hydrogen gas cannot be pumped through pipelines due to regulations. However, the cost of trucking to urban areas are lower compared to trucking from remote areas. The fluctuating cost of electricity and discrepancy in energy credits are the two main barriers to large scale hydrogen production through electrolysis.

Recommendations

California has helped create a new hydrogen economy for transportation, which has spurred investment activity from the private sector. More than a dozen developers applied for the most recent station grant solicitation, submitting more than 100 applications. Electrolysis firms previously working outside California are now establishing a presence within the state and companies that supply hydrogen tube-trailer trucks and certified drivers are now in demand to transport gaseous hydrogen to stations.

The Roadmap makes the following recommendations to provide a framework to help guide the priorities and investments of policymakers, regulators, consumers and business leaders:

- Begin the Journey to 100% Renewable Hydrogen Now
- Fund Scalable Projects for 100% Renewable Hydrogen Production
- Improve Low Carbon Fuel Standard (LCFS) Incentives
- Promote Tools to Lower the Cost of Electricity for Renewable Hydrogen Producers
- Address Hydrogen Distribution and Storage Challenges
- Expand the US EPA's Renewable Fuel Standard (RFS) Program
- Incentivize Consumers and Stakeholders
- Broaden the Hydrogen Community Through Education & Outreach

Update

Not applicable. Released in 2018.

References

Renewable Hydrogen Roadmap, report prepared by Energy Independence Now for California Hydrogen Business Council, May 2018. Available at https://einow.org/rh2roadmap

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Business
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