An Overview of Hydrogen Prospects: Economic, Technical and Policy Considerations

Abstract

Hydrogen is expected to play a role in the future low-carbon economy as an energy carrier, but its market penetration remains to be seen. Much of the existing literature generally focusses on comparison of marginal production costs and prices to make rather optimistic projections. This study argues that such analysis is myopic as important barriers are ignored. Following a Porter's five-force approach, we methodologically identify the economic market forces that shape the development of hydrogen markets, and discuss key obstacles in the supply chain. Using evidence of available hydrogen technologies and costs, the distribution network is identified as a major fixed-investment barrier to market entry, but it is argued that much of it could be overcome if natural gas infrastructure and technology is shared with the hydrogen sector. Natural gas, in turn, is projected to function as a transition fuel under current carbon emissions targets. This study finds that policy costs needed to promote hydrogen to achieve environmental goals can be substantially reduced if government and private investment decisions strategically focus on synergies with natural gas. The possible formulation of such policies is discussed at a lower level using Australia's hydrogen industry as a case study.

Keywords
Hydrogen; natural resource policy; natural gas; energy transition

JEL classifications: Q20, Q30, Q35, Q42

1. Introduction

The global energy system is progressively decarbonising, yet an affordable and secure supply of energy is required to sustain economic growth. As the world transitions towards a low-carbon future, hydrogen is increasingly becoming a subject of research focus. It is therefore timely to provide an original overview of the potential for hydrogen in the future global energy market, including synergies with established fossil fuel and renewable energy industries.

There is considerable literature on the technical, economic and policy aspects of hydrogen, plus its synergies with the natural gas and liquefied natural gas (LNG) industries, and the literature is quoted and drawn upon in the pages which follow. However, a comprehensive and integrated outlook based on the above-mentioned factors has not been treated adequately in earlier work—especially the linkage with gas and LNG. This provides the rationale for a novel contribution to further the knowledge on the prospects for hydrogen and to serve as a useful entry point for further interdisciplinary research on the subject in the coming years.

With hydrogen markets at a very early stage of development, there are plenty of questions, and some hype, about the economics behind technologies that will drive future growth. Given the amount of attention on this subject by media and energy enthusiasts, and the vast amount of technology-oriented hydrogen research articles, we find the need to realistically identify the key economic driving forces to better understand hydrogen prospects—and thus help to fill an important gap in the literature. Typically, economic analysis shines with ex post-analysis; that is, in markets that are already developed and for which data are available. This study is different in that we conduct a systematic, comprehensive review of the market fundamentals.

The methodological approach that we use to identify relevant economic market forces is based on Porter (1979, 1998, 2008a, 2008b). Porter's five-force method has proven to be useful for analysis of many market structures. This is not surprising as the five-force method provides a systemic classification of factors identified in industrial organisation economics since the introduction of the structure–conduct–performance approach of economists Edward Chamberlin and Joe Bain. The five forces are Porter's attempt to improve the SWOT (strengths, weaknesses, opportunities and threats) analysis framework by incorporating enhanced rigour to the assessment of industries (Porter et al., 2002). A condensed summary of questions for the hydrogen market in the five-force framework is offered in **Figure 1**.

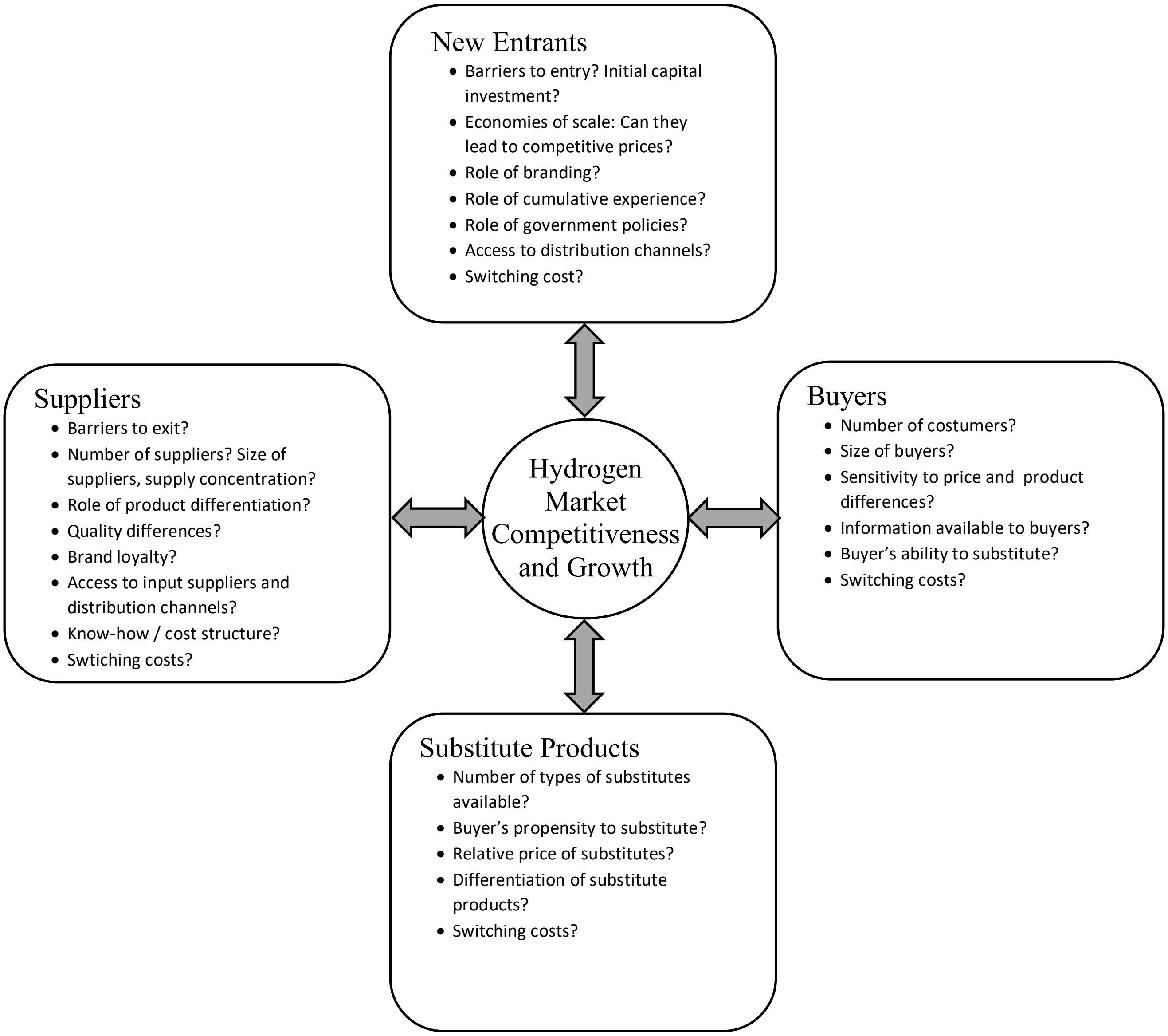

Figure 1: Hydrogen market competitiveness analysis using Porter's five-force scheme.

Much of the existing literature on hydrogen economics has focused on the break-even supply cost of hydrogen-stored energy, which is generally dependent on the production technologies beings used, scale of production, distribution networks and regional idiosyncratic factors—see Castillo et al. (2020); Apostolou and Xydis (2019); Rosen and Koohi-Fayegh (2016) for reviews, and Section 2 of this paper for our own review.

To summarise some of the industry expert views on future hydrogen costs in transportation, a sector that can be difficult to decarbonise, **Figure 2** reproduces the predicted break-evens in 2030 (Hydrogen Council, 2020, based on data for the United States, Europe, China, Japan and Korea). With hydrogen market prices expected in the US$4-6/kg range, most of the applications in **Figure 2** become viable, from a pure marginal-cost and marginal-revenue perspective. These promising cost values answer many of the questions in **Figure 1** in regards to price, cost, economies of scale, investment recoup and comparability to other energy supply sources, suggesting a generally optimistic view for the hydrogen industry.

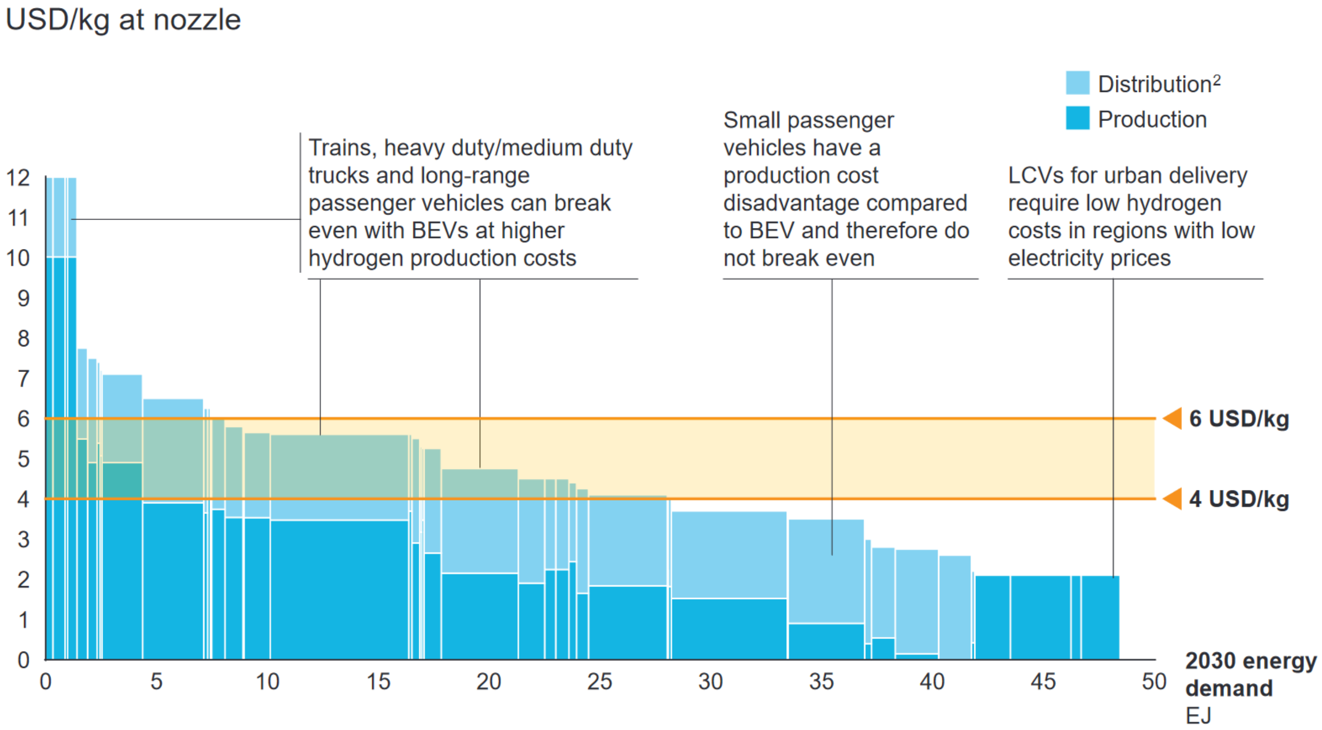

Figure 2: Break-even hydrogen costs at delivery points by 2030, based on industry data for the US, Europe, China, Japan, and Korea. BEV is battery electric vehicle, LCV is light commercial vehicle. Source: Hydrogen Council (2020).

An argument put forth in the present paper is that focusing exclusively on marginal costs of supply and prices is misleading. There are other crucial aspects (see **Figure 1**) for the development of hydrogen markets that often are overlooked or receive little attention. Thus, we attempt to expand the analysis through various parts of the supply chain, in general accordance with the five-force framework (Porter, 2008b).

One key aspect of the supply chain identified in our analysis is the distribution channel; that is, how hydrogen atoms can efficiently reach consumers in the energy end-use sectors. An analogy with the proliferation of the electric car industry is relevant: in the mid-2000s, the main barrier was not the technology for producing electric cars. Nor was it the production cost (which was thought to match that of internal combustion engine cars at scale) or the cost of the electricity (generally below that of petroleum fuel products). The main barrier was the lack of charging distribution infrastructure to reach end consumers. Thus, the joint development of electric cars and charging stations presented itself as a chicken-and-egg investment paradigm, especially knowing that the economic regulations in North America, Europe and other regions would most likely allow third-party access to the distribution networks. The situation changed in the past decade, with Tesla leading the charging infrastructure fixed investment under the logic that their car production technology was so comparatively advantageous that it would generate enough revenue to compensate for the chargers. In the hydrogen case, it could be put forward that there are limited signs of firms willing to invest in fuelling stations at a large scale. Hence, in the absence of government infrastructure support, this limits the potential of hydrogen development due to a chicken-and-egg game. We argue that this apparent shortcoming might be partially overcome by exploiting synergies with the natural gas industry. In any case, the government financial support required for hydrogen becomes substantially smaller when complementarities with the natural gas industry are considered.

Given this introduction, the balance of the study is organised as follows. We begin with the identification and analysis of key economic aspects of the hydrogen market structure and supply chain in Section 2. This is followed by an outlook of relevant factors affecting natural gas, a fuel that some experts believe will act as a bridge towards a low CO2 emissions future (Aguilera & Aguilera, 2020, Hefner III, 2009; among others), in Section 3. The potential for complementary and facilitating role of natural gas and LNG for hydrogen market development is explored in Section 4. Insights into the links between Australian LNG and hydrogen exports, and for domestic uses, are offered as a case study in Section 5. Opportunities and obstacles for hydrogen to gain a sizeable market share in the future are discussed in Section 6, leading to a broad perspective on the extent of hydrogen usage and the timing in the future energy landscape. Section 7 concludes.

2. Hydrogen market structure and value chain

Hydrogen is an energy carrier that could potentially be developed at large scale from abundant resources. It can be produced thermochemically from fossil fuels, or from water by applying electrolysis – with focus on using electricity from renewables such as solar and wind. At least 96 per cent of current hydrogen is produced with fossil fuels (mostly natural gas), whereas the remainder comes from electrolysis. The most mature electrolysis technology is the alkaline method, while proton-exchange membrane and high-steam electrolysis are at very early commercial stages. For alkaline and proton-exchange technologies, the costs of electrolysers have been estimated to be as low as US$500 and $1100 per kilowatt-electric, respectively (IEA, 2019).

The most important source of by-product production of hydrogen is the catalytic processing in refineries. About 80 per cent of global hydrogen consumption is attributed to refineries and production of ammonia (as fertiliser). Despite this delimited market space, there is potential for greatly expanded hydrogen consumption on account of its end-use versatility, its low emissions and its complementarity with natural gas development.

For commercialised hydrogen, its storage and transport (shown in the centre of **Figure 3**) are integral parts of the supply chain. Due to the low volumetric density of hydrogen in its gaseous state, a series of technologies may be utilised in order to improve the economics of storage. Compression of gaseous hydrogen generally represents the most attractive option for storage given the comparatively lower cost and greater availability of space. Other storage technologies including liquefaction, and carriers such as ammonia, have a superior volumetric density but higher cost. Hydrogen can then be transported via truck, rail, ship and pipeline utilising the storage techniques identified. Fuel cells are finally used to convert hydrogen to electricity or heat for the provision of energy services.

Overall, hydrogen accounts for around 1 per cent of global primary energy use (Ogden, 2018). If it were to be produced using low or zero emissions processes, then this ‘clean’ type of hydrogen could lead to deep decarbonisation across the energy sector in the long-term future.

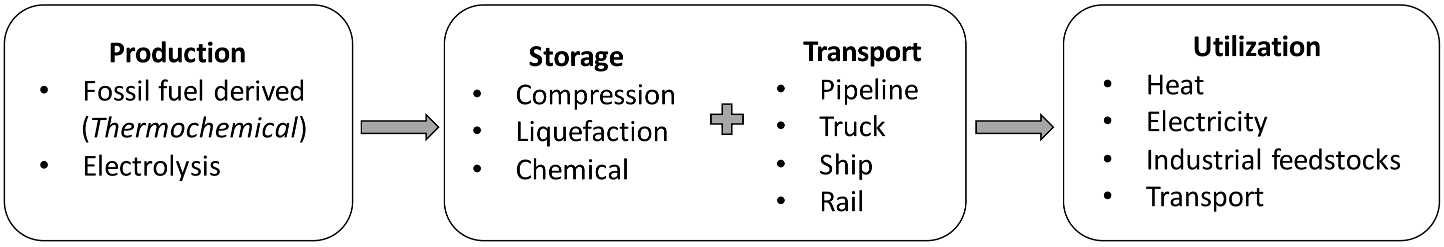

Figure 3: Hydrogen value chain (adapted from CSIRO, 2018)

2.1 Green hydrogen

Green hydrogen is produced electrochemically (**Figure 4**). It involves the application of an electrical current to split water into hydrogen and oxygen. However, to be considered green, it requires the use of low emissions electricity, that is from renewable energy sources[1] The present-day cost of this type of production is estimated at US$3–6/kg, which is around $25 to $50 per gigajoule—many times higher than average fossil fuel prices around the world, so clearly cost-reducing technological progress and supportive policy are necessary to accelerate hydrogen development. Still, it must be emphasised that green hydrogen is experiencing speedy cost declines. There are studies indicating that costs could be half the above-mentioned amounts within a decade (Glenk & Reichelstein, 2019). The most critical factor for the cost of green hydrogen is the price of the electricity from renewables—estimated to account for around two-thirds of the total cost, though the proportion should decline along with renewable prices—used in the electrolysis process. It is estimated that electrolysis requires an average of 33–40 kilowatt hours per kilogram of hydrogen produced, thus underlining the importance of renewable power costs in the process.

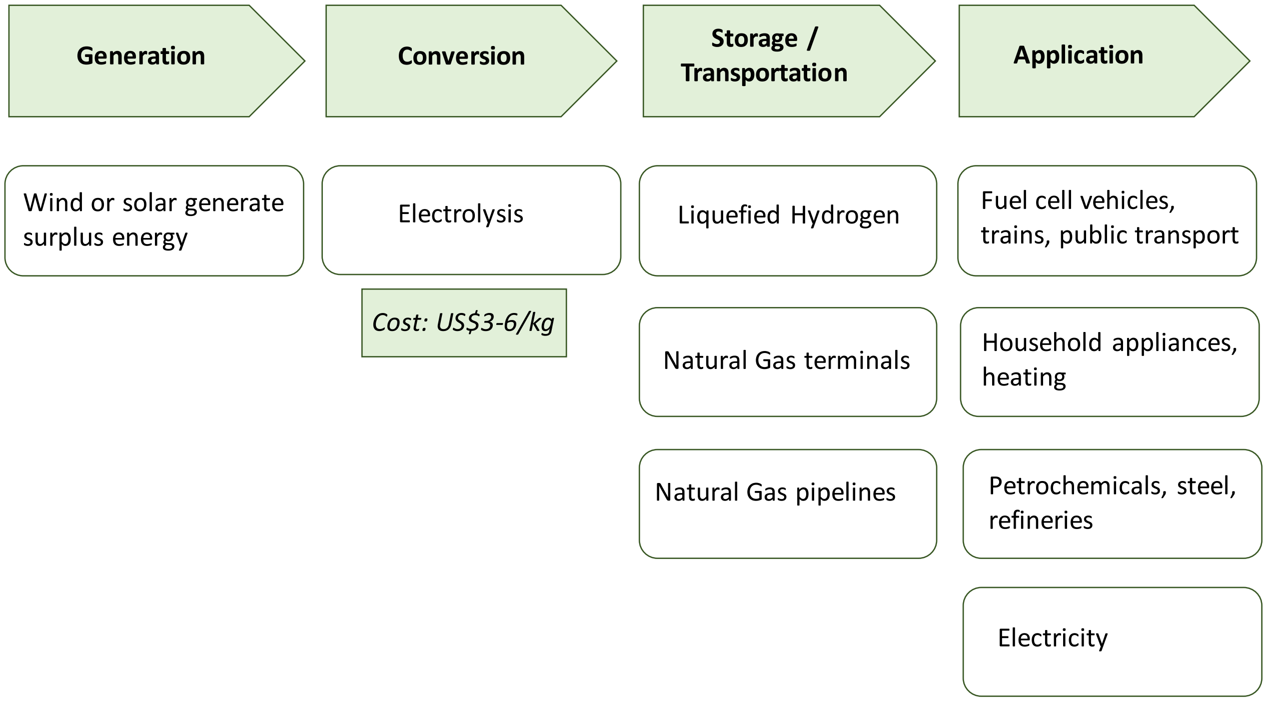

Figure 4: Green hydrogen (adapted from Venture Insights, 2017)

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[1] Another potential source of low-emission hydrogen is that produced from water by applying nuclear-based electricity – most commonly referred to as purple or pink hydrogen.

Figure 5 provides additional detail about the production costs of green hydrogen, for selected countries and regions, based on information from IEA (2019). Nations with strong potential for renewable energy development will logically have lower green hydrogen costs. The figure also shows a wide range of costs for each location, with the tops of the ranges representing average current-day costs and the bottoms estimating costs at unspecified future periods, assuming a carbon price of US$100 per tonne. Given the uncertainty of the economic prospects in the coming decades, the cost projections can be considered as quite speculative.

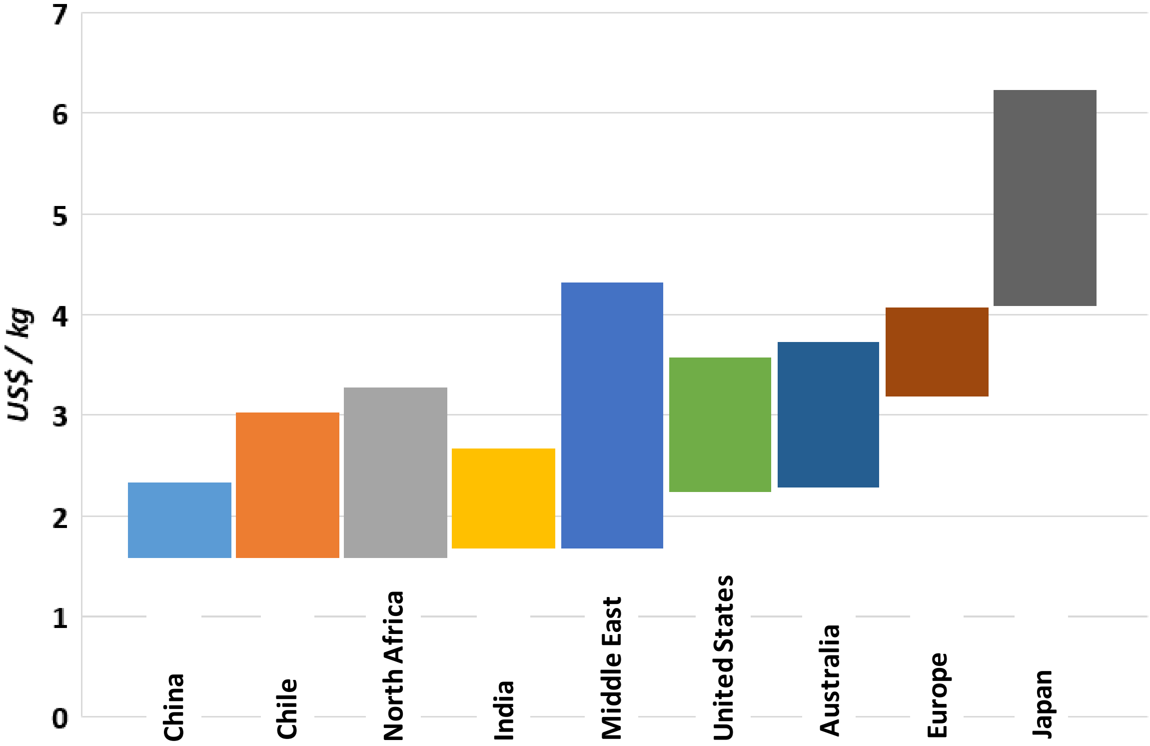

Figure 5: Production costs of green hydrogen (based on IEA, 2019)

Nevertheless, various academic studies have made attempts at quantifying the economic feasibility of hydrogen production. A review of the literature reveals a wide range of estimates—for different types of hydrogen production and in different countries—from around US$2 to $20/kg (Alanne & Cao, 2017; Ball & Weeda, 2015; Hwang, 2013; Le Duigou et al., 2013; Lee et al., 2009).

2.2 Blue hydrogen

When hydrogen is made from natural gas, the process generates CO2 emissions. If the gas-based hydrogen is produced in combination with carbon capture and storage (CCS), it is referred to as ‘blue’. Without CCS, it is often referred to as ‘grey’. Blue hydrogen can play an important role in a likely intermediate period of a few decades, helping to create hydrogen demand and thus enabling the introduction of green hydrogen to eventually satisfy the established demand. Blue/grey hydrogen is produced with a thermochemical process; mature technologies include steam methane reforming (SMR) (**Figure 6**, based on Energy Information Australia, 2019). Cost estimates for this type of production are some US$1–3/kg (CSIRO, 2018; IEA, 2019), depending on location and whether CCS is included. Policy support mechanisms for CCS, in combination with gas-based hydrogen production, will accelerate developments—as is occurring in Canada, the United States and Abu Dhabi, among other countries. An important driver for SMR is the price of natural gas (it may account for up to half of the total production cost), which varies considerably around the world (see **Figure 10**, Section 4.3). Based on **Figure 7**, it is apparent that the addition of CCS to the SMR process adds about US$0.50/kg in each of the locations considered. Compared with green hydrogen, the blue production is thought to have the greater potential in the next few decades, and it is here where the synergies with natural gas and LNG are to be found.

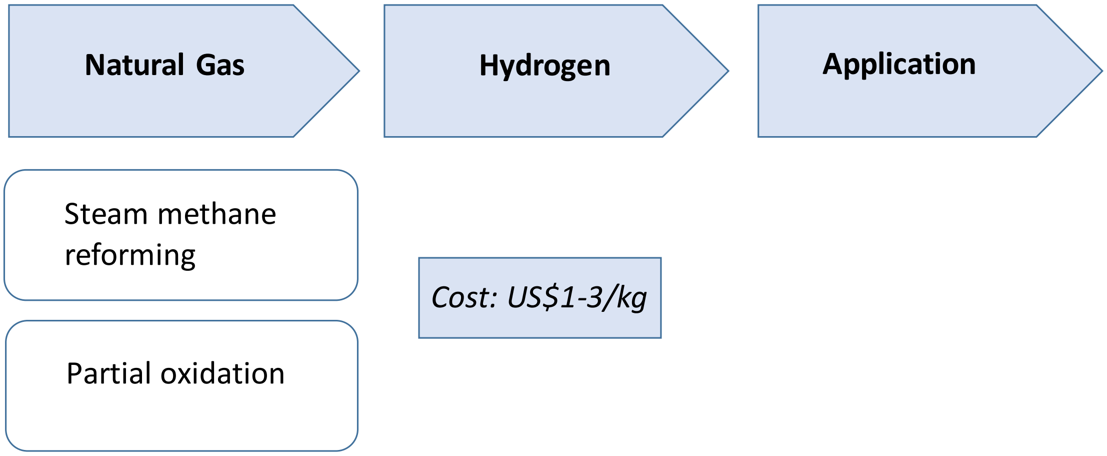

Figure 6: Blue or grey hydrogen, depending on whether CCS is used (adapted from Energy Information Australia, 2019)

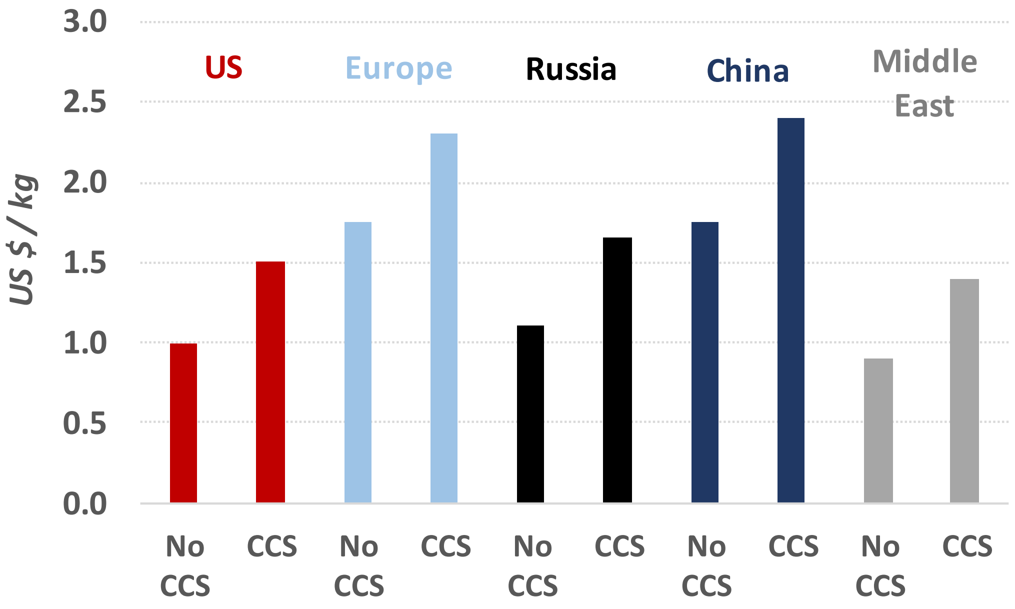

Figure 7: Production costs of blue and grey hydrogen (based on IEA, 2019)

3. Natural gas and the primary energy mix

Before exploring the links between natural gas and hydrogen, a view is presented on the role of natural gas in the future energy mix. Aguilera and Aguilera (2018) assess the world primary energy mix historically and also generate a projection to the year 2040 (**Figure 8**). The figure shows the estimated rapid penetration of gases—mostly in the form of methane, but also some solar and wind[2] —to the energy market. The growth of natural gas (methane) is based on its many advantages: its wide distribution, abundance, affordability and environmental benefits compared with the other fossil fuels. Moreover, the technologies associated with the unconventional gas boom (known as the shale revolution) may have a price-depressing impact on natural gas in the long run, as is apparent from the US experience, where rising unconventional gas supply led to a decline of prices. That resulted in a decommissioning of coal-fired power facilities and their replacement by plants run on gas, which has in turn reduced CO2 emissions in that country to levels not seen since the 1990s. Similar emission reductions could be expected in other parts of the world, as cleaner and cheaper gas replaces coal in power generation. That would represent a climate benefit of the shale boom and also give a boost to blue hydrogen

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[2] The concept of including solar and wind in the gases category was introduced by Hefner III (2009) and was explained as follows: "The Earth's atmosphere is a gas and wind is driven by the Earth's daily heat from the sun. The sun is mostly burning hydrogen gas and each day the Earth is bathed in virtually limitless solar energy."

development. It must be highlighted, however, that some research casts doubt on the importance of natural gas as a bridge fuel, given that it is still a fossil fuel (Howarth, 2014; IEA, 2021).

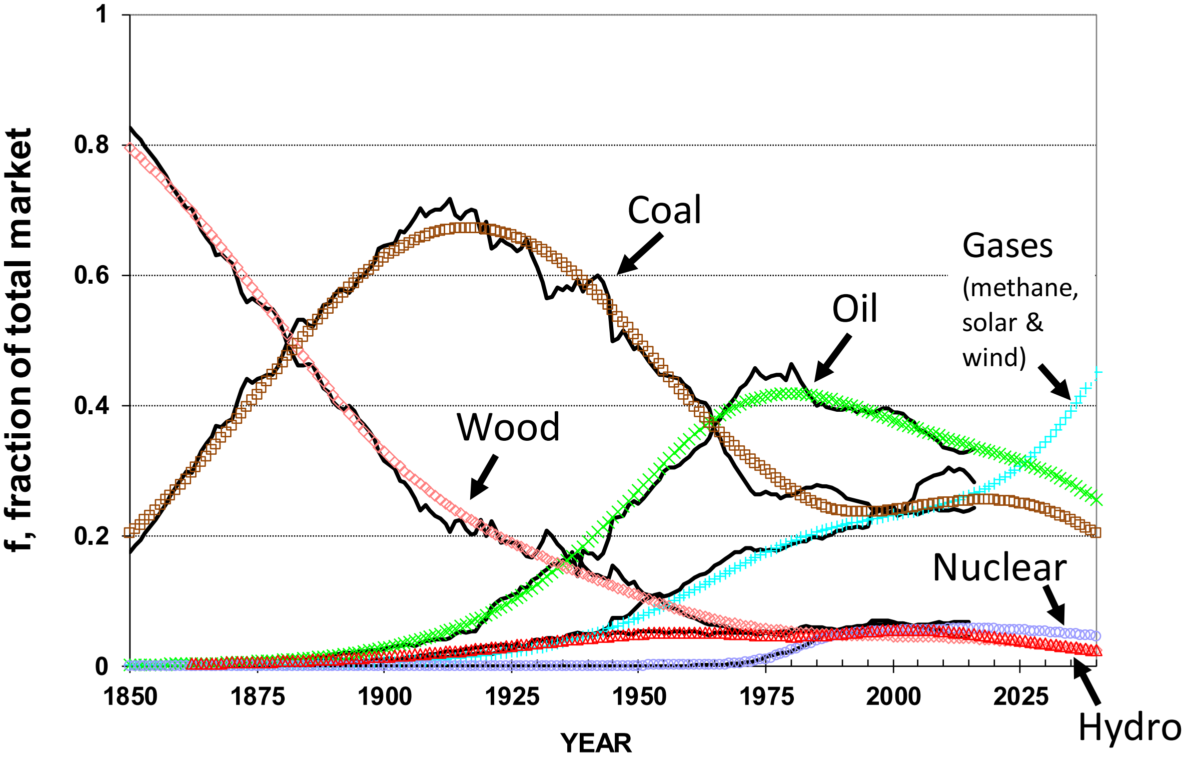

Figure 8: World primary energy mix, 1850-2040. Gases is comprised of natural gas (methane), solar and wind (Aguilera and Aguilera, 2018).

Despite the projected high levels of natural gas use, it is noteworthy that prominent consumers like China and India have relatively small shares of gas in their primary energy mixes. Going forward, the growing importance of gas is being driven by rising energy needs and by fuel switching from coal to gas, in order to reduce emissions, particularly in cities. An important determinant of this energy demand mix is the competition between different sources, where relative prices, and the policies that influence them, play a role. For example, Hefner III (2009) asserts that government intervention in the United States (e.g. the Power Plant and Industrial Fuel Use Act of 1978) had a significant negative impact on the penetration of natural gas in the energy market, and provided a boost to coal consumption (as is apparent in **Figure 8**, where the market share of coal stabilised and then rose around 1975–1980, after having been in steady decline for the preceding several decades). In addition, a European Council Directive from 1975 further restricted the use of gas in electrical power generation on the perception of scarcity, while policies favouring coal and nuclear were enacted (Söderholm, 2001). Going forward, climate policies will play an important role in determining the economic prospects of competing sources (IPCC, 2021). For instance, taxes on carbon give an advantage to renewables, and also to natural gas given it is less carbon intensive than the other fossil fuels.

4. H_2 links with natural gas

4.1 A potentially valuable bridge

What does the bright future of natural gas mean for hydrogen development? The two are compatible and complementary in a number of ways. The first obvious advantage is to use gas for the production of hydrogen, via the thermochemical process referred to earlier. This can play an important role in a low-carbon future for a transition period of several decades, ideally with the use of CCS—and on the assumption CCS itself becomes economically feasible within this period.

Natural gas infrastructure is also compatible with hydrogen development. In particular, well-developed pipeline networks could be used for transport of large quantities of compressed gaseous hydrogen over long distances. It has been shown that hydrogen could be blended with natural gas (around 10–20 per cent hydrogen) into the existing pipelines at minimal cost (Wang et al., 2018), and there is research to convert gas pipelines for exclusive hydrogen use. However, long-distance transportation on water will require technologies with greater hydrogen densities, such as liquefaction or combining it with ammonia. These technologies are being developed further given their potential role in the export of hydrogen via ships. This is where the link with LNG begins (Section 4.2). In terms of storage, a critical part of the natural gas delivery system, the use of underground caverns and depleted hydrocarbon reservoirs may be applicable to hydrogen—though further research is needed to assess the compatibility.

Economically, there are two important links between hydrogen and natural gas. First, as hydrogen can be transported in gas distribution pipelines following some modification, it can eventually be used as a backstop pricing instrument for natural gas. This will be particularly important for regional gas markets, like those in Asia and historically in Europe, which tend to exhibit high prices as a result of concentrated market power in a limited number of suppliers. Having the option of transporting hydrogen instead of natural gas could provide a safeguard or ‘insurance’ to protect against high gas price events. We argue that this is an important feature for policymakers to consider. Second, hydrogen may have a role to play in electricity markets as a carrier interconnecting the point where renewable power is produced and the places where it is demanded. Under current technologies, natural gas extraction cannot easily stop flowing, and if it is not consumed, its storage is costly and limited. Hydrogen produced from wind or solar energy has the potential to meet peak seasonal demand using pipeline distribution channels. These possibilities allow for more complex supply combinations; for instance, hydrogen produced from natural gas and renewable sources could be combined.

Programs that focus on demand management will be important for hydrogen market penetration, not only in electricity markets but also in industrial hubs. Finding appropriate combinations of hydrogen consumption and other resources, such as intermittent renewables, will result in optimal cost and efficiency outcomes. For instance, Carr et al. (2016) show that profits from wind power generation can be substantially increased with the hydrogen refuelling demand management optimisation routine they propose for an industrial park in Rotherham, England. Instead of constraining the output of wind turbines due to limited grid infrastructure, the surplus could operate an electrolyser for the production of green hydrogen.

4.2 Technical and market link with LNG

Development of a global hydrogen industry is largely dependent on the production, storage and transport technologies identified earlier, with many lessons to be gained from the production and export of LNG. However, it is too early to tell how the cost of hydrogen transport will develop and how fast a global market might develop.

Many of the process technologies and safety principles that relate to LNG will be applicable to hydrogen, and while there are different factors involved, the risk level is said to be similar (DNV GL, quoted in The Motorship, 2018). As for shipping technology, it might appear to be quite similar, but the facilities are not necessarily interchangeable. The biggest difference is the much colder temperature of liquid hydrogen, thus requiring expensive cryogenics technology (Aasadnia & Mehrpooya, 2018). The amount of energy required for liquefying hydrogen accounts for an estimated 30 per cent of the total energy input, compared to about 5 per cent for LNG (The Motorship, 2018). Still, when repurposing the liquefaction technology, the ships and the storage facilities can certainly draw on previous LNG designs, while the building of new equipment can also utilise previous research on LNG. Therefore, there would be a head start in countries with established LNG industries, like Australia.

In addition, countries that have experience in the production and export of LNG can transfer that experience to new resource industries in terms of the human resources and the intellectual property. As with the LNG markets, an important determinant for increased market share of hydrogen is policies and international agreements that facilitate trade and long-term commercial deals between producing and consuming energy companies. This would result in a market structure similar to the traditional gas and LNG markets in Europe and Asia, where predominantly long-term deals were made bilaterally over decades by large buyers and sellers. As capital investment in hydrogen advances, shorter term deliveries will likely become more common, as is occurring in LNG markets around the world.

4.3 Spot and short-term contracts in LNG trade

Figure 9 shows how spot and short-term trading of LNG has been on the rise over the past decade, but it is a gradual process. Although increased inter-regional gas flows resulting from ongoing LNG and pipeline projects are establishing more linkages among regional markets, this does not necessarily mean a sharp convergence in regional prices or the end of long-term contracts. For example, regional price differences could remain for several reasons, including the fact that costs of transportation—which comprise liquefaction, shipping and regasification—must be taken into account in price determination. Also, long-term contracts allow producers to mitigate demand risks to invest upfront in the capital-intensive LNG infrastructure, while providing buyers with valued security of supply (the latter gaining much attention during the energy shortages and high spot prices of 2021). The same is likely to apply to hydrogen markets initially, especially those located in geographically dispersed regions like the Asia Pacific.

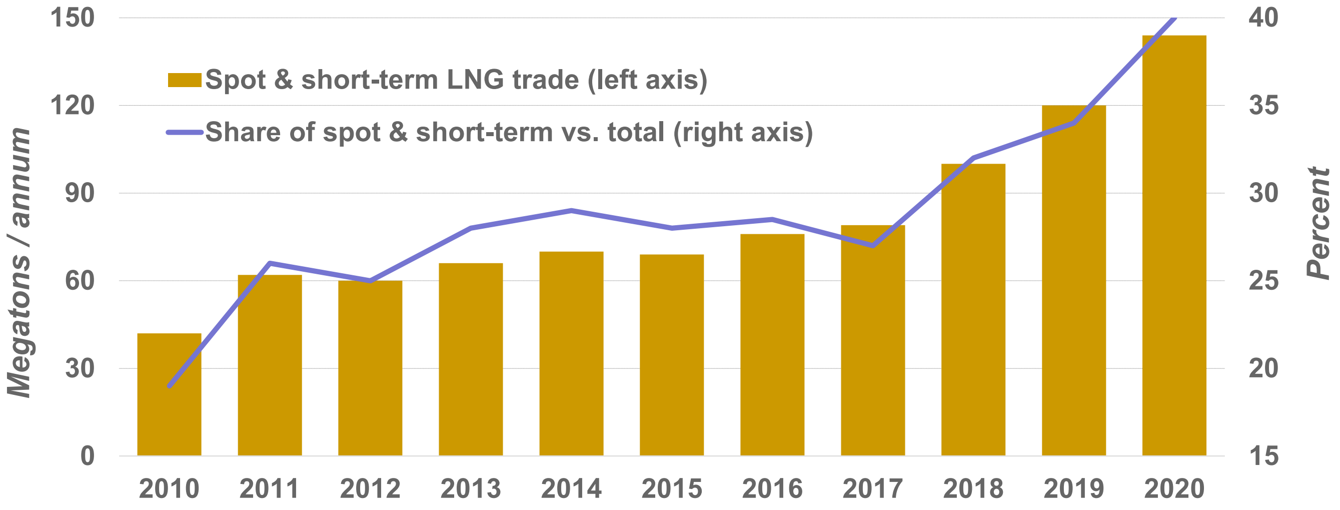

Figure 9: Spot and short-term versus total LNG trade (reproduced from GIIGNL, 2021)

Hydrogen markets around the world may eventually resemble the diverse regional market structures for natural gas (i.e. competitive in North America; oligopolistic in Europe, with a move to competitive; bilaterally monopolistic in Asia; government-regulated in Latin America, Africa, Eurasia and the Middle East). **Figure 10** shows a trend towards price divergence in the major regional natural gas markets from around 2011 to 2015. In the United States, prices were low (averaging some US$3 per gigajoule over the period) as unconventional gas production gained speed. As alluded to above, the reason is that gas prices in the United States reflect the fundamentals of supply and demand of gas itself—so-called competitive, gas on gas pricing. In other regional markets, like Europe and Asia, gas markets have different market structures, and transportation is more complicated, sometimes over bodies of water and requiring LNG shipping. Therefore, gas price formation is based on a link to oil prices, though there is some movement away from that, as seen earlier in **Figure 9**. In these regions, prices rose with the oil price during those years when oil was trading at about US$100 per barrel. Then, the gas prices declined along with the price of oil around 2015. In addition, there were large of amounts of gas supply at that time in the form of LNG, and that led to a glut, further suppressing prices. As global gas trade keeps expanding, due to continuous additions to LNG and pipeline capacity, it brings the different regions into more direct contact and that could lead to price convergence of relatively low prices – though that remains a subject of debate, especially with the extremely elevated spot prices of late 2021. In a longer-term perspective, however, low global gas prices would be positive for the production of blue hydrogen, where gas is the feedstock.

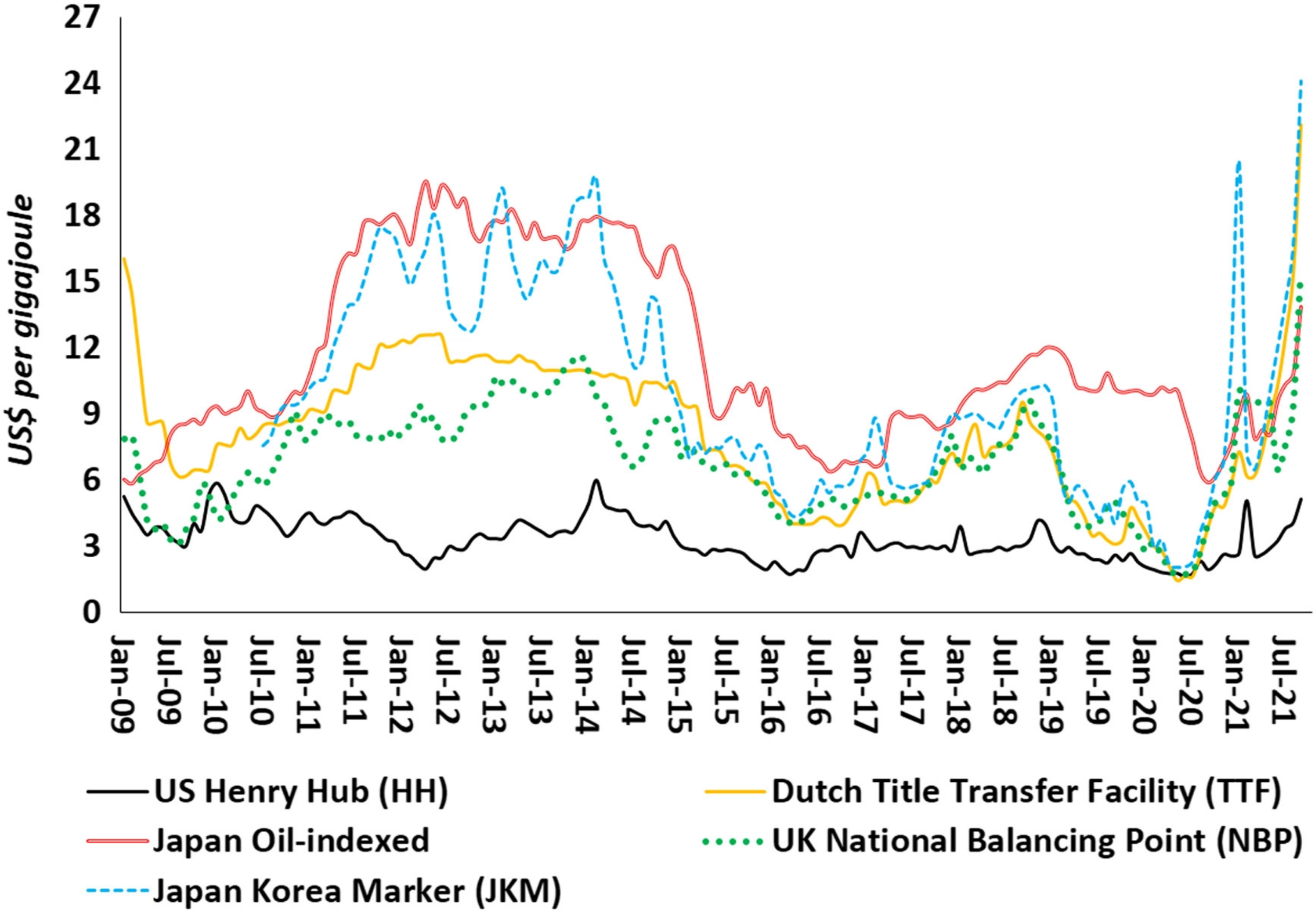

Figure 10: Natural gas price developments (IMF and Cedigaz, monthly).

Against the background of abundance and relatively low prices from 2015 to 2020, improved productivity is seen as vital to make natural gas competitive against coal and renewables. The major LNG companies invested heavily during the extended high price period prior to 2015, but many of their projects came onstream during a significantly lower-price market than first anticipated. To reduce costs, as detailed in Inchauspe et al. (2018), options utilised include better early-stage planning, cooperation between companies, standardisation of equipment, and the introduction of flexible technologies like floating LNG. The latter is simpler and less costly than the mega projects of recent years, where delays and cost blowouts became common. On the consumption side, floating import infrastructure is also being considered around the world, as it enables less-developed countries, who do not have the financial scale for construction of the massive onshore import facilities, to increase their gas usage as well. The floating vessels may also be applicable to the hydrogen export industry, where efficiency could be improved and costs reduced by completing production processes near the available gas resources.

5. Hydrogen plans in Australia

As a case study, this section discusses LNG and hydrogen in Australia, given that the country is the largest LNG exporter in the world (IGU, 2021) and has plans to be a major hydrogen producer and exporter as well. In its Low Emissions Technology Statement of 2020, the Australian Government set a goal of reducing green hydrogen costs to under 2 AUD per kg (˜US$1.50) by 2030. Moreover, a governmental group developed a national hydrogen strategy (COAG, 2019), which includes both export and domestic opportunities. Demand for hydrogen is expected from key LNG trade partners like China, Japan and South Korea. The Asia region will be responsible for most of the world’s energy consumption growth in the future (e.g. until 2040, according to IEA, 2020). This means Australia is well placed geographically to continue as a key exporter of energy to the region. Japan will be a major importer, as it aims to become a future hydrogen economy, while China has major hydrogen ambitions too (for example, plans to build a thousand refuelling stations for hydrogen vehicles by 2030). This is a reminder that consumers will play an important role in a hydrogen transition by generating the required demand. On the production and delivery side, lessons are certainly being taken from the planning and execution of LNG projects in Australia, where much has been learned about improving productivity and reducing costs.

CSIRO (2018) finds that hydrogen technologies in Australia are reaching a mature state and identifies plenty of potential for industry growth. However, lack of infrastructure (especially transport refuelling stations) is identified as the main obstacle for domestic expansion. An appropriate government policy framework will be crucial to incentivise private investment.

Urban private transportation prospects for hydrogen in Australia are very limited in the short to medium run. Hydrogen-powered cars are practically non-existent, and government-supported programs for running hydrogen buses have generally been economically unsuccessful. The first commercial refuelling station open to the general public is an experimental US$9.4-million private–public partnership in Melbourne (Fuel Cells Bulletin, 2017). Urban transportation buses were seen as a seeding initiative a decade ago, but are yet to prove economical viability. A study by Ally and Pryor (2016) shows that in Western Australia the fuel cost (shown in US dollars) of running hydrogen fuel cell buses surpassed all that of other technologies (hydrogen: $1.42/km; CNG: $1.06/km; diesel: $0.61/km; AdBlue: $0.32/km) and that the acquisition costs and maintenance costs for hydrogen fuel cell buses are also greater than for alternative motoring technologies.

The most significant domestic opportunities for hydrogen usage include heavy commercial vehicles, the mining and hydrocarbon industries, and electricity. According to the projections to 2050 in Maniatopoulos et al. (2015), only 20 per cent of urban electric vehicles (including buses) will be powered by hydrogen fuel cells, but 80 per cent of rigid trucks and commercial vehicles will use hydrogen. In mining activities, hydrogen has potential to fully substitute natural gas, diesel and electricity usage, whereas in the metallurgic industry, only substitution of electricity can be identified as a suitable hydrogen application (McLellan, 2009).

Several initiatives to develop hydrogen storage and production in industrial hubs are led with policy support. In its 2021-2022 budget, the Australian Government committed 1.2 billion AUD (˜US$900 million) towards the energy sector’s reduction of emissions. This includes support for the development of green hydrogen, but also for CCS – a prerequisite for blue hydrogen. The creation of hydrogen export hubs throughout the nation form a major part of the budget initiative. In other particular examples, the Australian Renewable Energy Agency (ARENA), a federal government body, provided a US$2.2 million subsidy to repurpose a Toyota car factory into a hydrogen industrial hub (Fuel Cells Bulletin, 2019), and private investors committed US$136 million to a major industrial hydrogen storage project in Canberra (Fuel Cells Bulletin, 2016).

In the medium to long run, hydrogen has potential to flow in the existing system of gas distribution pipelines in Australia. The National Electricity Market (the NEM, which covers Queensland, New South Wales, Victoria, South Australia, Tasmania and the Australian Capital Territory) has been faced with important questions revolving around the influence of Queensland’s LNG exports on electricity prices, and the under-development of gas resources in Victoria and New South Wales due to gas moratorium policies of these states. Hydrogen has the potential to offer solutions that could translate into cheaper electricity prices and greater economic efficiency than the alternatives, and our paper motivates this discussion for future research.

Notwithstanding domestic development, it is the hydrogen export market that is believed to have the greatest potential for Australia. ARENA/ACIL Allen (2018) identifies opportunities for hydrogen exports, tapping into Australia's abundant wind and solar power potential. Exports are most likely to occur in liquefied form, or as ammonia. In the ARENA/ACIL Allen (2018) medium scenario, it is predicted that Australian hydrogen exports will generate on average AU$1,256 million and additional 2,787 jobs each year by 2040. If Australia becomes a major exporter of hydrogen due to its LNG exports learning experience, infrastructure and international connections, a global market for hydrogen in the Asia Pacific is likely to emerge. Moreover, competition from other suppliers is expected to arise, and Australia's shares in exports destinations are hence expected to decline.

6. Analysis of barriers and prospects

6.1 Major development obstacles

In terms of demand-side challenges, any future hydrogen energy system will be subject to market preferences and competition from other energy sources. For example, devices that use hydrogen (e.g. fuel cell vehicles) must compete successfully, economically speaking, with devices that use competing fuels (that would include, e.g. hybrid or electric vehicles, and vehicles running on petroleum products).

The main limitation for fuel cell cars to gain market penetration is the sparse refuelling infrastructure and lack of economies of scale, leading to high hydrogen refuelling prices. However, the end user's cost of refuelling supply at stations can be substantially reduced with scale if high demand develops. In the United States, the average cost of hydrogen refuelling stations has been estimated in the $6–$9/kg range, which, after adding the costs of production, packaging and transportation, leads to a price of $13–15/kg in California. Reddi et al. (2017) demonstrate that with enough demand, levelled refuelling station costs could be reduced to about $2/kg. Despite the cost-disadvantage of hydrogen with respect to recharging battery-powered electric vehicles, the latter have some disadvantages. As electric power cars gain more market share, the demand for minerals used to produce batteries will cause substantial increases in the prices of batteries. Additionally, there are environmental concerns related to the disposal of battery waste. In the aviation sector, the weight of hydrogen represents a key limitation (low volumetric density compared to kerosene), including for storage on planes and at airports.

However, hydrogen has much more potential for powering heavy vehicles, large trucks, buses, trains and other vehicles used in mining and natural resource applications. This is because fuel cell systems become more useful and efficient when the ratio of energy storage per unit of mass is high (Ally et al., 2015), and because these vehicles can refuel at hydrogen production points or in industrial hubs. Heavy-duty road transportation vehicles (truck, buses and vans) fitted with hydrogen fuel cell equipment have the potential to cover about 90 per cent of each vehicle's segment daily operations (Kast et al., 2018). Governments have generally incentivised the use of hydrogen-powered buses in the United States, Europe and Australia, and a new state-of-the-art ADL Enviro 400 double-deck bus was trialled in Europe (Fuel Cells Bulletin, 2018), but industrial hub applications are expected to lead the new wave of increased hydrogen demand in transportation.

According to Mansilla et al. (2012), demand for the traditional uses of hydrogen—that is oil refining, biomass-to-liquid, gas networking and methanol—will have grown only moderately by 2050, but the demand for it as a fuel—currently around 1 per cent of total demand—will grow rapidly from 2030 to become the most important source of hydrogen demand by 2050, with a 35 per cent market share.

As for the global energy supply system, it has evolved over the past century into a massive infrastructure involving extraction, processing and transportation. Major changes to the system have typically taken decades. If hydrogen is to succeed as a fuel, it must be in the context of this energy supply system, where much of the infrastructure would have to be replaced or heavily modified (despite the linkages with the natural gas, LNG and renewably energy industries).

Between energy production at any scale and its use in an energy device, logistical operations play a necessary role. Like any product, once produced, hydrogen must be packaged, transported, dispensed and stored throughout the supply chain—a complex undertaking.

With regard to the safety of hydrogen development, public perception could be highly influential even if technology and regulation are capable of handling the possible hazards. Concerns over hydrogen explosions, whether legitimate or perceived, may prove powerful in influencing public policy. The examples of the backlash against the nuclear and unconventional oil and gas industries may serve as cautionary tales for the hydrogen industry.

Finally, uncertainty about policy, technology and commercial viability can lead to risk-averse behaviour, yet reducing risk to investors is a precondition for success. So considering all of these issues, the ultimate timing and scale of a hydrogen transition is difficult to know at this stage.

6.2 Requirements for increased H_2 market share

Despite the challenges, ambitious policies in support of hydrogen would help to accelerate its growth. Implementation of a deep climate policy is what could lead to that. The aim of climate policy is basically to reduce CO2 emissions, which can be accomplished by enforced standards or banning regulation, by introducing levies (e.g. taxes and permit rights) that increase the cost of emissions, or by supporting through subsidies energy alternatives that reduce the need to emit. Several countries around the world have announced hydrogen plans, which will incorporate various of these policy tools.

For hydrogen to gain market penetration, a combination of factors will need to cause switching points, which are expected to occur in the coming decades. Tlili et al. (2019) conduct a numerical hydrogen market penetration feasibility assessment, considering costs of production and distribution through different technologies. They conclude that the United States, Europe, China and Japan will all have opportunities for development of hydrogen, with the United States smoothly developing a cost advantage with respect to the other three regions before 2040. The cost advantage is mainly explained by low US natural gas prices, existing infrastructure and scaling. The study also covers feasibility of hydrogen for light vehicles by determining break-even points in time; that is the time at which the hydrogen market entry cost per unit equalises the price of petrol. The break-even predictions occur in 2025 for the United States and Japan, 2035 for Europe and beyond 2040 for China.

As presented earlier, research finds that both green and blue hydrogen still cost too much at present to enable it to be widely deployed. Despite the uncertainty, some experts believe that hydrogen production and applications could become more affordable sooner than expected (Citi Research, 2021; Nistor et al., 2016). And while blue hydrogen is cheaper than green hydrogen, rising carbon prices, for instance, could eventually shrink the gap, also with other renewables and possibly fossil fuels. Still, cost-reducing technical advances would be necessary. This can come from technological learning by doing over time, where the rate of progress or cost reduction depends on parameters such as capital investment expenditure, research and development, knowledge spillovers, economies of scale and other factors. Studies show that low initial technological learning rates in the early phases of commercial deployment result in increased costs. On the other hand, greater experience leads to lower costs and faster improvements in technology, especially when taking advantage of natural strengths. Having a comparative advantage across multiple dimensions can accelerate transitions, for example due to favourable geology or climate in the production of natural gas or renewables needed for hydrogen production, or geography that lowers transport delivery costs to consumers.

6.3 Energy mix in the long distant future

Figure 11 presents a broad estimate of hydrogen usage in the very long-run future (taken from Aguilera & Aguilera, 2020). By expanding the time horizon of the estimated energy mix shown earlier (**Figure 8**), a simulation is generated to show the contribution of different energy sources to the market until the year 2150. For instance, the scenario indicates that the fractional contribution of natural gas (methane) will resemble the cycle of oil—a gradual rise and fall in market share, with the methane peak occurring between 2050 and 2060. This will provide sufficient time to develop non-fossil sources, which, according to the results, become the market leaders in the second half of this century—though the combination of alternatives is not specified and uncertain, depending to a large extent on technical, policy and economic factors. The same is true for hydrogen, which may be derived from both the fossil and non-fossil sources. As for coal, the figure shows its share will not increase from much more than present levels (which is less than 30 per cent of the market) and start a definitive decline in the mid-2020s.

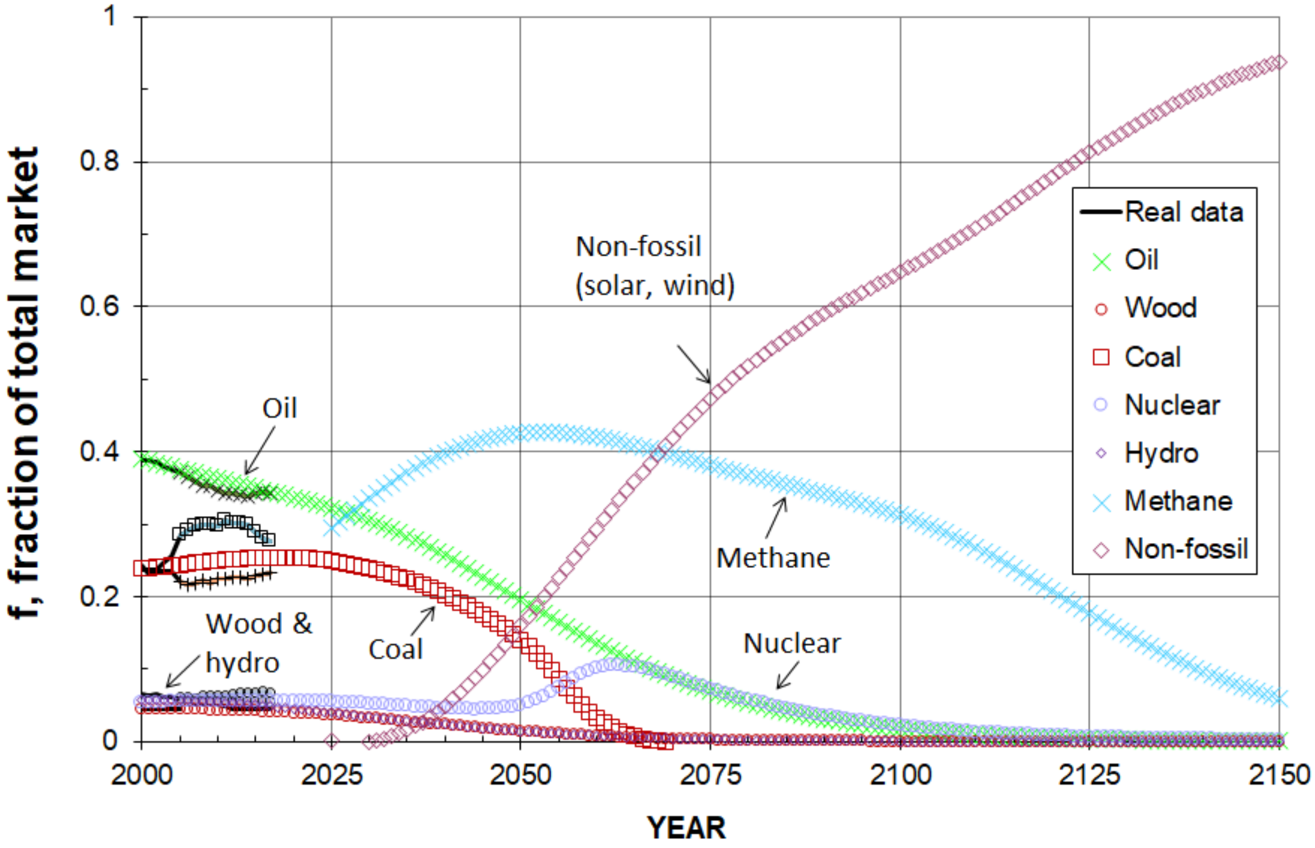

Figure 11: World primary energy mix, 2000-2150 (Aguilera and Aguilera, 2020).

This projection, however, does not take into account the implications for income that would determine the optimal speed of transition. As Barbir (2009) shows, the transition towards a lower-carbon economy (in which renewables and hydrogen would play an increased role) has to be neither too fast nor too slow to provide an optimal income steady state. Facing the recession associated with the COVID-19 pandemic, the transition might be expected to occur even slower in the short run as it is costly to the economy, and an exacerbation of the recession would not give an optimal steady-state output growth. In this context, environmental policymakers should be interested in finding innovative lower-cost transition solutions; focusing on the positive externalities between the hydrogen and natural gas industry may be one of them.

7. Conclusions

Based on the general assessment in this paper, it is clear that hydrogen development is inherently complex, requiring many major changes and coordination among diverse stakeholders with differing motivations; this includes fuel suppliers, vehicle manufacturers, consumers and policymakers, among others. Hydrogen infrastructure in particular is seen as a daunting barrier, particularly in the transportation sector, more because of logistics and scale-up issues rather than technological know-how. Opportunities are limited to few applications, including industrial hubs, heavy vehicles and some experiments to conserve and transport renewable energy. Policies have been generally directed at supporting hydrogen prices, urban bus transportation programs, technological development, and storage and transportation infrastructure. In this paper, we advocate policies that focus on building synergies with the natural gas industries, through two main pillars. First, synergies can be created with policies that support existing and new pipeline distribution networks, where hydrogen could act as a gas price backstop mechanism, solve electricity supply issues and facilitate increased use of wind and solar power in the energy mix. Second, there are plenty of potential synergies between hydrogen and LNG technologies, infrastructure and know-how, in countries involved with LNG intensively. Whereas the first pillar has been generally under-developed, the second pillar is likely to result in the formation of a major hydrogen international market in the Asia Pacific, with Australia taking a lead role. However, a transition towards hydrogen will take time and persistence, as well as the continuity of policy support over many decades.

Another implication of this investigation is that hydrogen should be seen as part of a portfolio approach to decarbonising the energy system and moving to a low emissions future. Thus, it will not be necessary nor practical for hydrogen to be the sole energy provider in the long distant future, but rather one in a group of sustainable resources.

Finally, a period of experimentation is to be expected; as with any new energy industry, not everything works immediately. Referring again to the natural gas industry, energy experts did not expect the suddenness and forcefulness of the shale gas revolution—it took years of trial and error, research and development, and capital investment to make the resource technically and then economically viable.

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