Executive summary

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HYDROGEN IS SEEN AS a means to decarbonise sectors with greenhouse gas emissions that are hard to reduce, as a medium for energy storage, and as a fallback in case halted fossil-fuel imports lead to energy shortages. Hydrogen is likely to play at least some role in the European Union's achievement by 2050 of a net-zero greenhouse gas emissions target.

HOWEVER, PRODUCTION OF HYDROGEN in the EU is currently emissions intensive. Hydrogen supply could be decarbonised if produced via electrolysis based on electricity from renewable sources, or produced from natural gas with carbon, capture, and storage. The theoretical production potential of low-carbon hydrogen is virtually unlimited and production volumes will thus depend only on demand and supply cost.

ESTIMATES OF FINAL HYDROGEN demand in 2050 range from levels similar to today's in a low-demand scenario, to ten times today's level in a high-demand scenario. Hydrogen is used as either a chemical feedstock or an energy source. A base level of 2050 demand can be derived from looking at sectors that already consume hydrogen and others that are likely to adopt hydrogen. The use of hydrogen in many sectors has been demonstrated. Whether use will increase depends on the complex interplay between competing energy supplies, public policy, technological and systems innovation, and consumer preferences.

POLICYMAKERS MUST ADDRESS THE need to displace carbon-intensive hydrogen with low-carbon hydrogen, and incentivise the uptake of hydrogen as a means to decarbonise sectors with hard-to-reduce emissions. Certain key principles can be followed without regret: driving down suppldduce-

1 Introduction

In the European Union's decarbonisation drive, hydrogen is seen as a solution for sectors with greenhouse gas emissions that are hard to reduce, as a means of energy storage, and as a fallback in case halted fossil-fuel imports lead to energy shortages. The attractiveness of relative performance of competing clean energy sources. Because of these uncertainties, we

The cost-competitiveness of different hydrogen production processes depend on the capital costs of the required installations, their technological efficiency in transforming input fuels into hydrogen, the input fuel and carbon prices.

Hydrogen supply capacity in the EU is currently estimated at 339 terawatt hours per year[1], approximately 3 percent of EU final energy demand (FCH JU, 2019). Of this, over 95 percent is hydrogen produced from fossil fuels, and less than 5 percent is produced via electrolysis (Cihlar *et al*, 2020). Production of fossil hydrogen in Europe is mainly done by separation of hydrogen from a stream of methane, a process that generates significant carbon dioxide

2.1 Alternative production pathways

Hydrogen production from natural gas and electricity are the most common methods, but there are others. Table 1 lists them, along with some rough cost estimates.

Table 1: Additional low-carbon hydrogen production methods

hydrogen from solar energy from North Africa. If deployment of additional wind or solar units in Germany becomes difficult because suitable/acceptable land is already utilised, while investment costs in Africa decline, imports of hydrogen might become competitive. However, consistent international rules would be needed to ensure that significant imports of hydrogen do not directly or indirectly increase net emissions in the producing country, for example through land-use change or replacement of renewable electricity for local populations by fossil fuels.

Figure 4: Import vs domestic hydrogen (€/MWh)

Table 2: Sector scorecard

[illegible]	[illegible] (% [illegible])	H [illegible]	[illegible]
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[illegible]	%		[illegible] / [illegible] - [illegible]
[illegible]	4%		H [illegible]
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Transport: Road

Passenger vehicles

- Hydrogen potential:
- Upper demand: 140 TWh. Medium demand: 50TWh. Lower demand: 0 TWh[9]
- 12 percent of EU greenhouse gas emissions

In road transport, hydrogen faces direct competition from electricity. Increasingly, the decarbonised future of passenger vehicles looks to be one of battery electric vehicles (BEVs). The price of batteries has rapidly dropped while range per charge is increasing. As a result, the global stock of fuel cell (hydrogen) vehicles is just 11,200 compared to more than 5 million BEVs (IEA, 2019). BEVs now enjoy a first-mover advantage as the conventional low-carbon passenger vehicle. They attract significantly more government and private-sector funding, particularly for charging infrastructure.

Nonetheless, there may be some scope for hydrogen if limitations arise because of raw material shortages, technological limitations of batteries or excess strains on electricity grids arising from too many poorly managed BEVs. Moreover, certain companies (Hyundai, Honda) are still actively developing fuel-cell electric vehicles (FCEV), ie hydrogen passenger vehicles. As markets grow and prices decrease, it is possible that FCEVs will one day compete more seriously with BEVs. Large-scale deployment of hydrogen refuelling networks would be fundamental to this but these currently still face the problem that while FCEV take-up is low, investment in refuelling networks is not attractive. As other economic sectors begin to demand more hydrogen, the roll-out of hydrogen refuelling networks may become economically more attractive.

Hydrogen offers quicker refuelling than battery charging, making it potentially more suited to vehicles in constant use, such as taxis and buses.

Heavy-duty vehicles

- Hydrogen potential:
- Upper demand: 200 TWh. Medium demand: 120 TWh. Lower demand: 10 TWh[10]
- 5.2 percent of EU greenhouse gas emissions (including buses)

Hydrogen appears to have greater potential for the heavy-duty road transport sector because hydrogen is able to store more energy in a smaller space and at lower weight than a lithium-ion battery. A challenge for manufacturers of battery electric vehicles has been producing batteries which contain sufficient energy but are not too heavy. For example, to provide the same range as a 1000 litre diesel truck, the battery of an electric truck would have to weigh about 14 tonnes. As the capacity and range of lithium batteries has expanded, this problem is gradually being overcome for small, passenger vehicles. However, hydrogen fuel cells could be deployed in heavier vehicles for which greater range and higher power output are required.

In this market segment, hydrogen would compete against biofuels and the use of electrically-derived fuels (via hydrogen). The speed of battery improvements has been rapid so far, and it is still very possible that innovations will allow battery-driven electrification to dominate heavy-duty transport. Overhead transmission lines may also play a limited role.

The most optimistic EU 2050 scenarios see approximately a 15 percent share of hydrogen

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FCEVs in the heavy goods vehicle stock (European Commission, 2018). Least optimistic scenarios would see 0-3 percent FCEV deployment. Some additional indirect hydrogen demand might occur through electrically derived fuels.

Light-commercial vehicles

- Hydrogen potential:
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producing synthetic fuels.

However, aviation remains firmly in the hard-to-decarbonise box, with technologies at a very immature stage of development. It will take many years of research and development before the potential of hydrogen relative to alternatives is clarified. Moreover, as one of the hardest sectors to decarbonise, aviation is a strong contender for residual emissions in a net-zero 2050 scenario that involves significant use of negative emissions technologies. Aviation production by eliminating the need for production of hydrogen from methane[20]. Such green ammonia projects are already underway[21].

Europe currently produces 17 million tonnes of ammonia annually and the future evolution of demand is uncertain. As the global population increases, demand for ammonia-based fertilisers will increase; food production must become more efficient to feed an increasing number of mouths from the same amount of land. However, public policy may drive out ammonia in favour of biological fertilisers or higher levels of organic production. The EU in 2019 updated fertiliser rules to promote fertilisers based on organic materials rather than chemicals[22].

Future demand for hydrogen in this sector will be determined by future demand for crude oil products, which in Europe is set to decrease. Meanwhile, sulphur restrictions are progressively being tightened, increasing the hydrogen demand per barrel of crude oil[26]. Ironically, sulphur restrictions on crude oil products such as jet fuel have in recent years likely increased the sector's greenhouse emissions because of the current carbon intensity of hydrogen (Catalá *et al*, 2013, Figure 4.5.5). In 2050, there will likely still be demand in the oil refining sector because of the use of hydrocarbons in certain chemical products.

Steelmaking

- Hydrogen potential:
- Upper range: 240TWh. Middle range: 150TWh. Lower range: 100TWh[27]
- 3.8 percent of EU greenhouse gas emissions

The EU produces 177 million tonnes of steel a year, 11 percent of global output[28]. Significant emissions are associated with the steel sector and hydrogen is widely regarded as fundamental to decarbonising the sector.

Most steelmaking greenhouse gas emissions are associated with the turning iron ore into iron prior to its processing into steel. Steel can be produced in blast oxygen furnaces (BOF) (60 percent of EU production; European Commission, 2018) and electric arc furnaces (EAF). The BOF route produces steel using coal and has little future in a decarbonised world, though efforts are being made to reduce emissions by improving efficiency, replacing some coal with hydrogen and retrofitting plants with carbon capture technology. However, unless carbon capture can be done at levels of emissions far above capabilities today, there will always be significant emissions associated with BOF.

Decarbonisation of steel production therefore relies on switching to the EAF (currently 40 percent of EU production). Here, the primary energy input is electricity[29], making green steel possible if the electricity is decarbonised. Two different feedstocks can be used with EAF: scrap steel and direct reduced iron (DRI), or a combination.

Globally, scrap steel contributes to about 25 percent of steel production. Increasing the use of scrap steel would be a welcome shift toward the circular economy[30], but is limited by availability of high-quality scrap[31]. Meanwhile, producing DRI for use in EAF involves reacting iron ore with a reducing agent, currently a mixture of hydrogen and carbon monoxide. This is already a technologically proven route, with deployment particularly in the Middle East where industry has access to low-cost natural gas, which is used for producing the stream of hydrogen and carbon gases for reduction.

All major European steelmakers are currently building or testing hydrogen-based reduction for use in EAF[32]. The target is to use pure hydrogen rather than a hydrogen/carbon mixture for reduction of iron ore. Using both scrap steel and DRI produced using hydrogen in electric arc furnaces is considered the most viable decarbonisation option for the sector within the EU (Hoffmann *et al*, 2020). A related question is whether the move to DRI-EAF

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[illegible] https://www.ssab.com/company/sustainability/sustainable-operations/hybrit.

will affect the location of steel production from close to coal/iron resources to close to cheap green-energy resources.

One issue is the long lifespan of steel plants – approximately 35 years. The production of steel through DRI-EAF using hydrogen is not yet economically mature. However the industry must be wary of locking in any further BOF capacity, with such facilities likely to become stranded assets by 2050.

3.3 Residential heating

- Hydrogen potential:
- Upper demand: 600 95 65TJ/Span/ActualText600 98TJ EMC 0 0 0 scn/GS gs/TT0 1 Tf1.556per demand: 675.52p

ing technology, hydrogen may still play a complementary role. Decentralised provision of hydrogen (ie gas bottles) could supplement residential heating on the coldest days to prevent excessive strain on local electricity distribution grids.

A final option involves keeping the natural gas network much as it is today but injecting biomethane[36] or synthetic methane produced by combining hydrogen with carbon dioxide. An obvious advantage is minimal disruption to the grid. However current levels of supply of biogas fall far short of demand, and synthetic methane is an inefficient source of energy and is very expensive.

3.4 Hydrogen as an enabler of renewable electricity deployment

In addition to deployment in end-use sectors, hydrogen could be used for energy storage, enabling the integration of increasing shares of variable renewable generation into electricity systems.

Historically, electricity grids have operated on the basis of volatile aggregate demand from end-users being met by a mix of inflexible base-load (nuclear, lignite, run-of-river) and peak-load power that is dispatched on demand (for example gas or hard coal), with relatively little storage. Increased adoption of variable renewable electricity sources is changing this model. A challenge for grid operators is to maximise the uptake of renewable electricity that is produced when the sun is shining and the wind blowing. A number of options, beyond the scope of this Policy Contribution, are under consideration, including the use of hydrogen produced from electrolysis.

Short-term flexible demand

Hydrogen production via electrolysis could be increased during times of excessive renewable power generation and reduced when supply is weak, allowing more efficient balancing of the electricity market. Kopp *et al* (2017) showed that already in 2016, a 6 MW electrolyser in Mainz, Germany was deployed with economic benefit to the German control reserve market.

Whether electrolysers can be competitive as providers of grid-balancing services will depend on technological and regulatory developments in the next few years. In particular, battery storage systems that already feature much lower storage losses than hydrogen will likely see their capacity costs drop dramatically as more batteries are produced and deployed. They may therefore be better suited than electrolysis to managing intra-daily or even intra-weekly fluctuations on electricity grids.

Long-term seasonal storage

Hydrogen could be a more useful option for managing fluctuations in renewable electricity produced in different seasons. Hydrogen could be produced during months of excess renewable electricity production, stored geologically, and then converted back into electricity during months of lower renewable electricity supply. Compared to batteries, hydrogen is a more plausible solution for seasonal storage because investment costs are almost independent of storage volume[37] and 'self-discharge' is low (Parra *et al*, 2019).

From an economically efficient perspective, whether hydrogen emerges as a seasonal storage mechanism will depend on the relationship between seasonal price differentials and the capital costs of deploying electrolysers along with storage. German electricity price differentials show that currently only for 5 percent of the time does the price differential (arbitrage gain) exceed €50/MWh. The evolution of this potential for arbitrage gain will inter alia depend on the deployment of renewable electricity generation sources and on the deployment of flexible demand side resources.

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Figure 7: Price differential, lowest vs highest hourly prices in Germany, 2019

Source: Bruegel based on SMARD.

4 Overview of market dynamics

The current cost structure of hydrogen is based on its production from natural gas (methane). But, as we have discussed, this supply is expected to be considerably transformed. The market consensus is that the price of low-carbon hydrogen will decrease over the coming years, lars (me)-2.p (s (m-(e dlg)-2 (en w)-7 (g)-2 (en w)-7 (g)-2 (g)-2 cr)15 7-2 (g)-2 cr)15 7-2 (g)ill[la(as)g el)11 (a)5 is economic to operate them. This will make additional renewables investments economically viable and an equilibrium could develop. Electrolyser capacity in this equilibrium will be determined not only by the cost of renewables and electrolysers, but also by the cost of competing flexibility providers (eg batteries, demand-response). Thus, if batteries continue their rapid pace of technological advancement, and/or innovation sees electricity demand become increasingly flexible, it is still possible that the capital costs of electrolysers will be too high to justify their part-load operation.

Non-EU countries are also investing in hydrogen production capacity. In some cases, this involves cooperation with Europe, such as between Germany and Morocco (BMZ, 2020). In other cases there is no European cooperation and hydrogen will potentially be traded on international markets. The ability of third countries to produce hydrogen une ifavol4 (unr]TJ038.8380 9d[-)Tj0-

Moreover, until a low-carbon hydrogen source at scale is secured for Europe, there is limited value in stimulating a massive ramp up in additional hydrogen demand, which would be met by carbon-intensive production methods[39]. Supporting low-carbon hydrogen should therefore be a policy priority.

The deployment of a significant volume of electrolysers should be supported to reduce their cost. This could be done using tools that proved successful for wind and solar technology (auctioning of feed-in premia). Policies to support the deployment of renewable electricity generation to fuel growing demand from electrolysers would also be a no-regret option. The deployment of other low-carbon hydrogen production should also be phased in when industry is willing to share some of the remaining technology risk.

From a geopolitical standpoint, developing commercial know-how in technologies used to produce clean hydrogen is likely to make Europe's exports more competitive in a decarbonising world.

Supporting green products

State support for the production of low-carbon products, particularly in markets currently dominated by emissions-intensive production

Focusing public support to the demand for low-carbon products and intermediate goods (such as low-carbon steel) has the advantage of being technologically neutral. Markets would be allowed to decide the most cost-efficient manner for production. Public revenue would be spent only for products for which a clear carbon-emissions reduction has been achieved. This would allow policymakers to adopt a neutral standpoint regarding the applicability of hydrogen technologies, and to avoid public money being spent on projects that eventually do not significantly reduce emissions.

The EU already has a tool for defining low-carbon benchmarks in the ETS product benchmarks[40]. A challenge would be choosing which products to support, and how much to support each product.

One drawback to this solution may be that one or two technologies are over-supported, while other options are ignored. The question then arises of whether the state is able to predict accurately which products and technologies should be supported. This is because an explicit focus on decarbonising one sector prioritises technologies that are suitable for that sector while not necessarily taking into account that support for a different technology may have wider benefits for the rest of the economy. For example, a focus on decarbonising heavy transport today might boost the competitiveness of new fuel cells and hydrogen tanks that then could be used in light vehicles, trains and aircraft, while a focus on decarbonising light vehicles today might instead extend the head start batteries have to all other modes of transportation.

Supporting R&D

Support for hydrogen research and development

Europe invests too little into R&D in general (D'Andria *et al*, 2017). Public support for low-carbon R&D is a no-regret option. However, prioritising support for different areas is more controversial.

ing the number of potentially viable decarbonisation options would make the low-carbon transition more resilient (eg if other technologies fail unexpectedly). Increased technology competition is also important to exert pressure on dominant technologies (eg electric vehi-

Roll-out of hydrogen vehicle charging stations

State support for the deployment of hydrogen vehicle charging stations

Hydrogen vehicle charging stations are an enabling infrastructure. Providing the means to refuel and operate hydrogen vehicles should stimulate private investment in the production and purchase of hydrogen vehicles. Some pilots have already been supported (fewer than 100 in Germany).

However, significant public support for hydrogen charging stations would likely not be sensible. As discussed in section 3, the case for a transition of most transport sectors to hydrogen appears weak when compared to the case for battery electric technology. There is a risk that public support for hydrogen refuelling stations would be at the expense of public support for electric charging stations.

European policymakers should continue to increase the stringency of decarbonisation policies for the transport sector. As discussed, with higher carbon prices or tougher policies, hydrogen solutions may be viable for heavy vehicles. In such a future scenario, private investment could cover the required charging stations (at either end of a trucking route, for example). If private consortia come forward with co-financing options for publicly available hydrogen charging stations, policymakers might consider offering small incentives, but this should not be a landmark policy.

Hydrogen vehicle charging stations are not today a priority for public support.

Certification scheme for low-carbon hydrogen

Developing a system for robust classification of the carbon content for each MWh of hydrogen

Knowing the carbon emissions associated with the production of each MWh of hydrogen will be an issue for future hydrogen consumption. Within Europe, calculations should not be necessary because hydrogen production falls under the ETS, and so carbon emissions are already priced in. But certification may be necessary for certifying the ‘greenness’ of hydrogen imports.

Designing a robust classification system will be difficult. For electrolysis, this would involve certifying the electricity input. When electricity for electrolysis is taken from the public grid its carbon content is more a matter of definition/accounting, than an objective value[42]. But even certifications of dedicated supplies from renewable electricity often do not pass the additionality test: has new renewable electricity capacity been built exclusively for hydrogen purposes, or has existing or already planned renewable capacity simply been ‘assigned’ to hydrogen production?

While a difficult task, European policymakers should think about designing a framework for the international trade in clean hydrogen. The extent to which hydrogen will become an internationally traded commodity remains to be seen, but if such a scenario emerges, Europe is likely to be a significant net importer. It would be wise, therefore, to start the conversation about how Europe can be sure its hydrogen imports are low carbon.

Competition policy/regulation holidays

Providing breaks from the rules of competition policy or regulation to encourage targeted investment

Providing some temporary exemptions from strict competition/network regulation rules designed for mature markets can be a tool for encouraging private sector buy-in. Horizontal and vertical coordination are both crucial during the earlier stages of building a new network. For example, initial investments in the production, transmission and consumption of

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hydrogen need to be well synchronised. Without the ability to ensure the provisioning of the

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