THE PROSPECT FOR HYDROGEN

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INTRODUCTION

On 26 May 2020 the European Commission published its Green Recovery Plan, the plan agreed by European Union (EU) leaders on 21 July. A multi-national financial framework for 2021 to 2027 has been agreed with Euro (EUR) 550 billion out of a total budget of EUR 750 billion EUR allocated to green projects in line with the European Green Deal approved by the European Parliament on 15 January 2020. The European Green Deal not only sets out a road map for supporting the development of a circular economy, but identifies the investment and financial tools to be used in achieving this. An EU Hydrogen Strategy was published on 8 July 2020 as a road map to boost hydrogen production, hydrogen being presented as a key technology to reach the goals set out by the European Green Deal, and the production of hydrogen technologies a key part of the EU's post COVID-19 recovery plan.[1]

While the EU's 2030 greenhouse gas (GHG) reduction target was already aggressive, the EU Green Deal's zero carbon ambition for 2050 has driven the debate from carbon reduction to carbon elimination. With net zero as a new policy priority policymakers see hydrogen, a zero emission product at production and combustion, as the solution to decarbonisation in sectors where renewable electricity is not a viable option.[2] Indeed, the main objective of the Hydrogen Strategy is the decarbonisation of sectors dependent on fossil fuels as well as an increase in the demand and production in end – use application sectors.

The financing announced by the European Union, and the policies adopted by a number of European countries, has catalysed activity among Exploration and Production (E&P) companies. E&P companies were already under pressure to clarify the implications of every project they embark on and explain their contribution to reducing GHG. With increasing social and environmental pressures complex questions have arisen about the role of fossil fuels in a changing energy economy and the position of E&P companies in society. At present the major E&P companies are investing 1.5 to 2.2% of their annual CAPEX in renewable projects. A key question is whether E&P companies are part of the problem or crucial to solving the GHG emission problem.

In terms of activity at the national level in Germany, a support programme for GHG neutral generation technologies as part of the coal phase out has been adopted. In the United Kingdom, the government has announced that it is investing nearly USD 1 billion to create carbon capture and storage clusters, following on from the proposal National Grid, Drax and Equinor made last year to develop the UK's first carbon neutral industrial cluster on the Humber.

In the Netherlands the government has announced that it is investing USD 3.1 billion in offshore wind turbines to power green hydrogen production.[3] Blue hydrogen also figures in the country's plans the Porthos project, led by a consortium comprising of State-owned companies, focusing on the capture of carbon dioxide (CO2) within the port of Rotterdam with a view to producing large-scale blue hydrogen by 2030.[4] Over the last three years plans more than 30 commercial carbon capture and storage (CCS) facilities have been announced representing a potential investment of around USD 27 billion.

Complementing the rhetoric of the EU is an ESG-focused capital market in which the valuation of companies manufacturing new clean technology rapidly inflates. As examples, Nikola, a producer of hydrogen power infrastructure, had an estimated value of United States Dollars (USD) 14.1 billion until negative media coverage a couple of months ago, nearly one hundred times its 2021 expected revenue,

[1] *A hydrogen strategy for a climate neutral Europe* European Commission 8 July 2020 (**EU Hydrogen Strategy**).
[2] *The Future of Hydrogen: Seizing today's opportunities* International Energy Agency June 2019 pp 23 and 24 (**IEA Report**).
[3] The term green hydrogen is used to describe hydrogen produced through water electrolysis using renewable power.
[4] The term blue hydrogen is used to describe hydrogen extracted from natural gas through a steam methane reforming process.

and Nelhydrogen, a producer of electrolysers and fuel cells, has an estimated value of USD 2.8 billion, nearly fifty times its 2019 revenue.

COVID-19 has exposed the endemic risk in economies, the risk from climate change more widely acknowledged. Hydrogen is increasingly viewed as the best option for long-term sustainable development as major shareholders in many companies' aim to limit their exposure to carbon emissions. Indeed, there is a widening practice of pricing the future climate damage associated with a product or regulation, companies recognising the need to anticipate how they would fare under carbon pricing scenarios, and to compensate for the shortcoming of a market place that fails to adequately account for climate risk.

Currently, however, hydrogen is not used as an energy carrier but is rather a form of final energy consumption used primarily as an industrial feedstock gas, in ammonia production, and in the conversion of crude oil to gasoline. In terms of current demand 38 million tonnes (Mt) of pure hydrogen are used in refining, and 31 Mt in ammonia production. 12 Mt of hydrogen and other gasses are used in methanol production and 0.01 Mt in transport.[5] The current supply of hydrogen is composed of 196 million tonnes of oil equivalent (Mtoe) from gas, 75 Mtoe from coal, 2 Mtoe from electrolysis and 48 Mtoe from bio-products. 97% of hydrogen production is from unabated fossil fuels, 2% produced from water using electrolysis. The IEA has calculated that less than 0.7% is either blue or green hydrogen.[6]

Yet hydrogen has sufficient potential advantages to seduce, its promise relating to its potential utilisation in the energy mix as an energy carrier and not a primary energy source. Efficiency and behavioural change will help lower overall energy demand but there is a need for some form of green gases or fuels to successfully transition to a zero carbon energy system. Hydrogen and derived fuels can be the missing link in the energy transition.

Electrification offers the cheapest and simplest route to decarbonise large parts of total final energy use: more than 60% of final energy consumption can be satisfied by direct electrification, renewable electricity cost-competitive and highly scalable. Electrification, however, cannot provide the solution to carbon abatement across all sectors for both technical and cost reasons. Hydrogen as a fuel and feedstock can play a significant role in the decarbonisation of hard to abate sectors provided that production is clean and with a low carbon footprint.

Once hydrogen is freed from its compound: it can be used in fuel cells as a transportation fuel; it can be added to natural gas to decrease the amount of carbon in heating; and, it can be used as a feedstock, as already noted, instead of hydrocarbons. Hydrogen can be handled in its pure form or be converted into other molecules such as synthetic methane or diesel, these conversions affording hydrogen the potential to convert different parts of the energy system. Hydrogen is a versatile fuel in terms of how it can be transported and has a variety of potential end-use applications.

Not only can hydrogen function as a versatile energy carrier that can be fed into the gas network, used in fuel cell vehicles, converted into synthetic fuels, or converted into the electricity for the grid. Perhaps of greater significance is that it provides an excellent clean energy storage for long periods. As the share of variable renewables increases energy storage will play an increasingly important role in bridging the time lag between energy production and energy consumption.[7]

Finally, the recent decline in the cost of renewable electricity, coupled with expected cost reductions and efficiency improvements for electrolysers, have strengthened the business case for green hydrogen. Although green hydrogen has enormous promise it, together with the renewable power generation on which

[5] IEA Report p 18.
[6] IEA Report p 32.
[7] *Hydrogen: A Renewable Energy Perspective* International Renewable Energy Agency September 2019 p 25 (**IRENA Report**).

it depends, needs to be scaled up dramatically to transform into an energy carrier that is both commercially viable and can support global energy supply. Between 2015 and 2018 only 1.2 Mt of green hydrogen was produced, largely explicable by the fact that hydrogen produced from fossil fuel has a current levelised cost ranging from USD 1 to 2.50 per kilogramme (kg), the levelised cost of green hydrogen varies between USD 2.50 and 6 per kg depending the technology.[8] [9]

The levelised cost of blue hydrogen ranges between USD 1.50 and 3.50 per kg, the potential of CCS benefitting from the shale gas revolution in the same way green hydrogen has benefitted from the cost reduction in wind and solar power. Although, as will be discussed, the widespread deployment of CCS is crucial to achieving the net zero ambition, between 2015 and 2018 only 0.6 Mt of blue hydrogen was produced.[10] [11]

This paper acknowledges that: firstly, although hydrogen as an energy carrier has the potential to decarbonise a number of sectors, the commercial viability of using hydrogen is dependent on each sector's particular characteristics[12]; and, secondly, that although policy towards hydrogen has changed overnight the ability to deliver projects has not.[13] Further, it recognises that regions have access to different low cost feedstock, and different carbon problems, and that as a result locally produced hydrogen will have different impacts.[14] The first hydrogen projects need to close the capability gap, the technology chosen depending on the region in which it is located and not the colour of the feedstock. Instead, the focus should be on the energy intensity of the product, the virtue of hydrogen is that it produces zero carbon emissions at the point of use. That is the central tenet of this paper.

EU HYDROGEN STRATEGY

As has been noted on 8 July the EU Commission published its Hydrogen Strategy. In Phases 1 and 2 EUR 24 to 42 billion is to be invested in the installation of electrolysers, and EUR 220 to 340 billion to scale-up and connect 80 to 120 GW of wind and solar power. Another EUR 65 billion is to be invested in hydrogen transport, distribution, storage, and refuelling stations.[15]

- Phase 1 from 2020 to 2024 will see the installation of 6 gigawatts (GW) of hydrogen electrolysers, producing 1 Mt of renewable hydrogen per year. The aim in this phase is to decentralise existing hydrogen production, and to retrofit plants with CCS technologies. A regulatory framework and appropriate state aid rules will be implemented to kick off the hydrogen market.[16]

- Phase 2 from 2024 to 2030 will see the installation of 40 GW hydrogen electrolysers, producing 10 Mt of renewable hydrogen per year. The aim in this phase is to establish cost competitive hydrogen

[8] IEA Report p 53.
[9] In the IRENA Report at p 28 the cost of producing green hydrogen today is identified as: USD 6.8 per kg using PV solar at a price of USD 85 MWh; USD 3.3 per kg using PV solar at a price of USD 1.5 MWh; USD 4.2 per kg using wind at a price of USD 55 MWh; and USD 2.7 per kg using wind at a price of USD 23 MWh IRENA.
[10] IEA Report p 53.
[11] In the IRENA Report at p 28 the cost of producing blue hydrogen today is identified as: USD 2.3 per kg at a price of USD 8 Mbtu; and USD 1.5 per kg at a price of USD 3 Mbtu.
[12] See for example IEA Report p 148 on which it is asserted that the final energy price for hydrogen is likely to have to be in the range of USD 1.5 to 3 per kg in major heating markets in order for it to compete with natural gas and electricity in providing heat in buildings.
[13] IEA Report p 28.
[14] See IEA Report at p 49 and p 55 for a comparison of the production cost of hydrogen in different parts of the world, and p 158 in which it is shown that whether hydrogen based power generation for load balancing can compete on price against natural gas depends on regional hydrogen, natural gas, and carbon pricing.
[15] EU Hydrogen Strategy pp 7 and 8.
[16] EU Hydrogen Strategy pp 5 and 6.

as an instrumental part of an integrated energy system, by way of establishing large-scale infrastructure and international trade.[17]

- In Phase 3 from 2030 to 2050 it is intended to establish the supply of renewable hydrogen technologies to sectors that have no feasible means or alternatives to decarbonise.[18]

The EU aims to establish a freely accessible, rules-based market for hydrogen by setting out clear criteria for the sustainability of the fuel. To this extent it is believed that the price of hydrogen should reward electrolysers for the benefits they offer to the energy system such as increased renewable generation levels, and a reduction in the burden of renewable incentives. To complement this the European Commission has stated its intention to develop a certification system for renewable hydrogen based on life cycle carbon emissions in order to target support to cleanest available technologies.[19]

The EU Hydrogen Strategy emphasises that a comprehensive hydrogen strategy can only be achieved by addressing the whole value chain, from production to demand. Measures to promote the use of hydrogen include support policies for the demand side, e.g. green hydrogen quotas for specific end use applications,[20] in addition to the implementation of tendering systems for carbon contracts for difference (CfD).[21] The EU Hydrogen Strategy acknowledges how the competitiveness of low carbon hydrogen can be secured by way of the introduction of a carbon tax,[22] noting that carbon prices in the range of EUR 55 to 90 per tonne of CO2 would be needed to make blue hydrogen competitive with hydrogen from fossil fuels today.[23]

Finally, the Hydrogen Strategy unequivocally supports the development of a green hydrogen value chain, emphasising how the generation of domestic demand will provide Europe with an opportunity to assume technology leadership along the entire value chain.[24] This aim is clearly an attempt to avoid missing opportunities as has previously been the case. The first phase of the EU's green policy from 2007 to 2020 was premised on the promotion of renewables and electrification both to meet carbon reduction targets and support the development and production of green technology in Europe. Although the EU is on target to meet its 2020 climate goals, the EU share of final energy consumption from renewable sources witnessing a 9% increase since 2007, and EU GHG emissions down 14% from a 2007 baseline, there has been a failure to catalyse such production. European subsidies have largely been to the benefit of non-European producers, European wholesale power prices rising to cover the cost of them.

BLUE HYDROGEN AND THE TRANSITION

SMR using natural gas is the most cost effective method for hydrogen production today, the majority of global production using SMR.[25] CCS can be used to decarbonise the production process, the result being blue hydrogen. The potential for the centralised production and distribution of blue hydrogen offers

[17] EU Hydrogen Strategy pp 6 and 7.
[18] EU Hydrogen Strategy p 7.
[19] EU Hydrogen Strategy p 16.
[20] EU Hydrogen Strategy at pp 10 and 11 proposes quotas for heavy duty road vehicles; fuel cell trains, and maritime transportation.
[21] The EU Hydrogen Strategy at p 14 recognises that the need to scale up production before green hydrogen is cost competitive will mean that support schemes are likely to be required. It maintains that a possible policy instrument would be to create tendering systems for carbon contracts for difference. Such a long-term contract with a public counterpart would remunerate the investor by paying the difference between the CO2 strike price and actual CO2 price in the EU European Trading Scheme, bridging the cost gap to conventional hydrogen production.
[22] EU Hydrogen Strategy at p 14 recognises how the ETS as a market-based instrument already provides a technology neutral EU wide incentive towards cost effective decarbonisation in all its covered sectors through carbon pricing. Further, it provides that in the revision of the ETS the Commission will consider how the production of renewable and low carbon hydrogen may be further incentivised while taking account of the risk for sectors exposed to carbon leakage.
[23] EU Hydrogen Strategy p 4.
[24] EU Hydrogen Strategy pp 17 to 19.
[25] IEA Report p 40.

opportunities to co-opt segments of the fossil fuel industry into energy transition, supporting natural gas extraction, transportation, processing, and carbon capture and storage. Crucially, existing gas infrastructure can to some extent be repurposed for the transportation of hydrogen, providing E&P companies with a way of avoiding stranded upstream and midstream assets, and with access to a new market in terms of selling hydrogen and its derivatives based on their experience selling gas. CCS not only allows for the recycling of oil & gas sector infrastructure, equipment and personnel, e.g., pipelines, compressors, turbines, platforms, reservoir engineers, but presents an opportunity for E&P companies to be part of the solution to GHG emissions.

The EU Hydrogen Strategy has expressly recognised a role for blue hydrogen.[26] Although it is clearly expressed that the priority is to develop green hydrogen, produced mainly using wind and solar energy, in the short and medium-term other forms of low carbon hydrogen, i.e. natural gas to hydrogen, are acknowledged as being needed to rapidly reduce emissions and support the development of a viable market.[27] The EU Hydrogen Strategy, however, understates the role of CCS.[28] As, has already been noted, global GHG emissions must drop 50% by 2030 and reduce a further 50% from that level by 2040 to achieve net zero by 2050. Given the mathematics of the net zero ambition CCS is necessary for both CO2 reduction and CO2 removal.[29] It is consistently neglected that CCS targets emission as it produces hydrogen without emissions at the point of use.

Global clean hydrogen production needs to grow 80 to 90% per year to meet the 2050 net zero ambition. CCS and blue hydrogen is crucial to create the impetus and scale need to meet this ambition. The answer to the question of blue versus green is therefore that we need both due to the cost of not deploying them. At present there are seven large hydrogen production facilities using CCS technology, the majority methane reformation these facilities having a capacity of 40 Mt of CO2 per year. It is predicted that 9% of emission reductions must come from CCS, this figure representing the deployment of up to 100 CCS facilities a year together with the necessary transportation and storage infrastructure.[30]

The majority of CCS projects are concentrated around industrial clusters and existing pipeline infrastructure close to storage sites. Although they are by their very nature geographically constrained, given the potential size and cost advantages of blue hydrogen production CCS projects will play a key role in the development of a hydrogen transportation and storage infrastructure. Blue hydrogen project delivery, however, comes with risk and uncertainty: a dependence on natural gas pricing, a reliance on EPC markets to deliver competitive project capital expenditure (CAPEX), and the cross chain risk inherent in the amalgamation of different market sectors into one project delivery team.

Blue hydrogen cost estimates vary significantly based on natural gas prices, CAPEX, and operating expenditure (OPEX). Natural gas and CAPEX typically make up 40% of the costs in regions with access to low cost gas, in contrast to regions with higher gas prices where the gas price alone can be up to 60% of the production cost. As a consequence, blue hydrogen production is only likely in regions: where there is a consistently low gas price or where it is possible to use project structures that effectively mitigate against variations in gas pricing; and, where there is suitable transportation infrastructure and CO2 storage facilities.[31]

Even in such regions the rapid and widespread deployment of CCS requires not only the adoption of CCS specific regulations comprehensive government strategies encompassing: one, consistent policies on

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[26] EU Hydrogen Strategy p 5.
[27] IEA Report at pp 182 to 185 discusses the short-term priority of using the existing gas infrastructure to scale-up low carbon hydrogen supply by tapping into dependable demand.
[28] See also the depiction of fossil fuel based hydrogen as a transition option in the IRENA Report at pp 15 to 17.
[29] The former involves managing emissions from the cement, steel, and chemical industries, and from coal-fired power plants, the latter involves enabling large-scale CO2 removal through engineered systems.
[30] See IEA Report pp 177 to 181
[31] IEA Report p 42.

carbon value; and, two, targeted financial support, i.e. loan guarantees, as a bridge to unsubsidised commercial financing. Due to the size of the investment required for such deployment private capital is required. CCS projects, however, have not been able to attract such private capital as the absence of consistent policies supporting CCS deployment limits their financial viability. Crucially, government policies must place a sufficiently high value on GHG emission reduction to incentive investment.

The majority of current CCS projects are funded pursuant to public private partnerships (PPPs) in which a company finances a project on its own balance sheet. The alternative, and more scalable funding model, is project finance in which investment is secured on the basis of project cash flows. Such cash flows need to be sufficiently high, predictable and long term for investors to provide capital, a predictability that is dependent on the consistent implementation of government policy. This is particularly the case for institutional investors whose financing of projects post commissioning is essential for the wider deployment of CCS facilities as the post commissioning refinancing of a project's debt results in the reduction of project costs.[32]

Indeed, government policies must balance a number of priorities: to attract private capital and provide a framework for project finance; to maintain alignment with market dynamics; and, as will be discussed in the conclusion, to balance the provision of public subsidies with value for the consumer. Regardless of which value chains governments wish to develop, policy efforts are needed with the aim of: establishing targets and long-term policy signals; supporting demand creation; mitigating investment risks; promoting research and development and knowledge sharing; and, harmonising standards and removing barriers.[33] Such policies include tax credits, feed in tariffs, carbon pricing, contracts for differences, grants, emission caps, and procurement mandates, the competent authority in each jurisdiction determining the policy mix that best suits the national or regional market.

Cap and trade polices typically place a limit on the GHG emissions permitted for an industry or economy. The cap includes transferrable allowances so companies can decide whether to reduce their own emissions or purchase additional allowances from others. Such schemes fail to provide certainty regarding the commercial value of reductions made, e.g. the European Emissions Trading Scheme (ETS) value remains below the necessary threshold for CCS investment. A fixed tax may be imposed on CO2 emissions, the pricing calibrated to achieve GHG emission reduction targets that are increased over time, e.g. such taxes can be priced higher than the cost of capture. Tax credits and incentives, either investment or performance based, may be used to promote investment in low carbon technology.[34] Finally, public procurement can play a key role in creating a supply chain, stimulating innovation investments, and reducing initial costs as governments are one of the largest purchasers of technologies and services.[35]

The large-scale development and deployment of CCS is also dependent on front-end infrastructure investment in shared transport and storage infrastructure that improve the economics of CCS facilities by lowering costs and risks. The hub and cluster model proposed by the British and Dutch governments provides such cost and risk reductions. A common transport and storage infrastructure: one, significantly reduces the cost of CCS; and, two, provides customers for such CCS facilities. The initial investors in transport and storage infrastructure, however, are expected to bear both the costs and cross chain risk. The very lack of investment on COS transport and storage infrastructure to date underlines that the perceived risks are too high without government loan guarantees or investment.[36]

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[32] *Net zero and geospheric returns: actions today for 2030 and beyond* Centre on Global Energy Policy, Columbia University, Report 2020, p 35 (**Columbia University Report**).
[33] IEA Report pp 175 to 177.
[34] A carbon CfD acts as a production credit, providing additional revenues for the low emission generation of power.
[35] Columbia University Report pp 37 and 38.
[36] See the IEA Report pp 177 to 181 for a discussion of the short-term priority of developing coastal industrial clusters to open gateways to lower cost and lower carbon hydrogen hubs, and Columbia University Report pp 42 and 43.

Although the provision of subsidies and targeted financial support will play a large role in stimulating the deployment of CCS there remains a need from the outset to demonstrate how blue hydrogen can be produced on a commercial basis without them. For this cost effective, reliable supply chains are needed to support commercial projects in order to short the hydrogen hype circle. The hydrogen industry is in its nascent phase with uncoordinated demand and supply, and significant gaps in supply chains. Most of the equipment used to date is retrofitted gas equipment, bespoke liquifiers and compressors not yet reliable. The capability and efficacy of technology are as important to the success of a project as its economics.

CCS projects currently benefit from lower energy costs and lower capital costs in comparison with the production of green hydrogen by water electrolysis. Although the carbon abatement cost is around EUR 50 tonnes of carbon dioxide equivalent (tCO2e) cheaper for CCS than for water electrolysis it is still relatively high for peak power generation and industrial heat.[37] The fact that high carbon prices are needed for CCS to achieve commercial viability, coupled with the expected significant decrease in the cost of green hydrogen production, explains the EU's clear preference for green hydrogen as a long-term solution to GHG emissions reduction.

More importantly, with net zero as the ambition, and the fact that not all CO2 emissions can be captured cost effectively, blue hydrogen is left vulnerable to the imperatives of climate rhetoric. Whilst green hydrogen's credibility currently suffers from it being untested at an industrial level, blue hydrogen suffers from its association with the continued usage of fossil fuels and the opportunity it provides to E&P companies to maintain their share of the energy market. This perceived dialectic is colour blinding policy makers. Regional differences between the choice of feedstock should be the focus and not the colour of the feedstock as the only way to achieve the net zero ambition in 2050 is to focus on the carbon intensity of the end product now.

THE CHALLENGES OF GREEN HYDROGEN DEVELOPMENT

As has already been noted, green hydrogen is not yet cost competitive with hydrogen produced from fossil fuel. According to the IEA 1kg of green hydrogen costs from EUR 0.10 to EUR 0.15 per kilo watt hour (KWh) to produce. In contrast hydrogen costs EUR 0.045 KWh to produce from fossil fuel.[38] The IEA, and IRENA, predict, however, that the gap will close with economies of scale and greater renewable energy deployment. According to IRENA the levelised cost of green hydrogen produced from solar generated power will drop from USD 6.7 in 2020, to USD 3.2 in 2030, to USD 2 in 2050 in the base case scenario, and from USD 3.2 in 2020, to USD 1.9 in 2030, to USD 1.2 in 2050 in the best case scenario. The levelised cost of green hydrogen produced from wind generated power will drop from USD 4.2 in 2020, to USD 2.8 in 2030, to USD 1.5 in 2050 in the base case scenario, and USD 2.6 in 2020, to USD 1.6 in 2030, to USD 0.9 in the best case scenario.[39]

The success factors to achieve such cost reductions and to make green hydrogen cost competitive are: investments beyond a critical mass in renewable power generation and electrolysis capacity; breakthrough technologies; the construction of large-scale transmission and storage infrastructure; and, a tailor made and enabling regulatory framework. The EU Hydrogen Strategy proclaims the ambition to construct 40 GW of electrolyser capacity and an additional 120 GW of wind and solar capacity by 2030. The sheer scale of this ambition testifies to the importance of economies of scale as a way of reducing costs and developing dedicated renewable power sources to increase the load factor of electrolysers. Electrolysers need cheap renewable electricity and must run almost continuously to cover their capital costs. [40]

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[37] It is predicted in the IEA Report at p 118 that in the context of a USD 100 tCO2e low carbon based fuels are likely to be a significantly more expensive alternative to fossil fuels in key regions for high temperature heat in 2030.
[38] IEA Report p 52.
[39] IRENA Report p 34.
[40] IRENA Report at p 27 details how electrolysers require high load factors to produce an affordable hydrogen supply.

The proclaimed ambition of the EU is not without cause. The generation of capacity of electrolysers in 2018 was 0.04 GW. At the current rate of deployment this could increase to 100 GW in 2030 and 270 GW in 2050. IRENA has estimated that to meet the net zero ambition this needs to be 270 GW in 2030 and 1700 GW in 2050. The renewable power supply in 2018 was 0.26 terawatts per hour (TWh). At the current rate of deployment this would grow to 450 TWh in 2030 and 1200 TWh in 2050. It has been estimated that to meet the net zero ambition this would need to grow to 1200 TWh in 2030 and 7500 TWh in 2050.

The latter set of statistics emphasises how currently one of the key impediments to green hydrogen production is the generation capacity and cost of renewable power.[41] Whilst the falling cost of wind and solar power have had an impact on the interest in producing green hydrogen,[42] wholesale and retail power prices in the EU remain far higher as a result of EU energy policy and the system costs caused by the more widespread renewable power generation in Europe. The additional cost in the feed-in-tariff paid for renewable power generation has been be passed through to industrial and household consumers, this higher cost having a detrimental impact on the competitiveness of industries and household budgets in the EU. As the share of renewable power generated increases, and power demand from water electrolysis grows, the additional cost incurred is unlikely to be sustainable.

The potential for green hydrogen is based not only on the price of renewable power falling faster than the price of natural gas and carbon capture, but the production of electrolysers on an industrial scale. The cost of electrolysers fell 40% between 2015 and 2019, the cost of producing green hydrogen falling 50% in the same period. Electrolyser costs are expected to halve in 2030 due to the increased scale and standardisation of manufacturing.[43] These reductions, however, will not on their own sufficiently impact on the production cost of green hydrogen, an improvement in the efficiency of electrolysers critical to their competitiveness. Governments therefore need to invest in the development of electrolysers as they did in PV solar after 2009 as the existing technologies used to produce green hydrogen are still too expensive to be deployed at scale.

Even if large cost reductions in green hydrogen production result from improvements in the efficiency of water electrolysis and the production of modular, standardised units on a mass scale, green hydrogen will remain a relatively expensive energy carrier.[44] As was noted in the previous section government policies need to be implemented that align market dynamics, attract private capital, and, provide a framework for project finance. Much discussed examples are: one, how the cost of capital of projects can be reduced through the use of a tender based carbon Cfd structure; and, two how the competitiveness of green hydrogen requires the introduction of a carbon tax, the carbon price or implied carbon cost depending on the end use.[45] A carbon price significantly higher than that typically found on the EU ETS, around EUR 25 to 30 tCO2e, is necessary to make green hydrogen competitive with natural gas.[46]

In reality, despite the recent political rhetoric EU Member States are unlikely to support an increase in EU carbon prices to a level which would not only make green hydrogen competitive but would result in economic dislocation and unemployment. The imposition of such additional carbon costs would render EU industries uncompetitive internationally without significant carbon import tariffs being imposed on products entering the EU. This is clearly contemplated in the EU Hydrogen Strategy it being expressly recognised that should differences in climate ambition levels around the world persist the Commission will propose a

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[41] IRENA Report at p 27 details how the cost of producing hydrogen varies pursuant to the power price and electrolyser CAPEX.
[42] IRENA Report at p 26 maintains that the dramatic fall in the cost power generated by onshore wind and PV solar has focused attention on the production of green hydrogen.
[43] The EU Hydrogen Strategy at p 4 emphasises the reduction in the cost of electrolysers.
[44] IEA Report at p 47 details the expected reduction in electrolyser CAPEX and the future levelised cost of green hydrogen production by operating hour for different electrolyser investment costs and electricity costs.
[45] EU Hydrogen Strategy at p 14.
[46] EU Hydrogen Strategy p 4.

carbon border adjustment mechanism in 2021 to reduce the risk of carbon leakage.[47] What is needed for the development of a market that supports the production of green hydrogen is international rules on the certification of the carbon content of hydrogen, and an international framework regulating the sequential expiration of colour certificates.

TRANSPORT AND STORAGE INFRASTRUCTURE

The European Commission has identified the repurposing of the existing European gas infrastructure as a fast and cost-effective option to provide the hydrogen sector with transport and storage infrastructure, infrastructure connecting supply and demand that is crucial for the expansion of the hydrogen sector. At present, however, while there is a harmonised legal regime for the ownership and operation of gas networks pursuant to the EU Third Energy Package Directive, the design of legislation is based on methane gas and a gas quality standard based on calorific value. The existing regulation of gas transmission and of gas quality standards will need revision as a result of blending hydrogen in the network.

In terms of the revision of EU legislation the EU Commission is proposing the revision of the Trans European Network for Energy and a review of internal gas market legislation to support a competitive decarbonised gas market. As is recognised in the EU Hydrogen Strategy, with increasing demand, the production, use and transport of hydrogen needs to be more effectively regulated to ensure that the entire system is efficient. The EU Commission has stated that this process should be combined with a strategy to meet transport demand through a network of refuelling stations linked to the review of the Alternative Fuels Infrastructure Directive and the revision of the Trans European Transport Network.[48]

Revising regulation is not, however, the main challenge. Hydrogen is comparatively small in size and as a consequence more easily leaks from pipelines than methane. Not only does hydrogen have a propensity to leak; it forms flammable clouds, easily ignites, and explodes.[49] Hydrogen therefore must be handled differently by limiting complexities, and adapting pipeline dimensions, volumes and pressures. Finally it causes structural damage to pipelines due to embrittlement. As a result, while the conversion of the existing natural gas infrastructure to hydrogen use is feasible, cost, material suitability, and safety concerns, will at least impact on the speed at which this is implemented. Whilst only retrofitting and adapting gas infrastructure is required when blending up to 20% hydrogen, material costs are incurred after blending more than this with the replacement of pipes and compressors.[50] Higher maintenance costs are also incurred due to increased safety risks.

Leaving aside the technical challenges the cost of hydrogen transportation is comparatively expensive due to the energy density of hydrogen as a fuel versus oil products and LNG. For long distance transportation hydrogen may be converted to liquid ammonia, liquid ammonia taking up less space than compressed hydrogen. Liquid ammonia, however, also has a significantly lower energy density than either oil or LNG. Further, the conversion process from hydrogen consumes considerable energy,[51] and the transportation of liquid ammonia is technically more challenging than LNG due to the lower temperature that is required.[52]

The cost of transporting hydrogen energy long distances could match the production cost, with the ability to reduce the cost of transportation limited.[53] The energy cost of the conversion of hydrogen to liquid ammonia is unlikely to be significantly reduced, the quantity and quality of steel needed in pipeline

[47] EU Hydrogen Strategy p 14.
[48] EU Hydrogen Strategy p 14.
[49] IEA Report pp 35 and 36.
[50] IEA Report pp 70 to 74.
[51] IEA Report p 60.
[52] IEA Report p 56.
[53] For a discussion of the long distance transportation of hydrogen by way of pipeline and ship see IEA Report pp 76 to 78.

construction fixed. The impact of hydrogen is therefore likely to be limited to regions with gas supply or large-scale renewable power generation, and the corresponding industrial demand.[54]

That having been said lithium ion batteries are an inferior means of storing energy than either pure hydrogen or liquid ammonia. The increased integration of renewables into the grid and their intermittency creates technical challenges which existing battery technology cannot solve easily due to the enormity of the energy storage requirements. It is considered highly unlikely that lithium ion batteries can achieve the cost effectiveness or scale to provide either the seasonal demand balancing that the European power system requires, or cope with the seasonal intermittency that renewable generation creates. In contrast, hydrogen is capable of storing energy for long periods and in large quantities.[55] Hydrogen as a storage medium therefore appears to be the only feasible alternative option to gas for seasonal energy storage, providing the necessary capacity and power supply when required.

CONCLUSION

The EU Green Deal sets out highly ambitious targets which will significantly impact on the European economy and population. In December 2018 the revised Renewable Energy Directive was adopted setting a target for 2030 of 32% of the power consumed being from a renewable source, a significant acceleration in the current rate of renewable deployment. In terms of GHG emission the current 2030 commitment is a 22% reduction by 2030 versus 2018 levels. The EU Green Deal plan would increase this reduction up to 40% versus 2018 levels. The question remains, however, as to how to put the renewable energy strategy into practice, a strategy that combines energy security and affordability with the reduction of GHG emissions.

A successful coal phase out and a near doubling of the capacity of renewable power generation will only get the EU to around 30% of the way towards its new Green Deal 2030 target. To achieve this target will therefore require much more fundamental changes to the economy and the way people live. With regards to the 2050 net zero ambition the deployment of renewable power generation and the electrification of energy consumption are not accelerating fast enough, the former constrained by intermittency issues and the lack of effective storage options and the latter likely not to exceed much above 60% due to technical constraints.

As has been noted the EU Hydrogen Strategy asserts a production target of 10 Mt of green hydrogen a year by 2030. This target demands a doubling of renewable power generation capacity dedicated to it, a demand that will inevitably deny the EU the necessary renewable power to feed its other energy transition ambitions.[56] Even if the renewable power supply can be secured the EU 2030 target would only see sufficient green hydrogen produced to replace current grey hydrogen use in refineries and fertiliser production. As has been discussed the realisation of the potential of green hydrogen is dependent not only on a significant increase in renewable power generation capacity, but cost reductions and efficiency improvements in the process of its production. Prohibitive technology costs, and the constraints created by the inadequacy of renewable power supply, are serious impediments to an increase in production in the near future.

The cost that are likely to be incurred in achieving the net zero ambition through the use of green hydrogen compels many European industries to moving manufacturing to countries which do not impose a carbon

[54] IEA Report at p 83 provides a table comparing the delivered hydrogen costs for domestically produced and imported hydrogen in 2030 illustrating this point.
[55] See IEA Report at p 159 which maintains that, depending on the costs of the stored electricity, compressed hydrogen storage becomes the most economic storage option at discharge durations longer than 25 to 40 hours.
[56] See IEA Report at p 43 where it is maintained that producing all of today's hydrogen output from electricity would result in an electricity demand of 3600 TWh, more than the total annual electricity generation of the EU.

abatement cost on production. This in turn compels the EU to either accept the loss of a large part of its industrial basis or impose a carbon border tax on products entering the EU from such countries. As has already been noted the EU Commission has stated that it will propose a carbon border adjustment mechanism in 2021 to reduce the risk of carbon leakage.[57]

The alternative, as already discussed, is that the EU recognise the importance of blue hydrogen not only in catalysing the development of a hydrogen market but in reducing GHG emissions. IRENA have included 78 ExaJoule (EJ) of total hydrogen production in their forecast by 2050. This includes 19 EJ or 7000 Twh, assuming 80% efficiency for electrolysis, from green hydrogen. Therefore 60 EJ of hydrogen will result from processes utilising fossil fuels.[58]

A comprehensive audit needs to be undertaken which considers: the total cost for industry and households of the production of hydrogen and its integration into the power system; its impact on the reliability of the power and related systems; its impact on the overall GHG reduction savings that result; its impact on economies in terms of their growth and ability to provide employment; and, its impact on relations with other countries. Only after conducting such an audit will it be possible to understand the potential significance of hydrogen and the speed at which will have an impact. Governments may then make considered policy decisions about: the prioritisation of green ahead of blue hydrogen; the provision of direct support in reducing the cost of production; the provision of credits and the implementation of a carbon tax; investment in necessary transmission, transportation and storage infrastructure; making hydrogen mandatory for certain end users; and, the use of public procurement in catalysing supply chains.[59]

With State-sponsored support it is important to consider not only compliance with State aid requirements but how to achieve the right balance of providing support and retaining value for consumers. The support provided for long-term carbon solutions must be market based. Although, as has been noted, the EU Hydrogen Strategy recognises that the need to scale-up production before renewable is cost competitive will mean that support schemes are likely to be required, the provisions of such schemes are expressly stated as being subject to compliance with competition rules. The proportionality of measures such as carbon CfD and their market impact is to be assessed carefully ensuring that these comply with State aid guidelines for energy and environmental protection.[60]

Refining and expanding the EU ETS should be the main driver for decarbonisation as such a systemic approach encourages the adoption of least cost applications and solutions. The EU energy market needs to be recognised as the most efficient way for system integration, and for preserving competition and fostering liquid markets. As Member States have different potential for the production of renewable hydrogen an open and competitive EU market with unhindered cross border trade has important benefits for competition, affordability and security of supply. The EU Hydrogen Strategy maintains that moving towards a liquid market with commodity based hydrogen trading would: facilitate entry of new producers: be beneficial for deeper integration with other energy carriers: and, create viable price signals for investments and operational decisions.[61]

The policy of unbundling should be also preserved, preventing hydrogen network operators from restricting access to supply and storage infrastructure. In order not to distort the level playing field for market based activities network operators must remain neutral. The EU Hydrogen Strategy recognises that to facilitate

[57] See the EU Hydrogen Strategy p 14.
[58] IRENA Report p 22.
[59] See IEA Report pp 175 to 177.
[60] EU Hydrogen Strategy p 14.
[61] EU Hydrogen Strategy at p 16 suggests that existing rules that enable efficient commercial operations developed for electricity and gas markets, such as access to trading points and standard product definitions, could be considered for a hydrogen market under the review of gas legislation for competitive decarbonised gas markets.

the deployment of hydrogen, and develop a market where also new producers have access to customers, hydrogen infrastructure should be accessible to all on a non-discriminatory basis.[62]

A cross-border approach should be adopted for any financial support schemes provided for renewable, decarbonised gases. An integrated EU certification regime is the only way to provide a fair competitive approach towards the carbon intensity of energy, and to foster a market in which there are options and liquidity. Carbon abatement should be rewarded at the EU level in a technologically neutral way creating a level playing field. The equal treatment of hydrogen with other carriers must be ensured to not distort the relative prices of different energy carriers as solid relative price signals allow energy users to make informed decisions about what energy carrier to use where, and make efficient decisions about whether to consume energy or not. The EU Hydrogen Strategy acknowledges this, maintaining that only an open and competitive EU market with prices that reflect energy carriers' production costs, carbon costs, and external costs and benefits can efficiently provide clean and safe hydrogen to end users who most value it.[63]

The EU Hydrogen Strategy and different national ones provide only a framework. Indeed, nineteen countries have issued hydrogen roadmaps and strategies that differ in terms of production and application. National targets should be aligned with EU level targets as this is the only way to reach 2030 and 2050 goals. Indeed, national, sector and sub-sector targets should be avoided. As noted above the development of hydrogen should be left to the largest possible extent to market signals, with carbon abatement being achieved at the lowest possible cost. This is easier said than done. As an example the steel sector in Germany is pushing for the adoption of legislation making hydrogen primarily available in sectors in which it is de facto indispensable for CO2 reduction, and for the provision of incentives for customers to pay a higher price for climate neutral steel.

There will be considerable legislative and regulatory activity going forward, not all of this activity necessarily aligned. The majority of countries rely on their existing gas transportation regulations to regulate hydrogen, these regulations not necessarily relevant due to the different nature and use of hydrogen. Much of how hydrogen storage and transport is regulated has developed over time from the industrial uses of hydrogen. The emergence of hydrogen as an energy carrier and how that is understood by governments will shape their decisions about the regulation of the transportation of hydrogen over long distances, and how it is to be provided as a fuel for long distance transportation.

Two key challenges facing policy makers how to ensure the sufficient and safe transportation of hydrogen, and, how to establish a grid of hydrogen refuelling stations. As has been noted the EU Commission has proposed: one, to revise the Trans European Network for Energy to ensure that the increasing use and long distance transportation of hydrogen is both safe and efficient: and, two, to review the Alternative Fuels Infrastructure Directive and revise the Trans European Transport Network to meet the growing transport demand for hydrogen through a network of refuelling stations.[64]

National policies and tax frameworks that tend to discriminate against hydrogen in favour of electricity need to be amended, e.g. the double taxation of green hydrogen production for industrial fuel switching. In Germany, as an example, carbon pricing has been extended only to applications in the transport and heating sector that have not yet been covered by the EU ETS, by considering tax and surcharge exemptions for the electricity used to produce green hydrogen, and by categorising green hydrogen as fuel that reduces GHG emissions. As has been emphasised, however, for a successful energy transition open and fair cross-border competition is needed between different technologies, between hydrogen, other climate neutral fuels and lithium batteries. Regulations, and in particular tax benefits, should not benefit one ahead of another.

[62] EU Hydrogen Strategy at p 16 suggests that third party access rules, clear rules connecting electrolysers to the grid, and the streamlining of permitting and administrative hurdles, will be developed to reduce undue burden to market access.
[63] EU Hydrogen Strategy p 16.
[64] EU Hydrogen Strategy p 14.

In a similar vein transparent and predictable legislation and regulation are essential prerequisites for investment in CCS. The lack of past projects as precedent results in inconsistencies in approach between the competent authorities, and leads to complex, protracted discussions before such authorities are able to definitively interpret the existing rules and grant the necessary permits. The emerging role of CCS has encouraged policymakers to adopt specific legislation that provides clarity with regards to: the right to use and ownership of storage space; government oversight of operational activity; and, concerns connected to the long term-liability of operators. As an example, EU Directive 2009/31/EC established a framework that regulates the risks associated with capture and transport including, requirements for the permitting of exploration and storage activities, monitoring and reporting obligations, and the limitation of liability.

It is the latter, the long-term liability obligations borne by operators, that make it difficult for investors to accept the risk inherent in the operation of CCS facilities. In the absence of limitations on liability storage operators will face indefinite obligations of an unlimited size. For CCS to be deployed globally governments need to implement regulations that embody a consistent approach towards such liabilities in terms of either the operator bearing the risk only during the operational phase of a project or the government bearing the risk during and after operations phase above a prescribed cap on the operator's liability.[65]

Finally, as has already been suggested, there is a need to evaluate the impact of hydrogen's development on relations and contracts with other countries. Indeed, the EU Hydrogen Strategy is seen as a way of redesigning Europe's energy relationship with countries in Eastern Europe and North Africa.[66] This evaluation should not only focus on the impact on existing gas supply arrangements, and on the construction and financing of LNG terminals and gas pipelines, but consider the impact of carbon import taxes on international trade in general. A carbon border tax creates the potential for trade disputes with the US and China, disputes that the World Trade Organisation (WTO) and its rules at present are not designed to handle. Without such a tax, however, it is hard to see how Europe can successfully pursue the ambition it has declared.

[65] Columbia University Report p 43.
[66] EU Energy Strategy pp 19 to 21.

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