MATERIAL ECONOMICS

MAINSTREAMING GREEN HYDROGEN IN EUROPE

Commissioned by

Breakthrough Energy

This white paper summarises an independent research project conducted by Material Economics and commissioned by Breakthrough Energy, exploring what Europe can do to accelerate the growth of hydrogen, and in particular renewable energy-based (or so-called green) hydrogen. Its key new insight is that Europe could mainstream green hydrogen faster than traditional assessments suggest by creating joint investment projects along the value chain, which would allow the initial green premium, or extra cost, of green hydrogen to be measured against the sustainability value-add of a final product, and not only against the cost of competing fossil fuels.

"This analysis demonstrates that green hydrogen can play a very important role in Europe's decarbonisation, but also that Europe now needs to act with speed and at scale if we want to accelerate the green hydrogen economy. This can be precisely the clean technology journey Europe wants and position Europe as a global leader in green hydrogen, helping to accelerate hard-to-abate sectors' decarbonisation while at the same time laying the ground for greater strategic autonomy and a green economic recovery"

– Ann Mettler, Senior Director, Breakthrough Energy

"European Green Hydrogen Acceleration Center supports this assessment of the future potential of green hydrogen in Europe. We are encouraged to see the short-term potential demand and the focus on taking a value chain approach to generate this, something we have successfully used in the European Battery Alliance."

– Jacob Ruiter, Member of the Executive Board, EIT InnoEnergy

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INTRODUCTION

Green hydrogen is all the rage these days, and for good reasons: By 2050, it might provide both enormous global economic value – €2.5 trillion in annual sales of hydrogen and equipment, by an estimate from the Hydrogen Council[i] – and environmental benefits. The carbon emission reductions might be as high as 6 Gt CO_{2e} annually (similar to current GHG emissions in the U.S.), and largely in sectors that have few other technological options to cut emissions. Hydrogen could also create millions of employment opportunities and in fact become a cornerstone of a future clean economy. The projections above are broadly comparable to the size of the current global oil industry, and hydrogen is equally versatile as both feedstock and energy carrier.

There is already plenty of green hydrogen momentum in Europe (and other regions). About 100 MW of capacity has already been built[ii], with a full 20 GW announced[iii] – for instance, in green steel, fertilisers, petrochemicals, and transport fuels. The European Union released its hydrogen strategy in July 2020 and has committed to "installing at least 6 GW of renewable hydrogen electrolysers in the EU by 2024 and 40 GW of renewable hydrogen electrolysers by 2030"[iv]. European industry has a plan to reach an additional 40 GW in Europe's neighbourhood (e.g. North Africa). Germany, France, Spain, the Netherlands, and others have all released national hydrogen strategies, and hydrogen is a part of the energy strategies of many more Member States. In the startup world, a recent venture capital scan showed 50–60% of all hydrogen startups[1] globally are located in Europe[v].

Green hydrogen can also play an important role in Europe's post-COVID recovery. It has several characteristics that are positive from a stimulus perspective: Developing it mainly involves major infrastructure investment projects; major parts of the supply chain could be located in Europe; it makes use of economic resources that might otherwise be underutilised in a post-COVID recession; and it is highly relevant for several Member States that have been hit hard by COVID. It also meets the criteria of "build back better"; Europe was already pursuing a green hydrogen transition before COVID, and allocating recovery funds could accelerate it.

Still, for all its promise, the early European momentum is still embryonic compared with the size of the opportunity. This white paper explores two questions: *How can Europe accelerate the growth of clean (or carbon-free) hydrogen, and in particular green hydrogen? And how can Europe capture a major share of the industrial value associated with green hydrogen and ensure strategic autonomy?*

The analysis focuses on green hydrogen, as we see that as the most promising and sustainable long-term solution. However, we acknowledge that blue hydrogen could also play an important role in a first phase of the hydrogen transition where demand for green hydrogen[2] might outweigh supply (due to e.g. limited renewables capacity or transport infrastructure).

Exhibit 1

REPRESENTATIVE ESTIMATES OF THE SIZE OF THE 2050 HYDROGEN INDUSTRY

SOURCE: HYDROGEN COUNCIL (2017), HYDROGEN SCALING UP – A SUSTAINABLE PATHWAY FOR THE GLOBAL ENERGY TRANSITION.

1. Includes green hydrogen production technology companies as well as downstream startups (e.g. compression, transport, and end-use sectors).
2. 'Blue' hydrogen is hydrogen produced (primarily) using steam methane reforming of natural gas in a process equipped with carbon capture and storage (CCS).

540 TWH OF GREEN HYDROGEN DEMAND AVAILABLE NEAR-TERM?

Our analysis suggests Europe could build up the green hydrogen industry faster than many current strategies suggest. The key insight is that many traditional cost competitiveness analyses disregard important aspects of how "sustainability" – broadly defined – is now unfolding in some of the major energy- and material-using value chains, and the strategies leading companies are pursuing. Traditional analyses look at the cost-competitiveness of green hydrogen relative to incumbent, fossil-based commodities. The conclusion is typically that green hydrogen solutions are (far) out of the money today, and that years of learning effects will be needed before costs will come down to competitive levels and green hydrogen can scale in earnest. For example, green hydrogen today costs approximately €4–5 per kg, while grey hydrogen costs €1–2 per kg (a hydrogen green premium of 3-4 € per kg).[3] Current CO_2 prices, at approximately €25 per tonne CO_2, only reduce the gap by about €0.3[vi] per kg H_2, or 10% of the difference.

Of course, such calculations are a crucial starting point when discussing the economic viability of green hydrogen. However, another crucial point is often missed: Such initial cost increases are often very small as a share of the total end-product cost, and in many of the relevant value chains, there are now end-product manufacturers who have set net-zero climate targets, who see green hydrogen as an important part of reaching those targets, and who are willing to engage far back in their value chains.

For example, Daimler aims to be carbon-neutral throughout its value chain by 2039, and VW[4] by 2050. Leading companies are starting to see that the sustainability value-add from a carbon-free end-product (manifested in higher sales volumes, higher prices, or lower regulatory risk) outweighs the extra cost incurred by shifting to green hydrogen far back in the value chain. Take hydrogen-reduced steel in a car as an example: A passenger car typically contains about one metric tonne of steel. Many analyses put the additional cost if this steel were reduced using green hydrogen instead of coke at around €100 per tonne[vii] (it could even be much lower in a scenario with a fully optimised production setup). The average net sales price of a car in Europe is about €29,000[viii], so switching to green steel breaks even if the car manufacturer believes it can increase the sales price by just 0.3-0,4 percent. In a more expensive premium car, the relative price increase would be much lower still.

Several large green car niches are also likely to emerge over the coming years: cars purchased through or influenced by public tenders, corporate cars at environmentally conscious companies, cars for environmentally conscious private consumers. Competing in these market segments will be much easier with green steel. There is also a real probability of future regulation of the CO_2 content of the car's materials in addition to the tailpipe emission regulation already in place, so manufacturers that decarbonise early will have a better regulatory risk profile. All in all, the case for switching to green steel looks much more persuasive in this holistic context than if just comparing to the cost of fossil steel.

The same logic applies in many other large value chains: In food and beverage, green ammonia for fertilisers currently costs around three times as much as ammonia produced using grey hydrogen, but increases the end-product cost (a bottle of beer, a loaf of bread, or a kilogram of pasta, for instance) less than 1%[ix] The argument is similar in logistics, clothing, and other value chains.

To generalise such results, we applied four criteria to estimate the current potential demand for green hydrogen across sectors:

1. Will the end-product cost increase by less than 1% if green hydrogen (at current prices of about €5 per kg) is used instead of the incumbent fossil technology? For instance, how much will the cost of producing a car increase given an increased steel price?[5] We used 1% as a cut-off for our analysis[6], but in many cases the cost increase is significantly lower.

2. Are the end-product manufacturers sufficiently large and financially stable to engage in investment projects for green hydrogen, given that each investment project is likely to require hundreds of millions of euros and take a decade or two to pay off?

3. Do the end-product manufacturers have ambitious climate targets? If the end-product manufacturers have communicated such targets, that is a good indicator that they see the commercial value of a transition and see value-add from sustainability. (See Exhibit 2 for key examples of leading European manufacturers with strict climate targets in the relevant value chains.)

4. Is green hydrogen competitive among the possible low-carbon technologies? Sectors with other, more attractive decarbonisation alternatives will have a lower uptake of hydrogen solutions. For example, most car manufacturers now seem to agree that battery-electric technology will be more attractive than fuel cell-technology for passenger cars. However, for heavy duty trucking there is likely a combined role for both fuel cell and battery-electric trucks.

[3] Green hydrogen is produced by electrolysis using renewable energy, while grey hydrogen is produced using natural gas in a steam methane reforming process. Cost estimates are based on a Material Economics analysis using multiple sources, e.g. BNEF, FCH-JU, Lazard. Note that this average cost depends highly on factors which vary across Europe, e.g. renewable electricity prices and the cost of required transport (ranging from negligible for local production to about €3 per kg for maritime freight).

[4] VW has also recently released the ID3 model, marketed as its first "carbon neutral" car. This does however include offsetting for some emissions that today cannot be avoided (incl. in the supply chain).

[5] Note: under optimal conditions with very low renewable electricity costs and fully integrated steel production the green premium might even be eliminated completely

[6] One exception to this rule is in the case of green hydrogen for hydrogenation in refineries. Here the premium is higher than 1%, but many experts mentioned that as the Renewable Energy Directive is revised next year it is very likely that green hydrogen can count towards mandated GHG reductions for diesel and gasoline, something which today only can be done through blending with bio-based fuels. Refineries are already realising this and therefore see a business case for green hydrogen already today (as it is then instead compared with the cost of biofuels).

Exhibit 2

EXAMPLES OF LEADING COMPANIES IN HYDROGEN-RELEVANT VALUE CHAINS WITH AMBITIOUS CLIMATE TARGETS

GREEN FERTILIZER

Unilever	*Zero net emissions for all products 2039*
Nestlé	*Zero net emissions 2050*

GREEN H_2 STEEL

DAIMLER	*Carbon-neutral new passenger car fleet 2039*
SKANSKA	*Net zero carbon emissions 2045*
	Climate neutral value-chain 2050

GREEN SHIPPING

MAERSK	*Net zero emissions by 2050*
CMA CGM	*Carbon neutral by 2050*

FUEL CELL TRUCKING

H&M	*Climate positive value-chain 2040*
DHL	*Net zero emissions by 2050*

SOURCE: COMPANY WEBSITES

A full 540 TWh of green hydrogen demand in the EU already meets all four criteria. Key sources of such potential demand include green fertiliser, green shipping fuels, green steel for vehicles and some buildings/infrastructure (public tenders), some industrial heating (for e.g. glass production), and parts of fuel cell mobility (Exhibit 3). Of the total, 220 TWh[7] involves a shift of existing grey hydrogen demand over to green hydrogen.

In many of these sectors, green hydrogen investments have already been announced, giving further support to the assessment that green hydrogen solutions can already be economically viable if the holistic end-product perspective described above is applied. Key examples include Yara and Ørsted planning a green hydrogen plant in the Netherlands for fertiliser production, Fertiberia and Iberdrola doing the same in Spain, Shell developing a green hydrogen project for use in its refinery near Rotterdam to decarbonise fuel production[x], HYBRIT going into hydrogen-reduced steel-making in Sweden, and Maersk, Ørsted, SAS and others collaborating to produce green hydrogen-based transport fuels in Denmark[xi].

How should these 540 TWh be interpreted? First, we do not mean to suggest that 540 TWh of green hydrogen could be sold to these segments tomorrow, or that all the companies in these sectors will pursue green hydrogen investment strategies. Instead, the interpretation should be that in these segments, the holistic business case for green hydrogen is largely in place, and demand-side fundamentals do not have to hold back progress. Climate mitigation is seen as important enough, and green hydrogen is attractive enough as a low-carbon technology, that there is an opportunity to set up the type of joint green hydrogen investment projects that the Yara, Shell, HYBRIT, and Maersk examples represent.

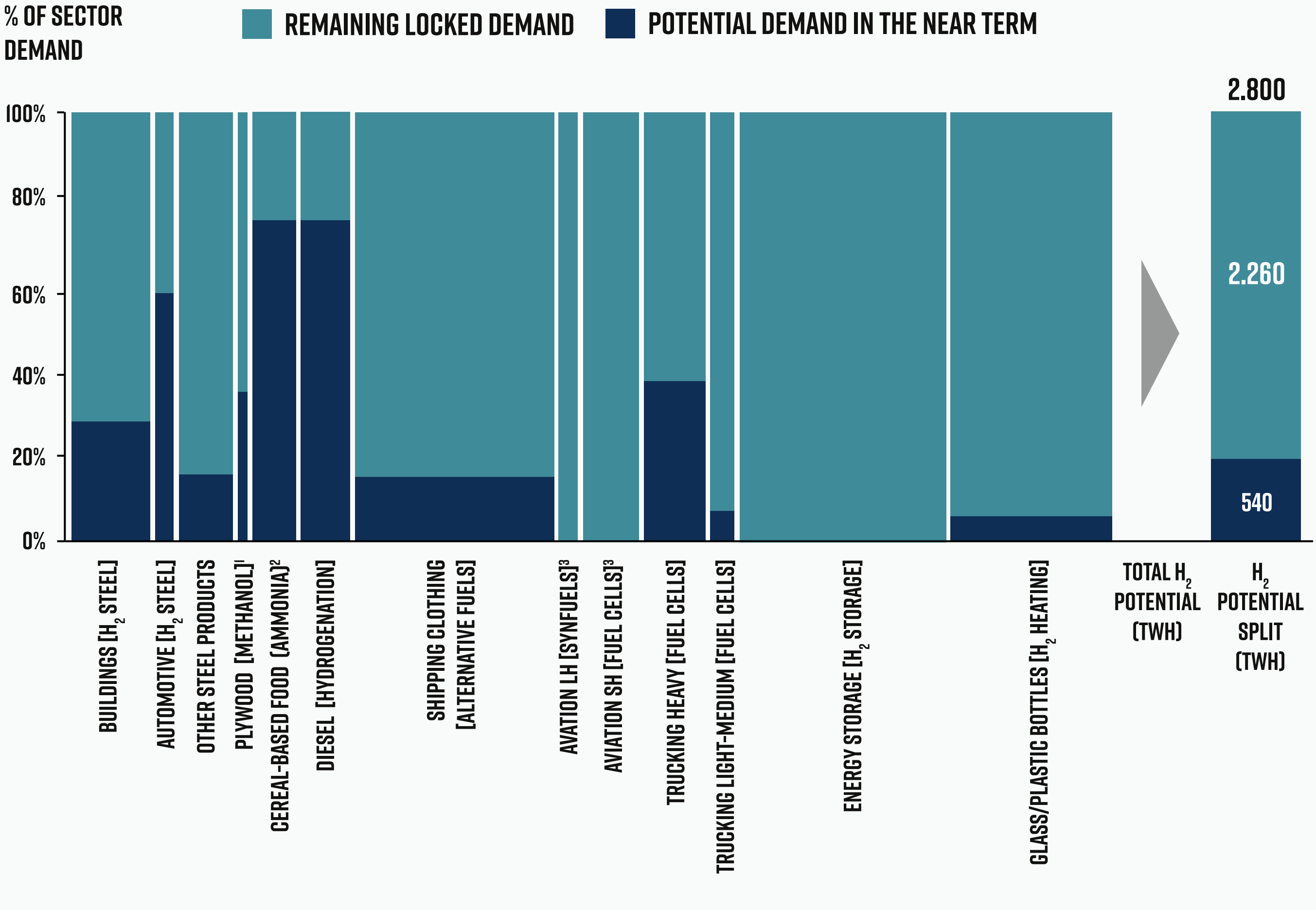
One important barrier that companies even in these sectors will have to overcome is that purchasing department priorities and approaches are often set up to achieve very different objectives: Purchasers typically have targets for year-on-year cost reductions, and work with competitive cost-based tenders to achieve those targets. The type of long-term value-chain partnerships discussed here, which only pays off with a holistic business case including sales, marketing, and regulatory benefits, runs counter to these traditional purchasing methods and is a big shift for many organisations.

Going forward, this potential demand could grow further: Green hydrogen costs will come down due to scale and learning effects, more companies are likely to adopt strict climate targets, and green hydrogen policies are likely to fall into place. These changes will allow additional demand to be created. If hydrogen costs come down to €1,7-2 per kg (not unfeasible, see Exhibit 6 below), companies continue to set ambitious climate targets at the same pace as over the last five years, and contract-for-difference support schemes of 50-60 Euro per ton CO_2 are put in place, the potential demand that meets the four criteria above grows from 540 TWh to 1200–1400 TWh[8].

7. This is the fraction of current grey hydrogen demand that we have estimated can be converted to green hydrogen demand. The total grey hydrogen demand in Europe today is about 310 TWh annually, primarily for production of diesel and ammonia.
8. The detailed assumptions going into these calculations are presented in the PowerPoint appendix to this article.

Exhibit 3

POTENTIAL DEMAND FOR GREEN HYDROGEN FROM END-USE SECTORS



1. EXAMPLE PRODUCT: METHANOL IS USED IN FORMALDEHYDE, WHICH IS INCLUDED IN MANY DIFFERENT PRODUCTS
2. EXAMPLE PRODUCT: GREEN PREMIUM OF GREEN AMMONIA FERTILIZERS USED IN WHEAT PRODUCTION FOR BREAD
3. LH: LONG HAUL, SH: SHORT HAUL

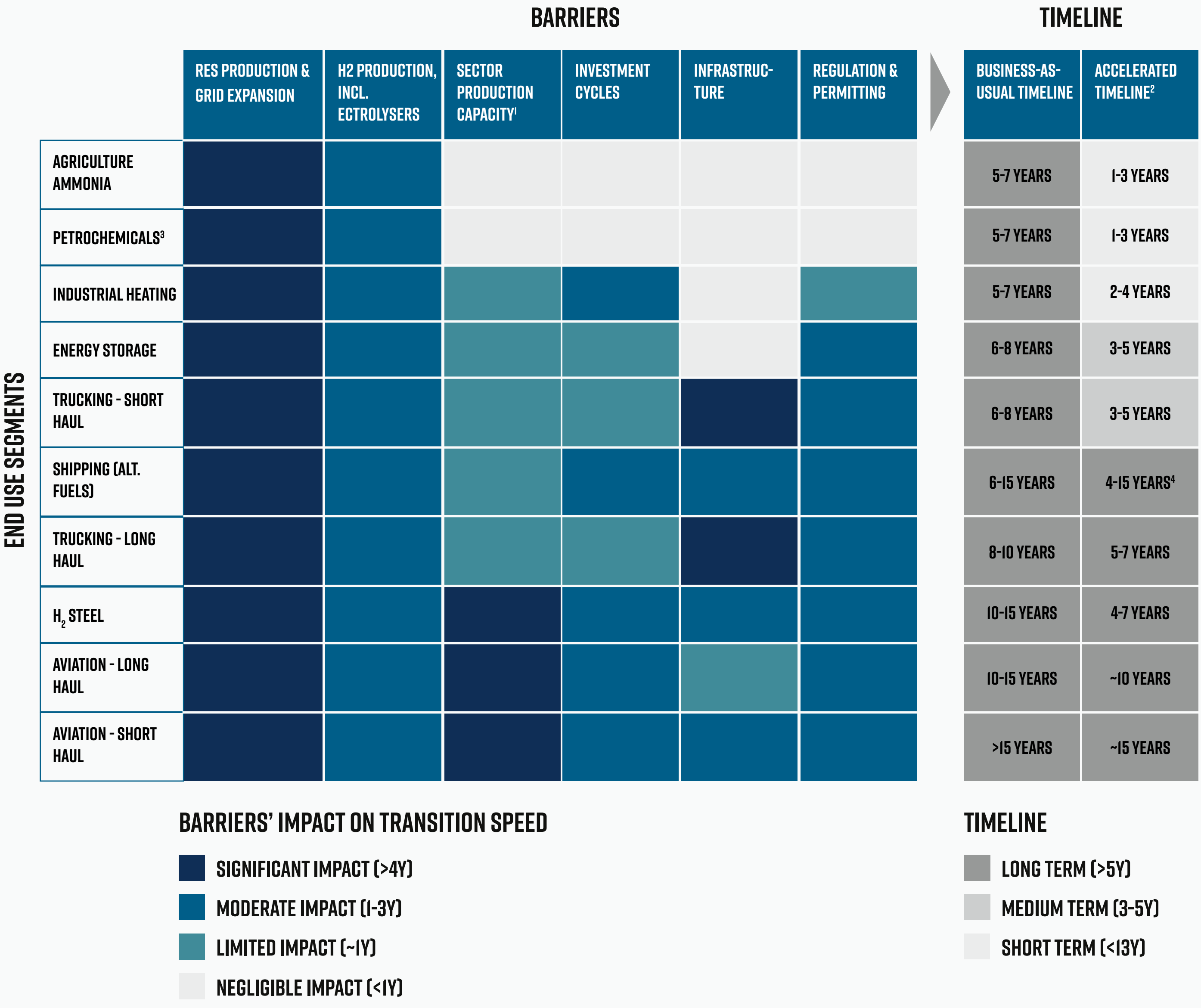
SOURCE: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES (E.G. EUROSTAT, EEA, IEA, FCH-JU)

ACCELERATING BUILDOUT: REMOVING BARRIERS

So, if demand-side fundamentals do not have to be the main bottleneck in these sectors, what is? What sets the timeline for how quickly Europe can mainstream green hydrogen? In short, the answer is various practical barriers on the supply and production side, most of them related to construction and permitting. Exhibit 4 shows the main barriers and what timelines they set for each relevant sector. The overall conclusion is that business-as-usual timelines range from 5 to 15+ years, with an average of 8–10 years. An assessment of what these timelines could be if the EU and its Member States systematically removed barriers and accelerated progress show that the average could instead be 3–7 years. Removing such barriers is indeed one of the most important action areas for Europe to accelerate the mainstreaming of green hydrogen.

Exhibit 4

BARRIERS AND TRANSITION TIMELINES



1. PRODUCTION CAPACITY OF KEY MATERIALS OR PRODUCTS, E.G. STEEL, AMMONIA, FUEL CELL TRUCKS ETC.
2. DOES NOT TAKE INTO ACCOUNT ADDITIONAL DELAYS THAT WOULD OCCUR IF ALL SECTORS WERE TO PURSUE HYDROGEN AT THE SAME TIME, I.E. EACH IS EVALUATED INDIVIDUALLY
3. INCLUDES REFINERY AND METHANOL PRODUCTION
4. AS SHIPPING ENGINES CAN BE RELATIVELY QUICKLY SHIFTED TO AMMONIA SOME DEMAND CAN COME WITHIN A FEW YEARS, BUT A LARGE SCALE OVERHAUL WILL LIKELY TAKE SIGNIFICANT TIME

SOURCE: MATERIAL ECONOMICS ANALYSIS BASED ON SEVERAL EXPERT INTERVIEWS

Renewable energy[9] buildout, and the associated grid expansion, stand out as the largest bottleneck by far to substantial green hydrogen growth. To cover a potential demand of 540 TWh green hydrogen, approximately 120 GW of additional renewable energy sources will be needed in Europe, assuming 70%[10] of the electricity is produced within the EU. To put these volumes in context, they are approximately equivalent to the total installed wind capacity in Europe today. To cover 1200 TWh of green hydrogen demand, a full 280 GW of electricity supply would be needed. Exhibit 5 visualises the required growth relative to what is needed for Europe to reach its target of 65% renewables penetration.

Such a build-out, just to deliver renewable energy to the first 540 TWh, will present massive challenges, especially when considering that several other sectors also see major increases in electricity demand: passenger transportation, industrial heating, and residential heating (through heat pumps), to name a few. This puts pressure on both electricity generation and grid expansion.

One way to reduce the pressure is of course that more hydrogen production gets located outside Europe, for instance in sunny locations in North Africa or Australia. That is likely a good solution for parts of the hydrogen supply.

But there are also major opportunities for Europe to accelerate renewable energy build-out within its borders: Permitting for new renewable energy supply, for instance, should take 2–3 years, as stipulated in the 2018 Renewable Energy Directive[11], but today's average is closer to 5 years. And in many cases, the outcome of permitting processes is very difficult to predict, as rules and practices vary from place to place. Such protracted permitting processes and unpredictable outcomes are arguably the single largest barrier to mainstreaming green hydrogen, and we will come back to it below as one of the major improvement areas for Europe.

On the contrary, electrolyser supply might prove less of an issue: The independent expert interviews conducted as part of the research for this white paper all indicated that the big electrolyser manufacturers (e.g. Nel, Siemens) are well-prepared to ramp up production quickly.

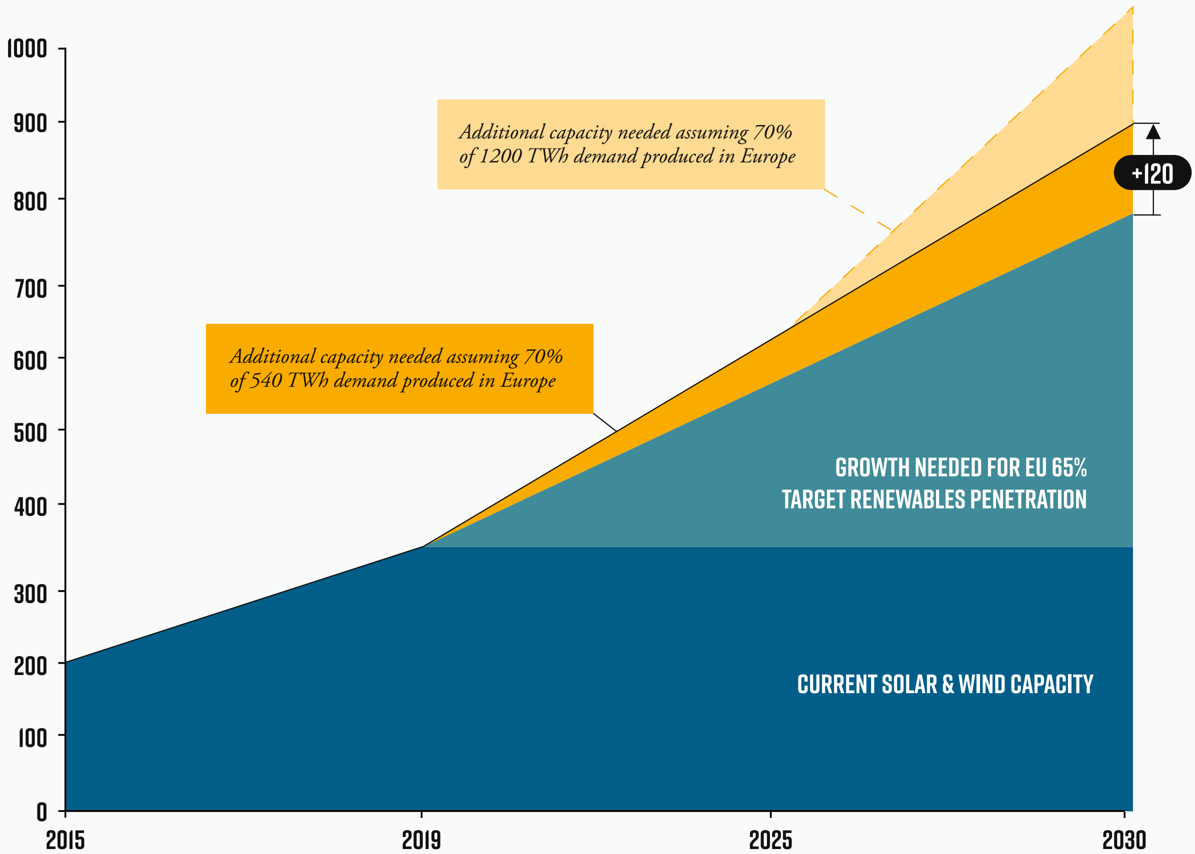
Finally, there are many issues regarding regulation, standards and permitting hindering the buildout of green hydrogen. For example, the lack of a system for guarantees of origin make it difficult to prove that hydrogen is green, and there is no fair access regulation for existing hydrogen pipelines. Also, for the transport sectors, there is a need to agree on standards for green hydrogen fuelling infrastructure.

9. Renewable energy sources include wind, solar, hydropower, ocean energy, geothermal, etc.
10. Some of the renewable electricity is likely to be imported; the exact share is impossible to know today, so the 70% assumption should be seen as an illustrative estimate.
11. See https://ec.europa.eu/energy/topics/renewable-energy/renewable-energy-directive.

Exhibit 5

DEDICATED RENEWABLE ENERGY SOURCES NEEDED VS. REQUIRED FUTURE BUILDOUT IN EUROPE

HISTORICAL AND REQUIRED FUTURE ELECTRICITY PRODUCTION CAPACITY FROM RENEWABLES
CUMULATIVE GW



1. ~10 GW ALREADY FORECASTED CAPACITY FOR H2 PROD. ACCOUNTED FOR (REDUCING ADDITIONAL CAPACITY NEEDED FROM 280 TO 270 GW)
2. BASED ON DEMAND FROM 540-1,200 TWH IN EUROPE, WITH 70% BEING PRODUCED IN THE REGION

SOURCE: IEA ETP 2017, SOLAR POWER EUROPE, WIND EUROPE, MORGAN STANLEY, MATERIAL ECONOMICS ANALYSIS

SHOULD EUROPE SET ITSELF AN EVEN HIGHER AMBITION?

The perspective above raises an important question about how ambitious Europe could be on green hydrogen: Most of the 540 TWh could be in place before 2030, as could parts of the additional 660–960 TWh, if Europe accelerates implementation and removes barriers. The EU's current target of 40 GW of green hydrogen capacity within its borders by 2030 translates to 160–200 TWh of production.[12] Since the EU looks so favourably at hydrogen, and particularly green hydrogen, there is a good case for asking whether Europe should set itself even higher ambitions for 2030 next time it reviews its hydrogen targets. In addition to production targets, Europe could also consider setting demand targets in specific sectors as is foreseen, for example, in Germany's hydrogen strategy.[13] This will help provide clarity for industry and allow for imports and international collaboration if local production cannot be realised fast enough. Higher targets for production and demand would make a big difference: It would set a different expectation among all the important stakeholder groups on both the public and private side, it would create different planning assumptions, and it would increase the sense of urgency.

GETTING GREEN HYDROGEN TO COST COMPETITIVENESS

Mainstreaming green hydrogen in Europe will mean a major industrial transformation. Delivering 1200 TWh of green hydrogen, as an example, would require total investments in the range of €545–690 billion: €90–105 billion in electrolysers, €250–300 billion in renewable energy capacity[14], €30–60 billion in transport infrastructure and €175–225 billion in the end-use sectors[xii].

In parallel, the cost of green hydrogen needs to be reduced from €4-5 per kg, to a level of €1.5–2 per kg, for it to be fully cost-competitive with grey hydrogen. This cost gap might look daunting, but breaking it down into its components and comparing to learning rates of other similar technologies reveal it to be a feasible prospect in a 5-10 year time horizon (Exhibit 6). Electrolyser production is today a largely manual process (labour can be over 65% of total costs for alkaline electrodes), so just automation will yield big savings. This is already happening; Nel, for example, is expanding its Herøya plant with fully automated production capacity[15].[xiv] More generally, applying an average learning rate of 13% cost decrease for every doubling of cumulative capacity – a quite conservative assumption compared to other similar technologies (e.g. batteries) – shows that European industry's 2030 target of 2x40 GW alone would result in a cost decrease of about 67% going from €1015 to €330 per kW_{el}.[xv] for the electrolysers. Of course, electrolyser demand from other world regions will also contribute to the learning effects. In fact, our analysis suggests that cost-competitiveness between green and grey hydrogen might well be reached at approximately 1100 TWh global annual demand (with an assumed renewable energy price of €20 per MWh). While no-one can today know exactly how green hydrogen costs will evolve, all indications point towards a rapid cost decline. This is crucial planning assumption for both companies and the public sector. In hindsight, the planning assumptions used for other low-carbon energy technologies such as solar PV, wind, and batteries were often too conservative.

Another key question for green hydrogen is where and how the production should occur to realise cost decreases. We believe we will see a dual pattern: On the one hand, renewable electricity makes up for more than half the green hydrogen production cost. Renewable electricity is typically cheapest at the circumference of Europe: wind in the Nordics and on the Atlantic coast, and solar power in Southern Europe. On the other hand, the cost of transporting hydrogen is nontrivial (at €0.15–0.25 per kg per 1000 km[xvi]), favouring local production where possible. Localization decisions taking advantage of both these factors are already emerging, creating hydrogen hotspots. For example, Fertiberia and Iberdrola's green fertiliser production will take advantage of Spain's ample renewable energy resources. In Rotterdam, a 'hydrogen valley' is emerging with Gasunie, Shell, Ørsted, and Yara all investing in green hydrogen projects, taking advantage of the Rotterdam cluster's demand and infrastructure, and offshore wind power from the North Sea.

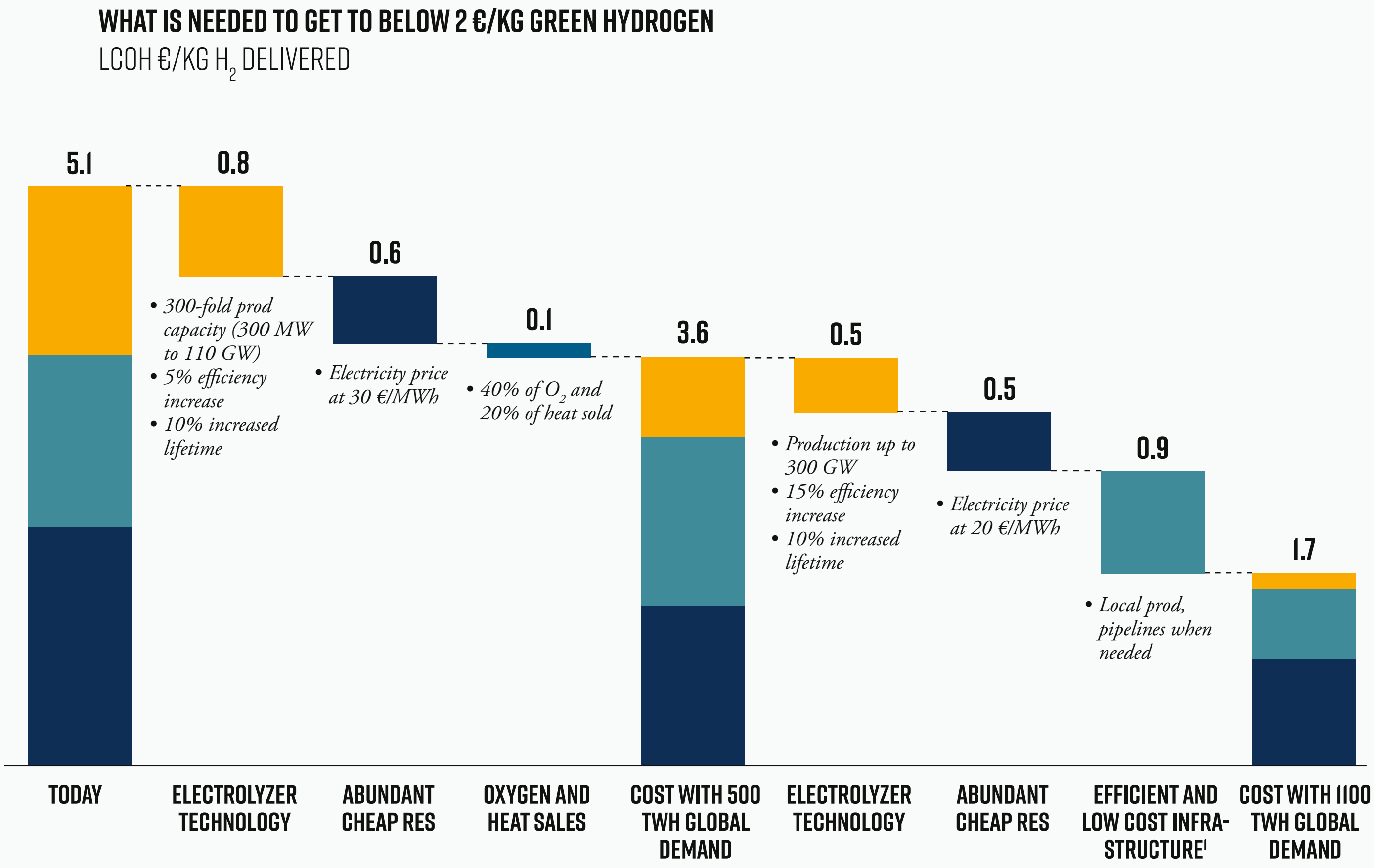
This is good news for Europe, as it means green hydrogen opportunities are accessible for many Member States and regions. Ensuring sufficient pipeline (and needed storage) capacity to transport H_2 to central European demand clusters where local production is not sufficient will be a key priority for an efficient hydrogen economy. For hydrogen, pipelines are typically a more cost efficient mode of transport than electric transmission[16]. Where transport and storage is needed, repurposing existing underutilised gas pipelines is often attractive, or else building "hydrogen highways" with high-capacity pipelines, potentially combined with strategically utilised salt cavern storage (for buffering). This is not to say that strengthening European electric transmission lines is not important, however – in fact, this is also a crucial part of wider decarbonisation strategy for Europe.

In the end, exactly where electrolysers and resulting transport needs will become an economic optimisation problem where there may well also be some use cases (e.g. production of sustainable aviation fuels) where it makes sense to produce and import the end product from outside Europe in locations with very low renewables costs and few land constraints (e.g. North Africa, the Middle East, and Australia).

12. The EU Commission's strategy is to install at least 40 GW of renewable electrolysers by 2030. The strategy also mentions that EU industry is rising to the challenge, with an ambitious plan to reach 2x40 GW of electrolysers by 2030 (another 40 GW Europe's neighbourhood, i.e. North Africa and Ukraine with export to the EU as an "industry ambition"). Assuming 4000–5000 run-hours per year, this translates to a total of 160–200 TWh annually within EU borders, and as much outside its borders.
13. See https://www.bmbf.de/files/bmwi_Nationale%20Wasserstoffstrategie_Eng_s01.pdf.
14. Note that this is the share of investments in Europe assuming 70% of hydrogen is produced here; additional investments will be required elsewhere to account for H_2 production outside Europe, for instance, in Northern Africa.
15. Note that the large increases in production capacity needs will outweigh the potential reduction in need for manual labour in the production process for electrolysers (having a net positive effect on jobs in the electrolyser industry).
16. Highly utilised, high capacity pipelines have much higher energy throughput reducing effective cost of transport.

Exhibit 6

PATH TO GET TO <€2 PER KG GREEN H_2 (END-STATE BASED ON ~1100 TWH DEMAND)



ELECTROLYSER TECHNOLOGY INNOVATION

- *Acceleration of project deployments*
- *Mobilisation of investments*
- *Innovation support focused on efficiency gains and electrolyser lifetimes*

ABUNDANT CHEAP RES

- *Rapid deployment to reduce costs*
- *Optimised utilisation of electrolysers*
- *Large scale production in European circumference, e.g. Spain, Portugal, the Nordics (and potentially N. Africa) for excess H_2 needs*

EFFICIENT AND LOW COST INFRASTRUCTURE

- *Optimised balance of local (prioritised if possible) and centralised production*
- *Dedicated high volume pipelines*
- *100% repurposed pipelines where possible*
- *Centralised large storage solutions*

1. ASSUMING AVERAGE COSTS OF TRANSPORT AND STORAGE TODAY IS 1.5 €/KG H2 PRODUCED. IN 2030, 50% LOCAL PRODUCTION, 40% TRANSPORTED BY PIPELINES AND 10% TRANSPORTED BY ROAD/MARITIME FREIGHT

SOURCE: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES (BNEF, FCH-JU, ETC.) AND EXPERT INTERVIEWS

WINNING THE GLOBAL RACE

The industrial transformation inherent in a green hydrogen economy is precisely the type of positive change that Europe wants to see: It will contribute to lower greenhouse gas emissions, strategic autonomy, broad innovation, new investments, economic growth, and ample employment opportunities. It is a prize worth fighting for. A fast transition is also likely to increase the competitiveness of European products abroad.

At the same time, international competition in green hydrogen is fierce. Just the production of electrolysers looks to be an industry with global revenues in the tens of billions of euros by 2030, and the first companies able to develop fuel cell-powered trucks, hydrogen-derived fuels, green fertilisers and alternative fuels will increase their global competitiveness. Europe is a leader when it comes to existing demand and policy, innovation, and high-quality electrolyser production. However, it faces strong competition from China on electrolyser costs, from Australia and the Middle East on renewable energy, and from Korea and Japan when it comes to fuel cell-technology.

The global race for market shares and industrial value creation in different parts of the green hydrogen value chain has only just begun.

Europe has a good starting point:

- **Europe has strong** demand clusters and supporting po licy priorities: Over 300 TWh of hydrogen is used today in Europe, much in industrial clusters such as Rotterdam and North Rhine-Westphalia that can be green hydrogen "test beds". Also, Europe is the most ambitious region for decarbonisation, with a strong public focus on climate.

- **Europe is an** (early) leader on innovation: Analysing the hydrogen startup landscape shows 50-60%[xvii] of global startups are based in Europe. This startup ecosystem is crucial for ensuring Europe remains an innovation leader in hydrogen production.

- **Europe is a leading** electrolyser producer: Several of the global leaders in electrolyser technology are based in Europe (e.g. Thyssenkrupp, Siemens, Nel, McPhy), and Europe has a 25–30% global market share in electrolyser production. These companies also have a reputation for the highest-quality, most reliable electrolysers.

- **Europe is also** a leader in announced green hydrogen projects: It already has roughly 1300 kton of annual production capacity announced. Only Australia is higher, with 1500 kton[xviii].

Europe also has several drawbacks, especially:

- **Electrolyser cost competitiveness vs. China:** According to certain reports, China may have up to 80% cheaper electrolysers[xix]. However, there are also reports of uncertain reliability and after-sales service. Also, a major part of the current cost gap is due to manual labour still representing more than half of production cost. With automation, China's lower labour costs will play less of a role, narrowing or ideally closing the cost gap.

- **Renewable energy availability:** Europe's long-term wind and solar electric energy potential is estimated to be approximately 110 EJ per year, compared with long term potential of 292 and 275 EJ per year[xx] in Australia and the Middle East (e.g. Saudi Arabia), respectively. Both Australia and the Middle East are also looking to become green H_2 export superpowers and have already announced multi-billion, multi-GW projects (Neom in Saudi Arabia, and the Asian Renewable Energy Hub in Australia). However, southern Europe (especially Spain and Portugal) comes close in solar radiation and may be competitive when also considering transport needs. Also, as noted earlier, Europe has large wind and hydro resources, which should be leveraged.

Double-clicking on Europe's position in hydrogen-related technology innovation, the green hydrogen transition opens whole new fields of technology: On the supply side, the obvious new technology area is electrolysers, which consists of a myriad of individual technologies, each with a supply chain of its own. On the demand side, there are also several huge technology areas (fuel cells, alternative fuel production, hydrogen-reduced steel, etc.), each of which also breaks down into multiple individual technologies and components. Developing, producing, selling, and maintaining all this equipment is a major industrial opportunity for Europe.

Europe's recent history in capturing such industrial opportunities is mixed at best. In similar areas such as solar PV, batteries for electric vehicles, and in the broader digital and online technology fields, Europe punches below its weight, and most of the globally leading firms come from elsewhere.

Europe should aim to make green hydrogen different. It should aim to be not only a big user of these technologies, but also to capture a major share of the industrial value. This is a positive challenge both for the private and public sector. European and Member State public organisations have a key role to play here, especially in terms of catalysing industry-led change, removing barriers, and working closely with industry when it comes to prioritising innovation efforts. More on this below.

ACTION AREAS FOR EUROPE

We believe this white paper has shown that green hydrogen is a very attractive opportunity for Europe and that it is possible to see a much faster acceleration than what current strategies indicate. Major demand can be unlocked in the near term in Europe and timelines are largely set by how fast Europe's public and private sectors can mobilise.

If Europe wants to be a future global leader on green hydrogen, which is possible, it should accelerate efforts now.

Four action areas stand out to achieve the acceleration: establish lead markets, mobilise massive investments, accelerate innovation, and establish enabling standards and policies (Exhibit 7).

Exhibit 7

ACTION AREAS FOR EUROPE

ESTABLISH LEAD MARKETS

- *Key candidates include green fertiliser, H2 for refineries and petrochemicals, fuel cell trucking, and green steel for mobility and buildings (public procurement), and green shipping.*
- *Develop downstream policy interventions and investigate potential contract-for-difference mechanisms and portfolio standards*

MOBILISE MASSIVE INVESTMENTS,INCL. IN RES

- *Policymakers to provide strong convening support to platforms orchestrating value-chain collaborations (EGHAC, CHA)*
- *Expand use of de-risking demonstration funding (e.g. InvestEU) and financing guarantees (from e.g. Innovation Fund)*
- *Enable significant public OPEX support*

ACCELERATE INNOVATION

- *Public collaboration with industry when identifying R&D priorities and strengthen knowledge flows*
- *Support establishment of "hydrogen valleys"[1] near industrial clusters*
- *Earmarked funding for hydrogen innovation*

ENABLING POLICIES AND STANDARDS.

- *Consider increasing the ambition of European and Member state targets, focusing them on demand as well as of production targets*
- *Speed up timelines for all the detailed policies and standards that are required (fair access, fuelling standards, certificates of origin, et cetera), getting it "right" when all the relevant regulations are being revised next year (e.g. Renewable Energy Directive, Energy Taxation Directive, TEN-T[2], etc.)*
- *Get permitting times for RES down to the stipulated 2-3 years and promote greater energy system integration*

1. SPECIFIC CLUSTERS OF INNOVATIVE HYDROGEN PROJECTS, COMPANIES, AND INITIATIVES
2. TRANS EUROPEAN TRANSPORT NETWORKS

1. ESTABLISH LEAD MARKETS

Accelerating the demand for green hydrogen is one of the most important things that Europe needs to do now and is well characterised by a comment from one of the expert we interviewed during the research "What Europe should do? Create demand, demand, demand!". Private-sector initiatives have a very important role to play in mainstreaming green hydrogen in Europe. Policy will also have to play a very important role: There are many sectors where companies are too small to take on a green hydrogen transition without public support, where costs are still too high, and where there is still little real customer interest in a green product. Also, for the sectors identified as most promising in our analysis, and where there is already a lot of momentum, there is no doubt that the transition will be faster with policy support.

Different types of lead markets are the obvious policy mechanisms to look at; they should be explored as a major part of creating the green hydrogen acceleration. Lead markets are a well-known way to kick-start the large-scale industrialisation of new technologies by creating early demand, improving first-mover economics, and reducing risk. When applying this concept to green hydrogen, a few aspects stand out:

• **Target the most promising** demand sectors. When looking at which sectors to especially focus on in the short term for Europe, five stand out: green fertiliser, green steel in mobility and buildings[17] (public procurement), fuel cell trucking, green hydrogen in refineries and petrochemicals, and green shipping. These stand out due to a combination of low end-product green premiums, relatively quick transition times, and existing industry momentum with large players.

• **Downstream policy interventions** seem particularly promising. In many of the relevant value chains, the end-product manufacturers look to be the driving force in the green hydrogen transition, as explained above. Creating incentives to help them transition even faster will likely also play a role over time. Examples could include incentives on the CO_2-content of materials in vehicles or the materials in buildings. It will also be important to consider the fact that many of these markets are international, meaning that Carbon Border Tax Adjustments may be needed, something which is already high on the Commission's agenda.

• **Contract-for-difference mechanisms** and portfolio standards have been mentioned in many of the interviews conducted for this project as promising lead market mechanisms for green hydrogen. Also, updating the Renewable Energy Directive to allow the use of green hydrogen to count towards CO_2 accounting will help promote lead market demand.

17. Another potential early lead market could be e.g. steel for wind farms, however the annual steel needed for this is significantly smaller than steel needed in the automotive or buildings sector (and have therefore not highlighted it as a separate lead market).

2. MOBILISE GREEN HYDROGEN INVESTMENT PROJECTS

Ultimately, the private sector will have to initiate most of the huge investments required to mainstream green hydrogen. There is already plenty of early momentum, as described above: Early movers see the business benefits of going green, and they are choosing to make long-term investments even when the near-term cost competitiveness is not fully in place, often in partnerships along the value-chain. We believe it would be in the interest of many more companies to take this approach: With the current market dynamic, we see a major risk that the companies that wait for public policy to fall into place before investing in green hydrogen risk being left behind.

Policymakers and the public sector have a role to play in orchestrating and catalysing industry collaboration. In a different area, the European Battery Alliance (EBA) orchestrates projects by bringing together actors along the electric vehicle value chain. It is widely seen as a successful example of European industrial mobilisation. Now the European Green Hydrogen Acceleration Center (EGHAC)[18] and the Clean Hydrogen Alliance (CHA)[19] are pursuing similar strategies for hydrogen. The public sector can play a very productive role in supporting and convening such platforms, at both the European and Member State levels.

Another key role for the public sector in mobilising investment is to ensure access to financing for early movers, who inevitably carry a higher risk. There are many public financing tools to accomplish this, such as Carbon Contracts for Differences, something the EU hydrogen strategy has already identified. A financing tool used today is the Energy Demonstration Projects Facility (EDP[20]) which will continue in a similar form under InvestEU or Future Mobility funds (part of the Connecting Europe Facility). This allows the European Investment Bank group (EIB and EIF) to be an early anchor investor, attracting private investors.

An important aspect that will require financing innovation is the need for more operating expenditure (OPEX) support, and not just the typical CAPEX support (as OPEX, in particular electricity, can be more than 80% of the total cash cost). EDP, which will be continued under the InvestEU programme for 2021–2027, is not tailored for this type of support (but can provide it to some extent), so new, dedicated tools should be developed. Another crucial tool that should be leveraged is the Innovation Fund, which both can support OPEX to some extent and can be combined as a grant (and thus guarantee) part of other EU loans, decreasing risk for other investors. Finally, it will be important to ensure money goes to replicable investment projects, allowing for rapid scale-up once projects are proven.

To summarise, Europe (including national promotional banks) especially needs to expand the use of early high risk public financing (recent announcement of EIB's €1 trillion green "roadmap" is encouraging) that will ultimately help provide low cost debt and low cost equity for green hydrogen projects. Europe also needs to increase the possibilities for OPEX support if it wants to mobilise massive investments for green hydrogen. Replicable investment projects should have high priority. As InvestEU defines the successor to EDP, it will be crucial to link it with, for example, the Innovation Fund, allowing those grants to act as a financial guarantees and support OPEX costs, thus further reducing risk.

18. See https://bc.innoenergy.com/eghac/.
19. See https://www.ech2a.eu/.
20. See https://www.eib.org/en/products/mandates-partnerships/innovfin/products/energy-demo-projects.htm.

3. ACCELERATE TECHNOLOGY INNOVATION

The most important part of accelerating technology innovation and deployment of these innovations may be that Europe acknowledges its mixed track record in this area and asks itself how it can make sure the results this time are different. Possible components in a solution include making sure the existing DG collaboration on hydrogen has all the political mandates it needs to act as an effective lubricant in the EU system, earmarked high-risk funding for hydrogen-related innovation (from e.g. the Innovation Fund and InvestEU), alignment of the Commission's R&D strategy with its Industrial Policy, and a close dialogue with industry about what innovations it should prioritise in its research calls (making e.g. Horizon Europe calls, including the EIC calls, more targeted). Europe needs to make sure that it addresses all 3 "D's" of the innovation cycle (Discovery, Deployment, and Diffusion), and for green hydrogen especially deployment gap funding is important. Most important of all to accelerate innovation, perhaps, is fast progress in the other three action areas mentioned in this chapter.

4. ESTABLISH ENABLING POLICIES AND STANDARDS

Also, There are a large number of enabling policies that need to be put in place to mainstream green hydrogen: rules for allowing the use of hydrogen in natural gas networks, fair access to different types of infrastructure, CO_2 accounting standards for different type of hydrogen and hydrogen-derived products, guarantee of origins, standards for hydrogen fuelling stations, rules for international trade and infrastructure assets, etc. It will also be crucial to align the taxation of energy products and electricity with EU environment and climate policies to ensure a harmonised taxation of both storage and hydrogen production, avoiding double taxation. This is the type of rule-making that the EU is very used to.

The challenge this time is the sheer number of standards and rules that need to be put in place in a few short years. As in the innovation area, the EU should review what it can do to accelerate this rulemaking, while of course maintaining transparency, inclusion and due process. A good starting point is that many of the key pieces of regulation, for example the Renewable Energy Directive, Energy Taxation Directive, and the Trans-European Transport Network, are up for revision in 2021. If Europe can get the hydrogen aspects of these Directives right, that will help greatly in accelerating green hydrogen progress. One way to increase the chances of this happening could be to strengthen the political mandate of the current DG collaboration on hydrogen.

Green hydrogen is a massive opportunity for Europe, industrially as well as environmentally. Mainstreaming green hydrogen will mean a major industrial transformation, with huge investment and innovation potential. This is precisely the type of clean technology journey that Europe says it wants, and it can help Europe achieve its core goals of building back better and securing strategic, open autonomy. This is a prize worth fighting for, and Europe should do its very best to capture this opportunity.

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