

12 Insights on Hydrogen

IMPULSE



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Preface

Dear reader,

Hydrogen has generated enormous hype over the past two years. Some twenty countries, collectively accounting for nearly half of global GDP, have already adopted hydrogen strategies, or intend to do so. On two previous occasions, rising interest in hydrogen fizzled out without lasting effect. Can we expect a different outcome this time around?

The world is striving to achieve climate neutrality, and renewables have become the cheapest form of new generation across the globe. But not all applications lend themselves well to direct electrification. Green molecules have a role to play, but there are several unanswered questions: From which sources should they be obtained? How should they be

stored and transported? And in which applications are they indispensable?

In *12 Insights on Hydrogen*, we sought to shed light on these uncertainties by offering a quantitative, evidence-based assessment that compiles the wealth of existing hydrogen research into one, internally consistent discussion.

We hope you enjoy reading this impulse!

Dr. Patrick Graichen
Executive Director, Agora Energiewende

Frank Peter
Director, Agora Industry

Key findings at a glance

A

There is an emerging consensus that the role of hydrogen for climate neutrality is crucial but secondary to direct electrification. By 2050, carbon-free hydrogen or hydrogen-based fuels will supply roughly one fifth of final energy worldwide, with much of the rest supplied by renewable electricity. Everyone agrees that the priority uses for hydrogen are to decarbonise industry, shipping and aviation, and firming a renewable-based power system. Therefore, we should anchor a hydrogen infrastructure around no-regret industrial, port and power system demand.

B

Financing renewable hydrogen in no-regret applications requires targeted policy instruments for industry, power, shipping and aviation. This is critical for incentivising hydrogen use where carbon pricing alone cannot do the job quickly enough. While policy options are available at a reasonable cost for industry, power and aviation, there is no credible financing strategy for hydrogen use by households. Blending is insufficient to meet EU climate targets and carbon prices high enough to deliver hydrogen heating would be unacceptable for customers.

C

Gas distribution grids need to prepare for a disruptive end to their business model, because net-zero scenarios see very limited hydrogen in buildings. To stay on track for 1.5C, Europe needs to reduce consumption of natural gas in buildings by 42 percent over the next decade, as per the EU Impact Assessment. Similarly, land-based hydrogen mobility will remain a niche application. Any low-pressure gas distribution grids that survive will be close to ports, where refuelling and storage infrastructure could provide an impetus for the decarbonisation of the maritime and aviation sectors.

D

Europe has enough green hydrogen potential to satisfy its demand but needs to manage two challenges: acceptance and location of renewables, as each GW of electrolysis must come with 1-4 GW of additional renewables. To keep industry competitive, the EU should therefore access cheap hydrogen (green and near-zero carbon) from its neighbours via pipelines, reducing transport cost. Imports from a global market will focus on renewable hydrogen-based synthetic fuels.

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I Hydrogen in a net-zero Europe

The EU has set a climate neutrality target by 2050, and Germany has decided by law to bring its climate neutrality forward by five years to 2045.¹ The scale of the challenge is unprecedented, but we have all the tools we need to accomplish this formidable feat.

Renewable energy sources and energy efficiency are the main actors of decarbonisation in 2030

According to the many recent studies analysing pathways to net-zero and interim milestones,² electrification coupled with carbon-neutral power and energy efficiency will be able to deliver the bulk of energy system decarbonisation over the next decade to 2030. This consensus is well visualised in Figure 1, from McKinsey's net-zero Europe study. Carbon-neutral power and energy efficiency account for nearly two-thirds of total abatement between 2017 and 2030.

Most carbon-neutral power needs to be provided using renewable sources, which will require a massive scale-up. Agora's report "Climate-Neutral Germany 2045" sees a quadrupling of renewable generation from today to supply 100 percent of electricity demand³ by 2045.

On a global level, the IEA report "Net Zero by 2050" showed that 50 percent of emissions savings between now and 2030 must come from wind, solar and

energy efficiency if global net-zero emissions by 2050 are to be achieved.⁴

Full decarbonisation will need more than renewables and energy efficiency – Could green molecules fill the gap?

Some key industrial processes and transport modes will be difficult to electrify directly. The solution is to find a technology that can act as an extension to renewables for decarbonising these energy loads.

A promising solution is hydrogen. At the point of use, hydrogen is carbon-free. Hydrogen can be generated without carbon emissions using renewable electricity, or nearly carbon-free from hydrocarbons coupled with carbon capture and storage. Hydrogen also has a variety of potential uses across many energy and feedstock sectors. These are compelling arguments for including hydrogen in the net-zero toolkit. Indeed, the European Commission's hydrogen strategy envisions the creation of a 'hydrogen economy' in which hydrogen plays a role in every sector of the economy, from industry through transport to power and heating.⁵

The idea of the hydrogen economy has regained momentum over the past three years⁶ but key differences have emerged between proponents of a maximised hydrogen economy and proponents of mass direct electrification. Now that the initial hydrogen hype has faded, the debate has become more nuanced, focusing on framing aspects such as

1 See Reuters (2021), CLEW (2021), German Government (2021).

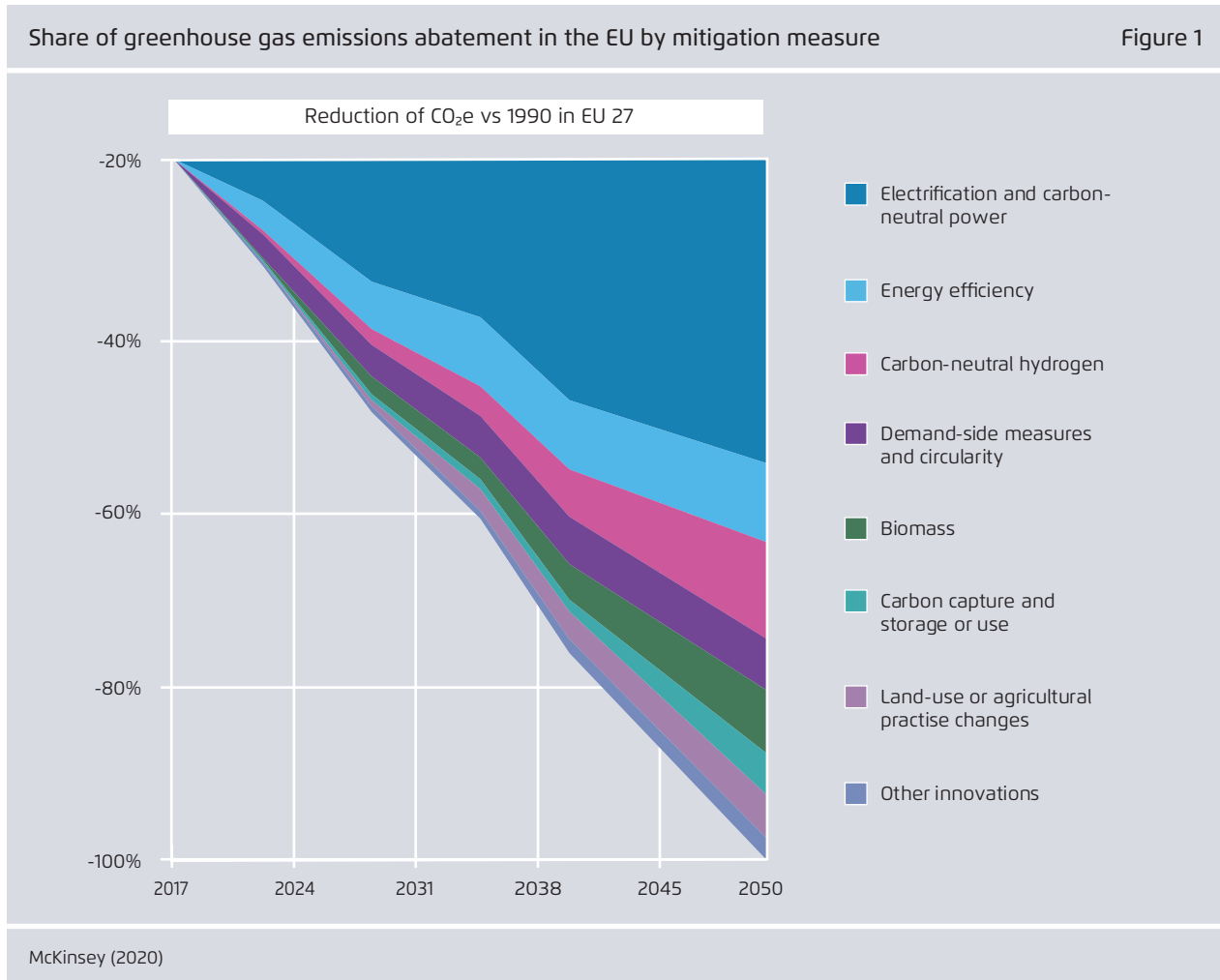
2 See JRC (2020).

3 See Prognos et al. (2021).

4 See IEA (2021a).

5 See European Commission (2020).

6 See, e.g., IRENA (2020) fig 2 on how the number of hydrogen strategies adopted over time.



steering, certification, support mechanisms and integration within existing regulatory frameworks such as TEN-E.

Renewable hydrogen requires incentives ...

The European Commission has made it clear that in the long run only hydrogen produced from electrolysis is sustainable. Currently, however, renewable hydrogen is not yet cost-competitive relative to its fossil-derived cousins or gas combustion. Figure 2 shows that even with CO₂ prices of 100 to 200 EUR/tonne, the EU ETS would still fall short of incentivising the average renewable hydrogen project over

fossil-derived hydrogen with or without carbon capture in 2030.⁷ Therefore, additional policy intervention and support will be required during this decade to reduce the cost of renewable hydrogen vis-à-vis its alternatives.

⁷ Though fossil-derived hydrogen with CCS is not considered sustainable in the long run due to residual emissions, it becomes competitive against unabated hydrogen at CO₂ prices of 80–100 EUR/tonne.

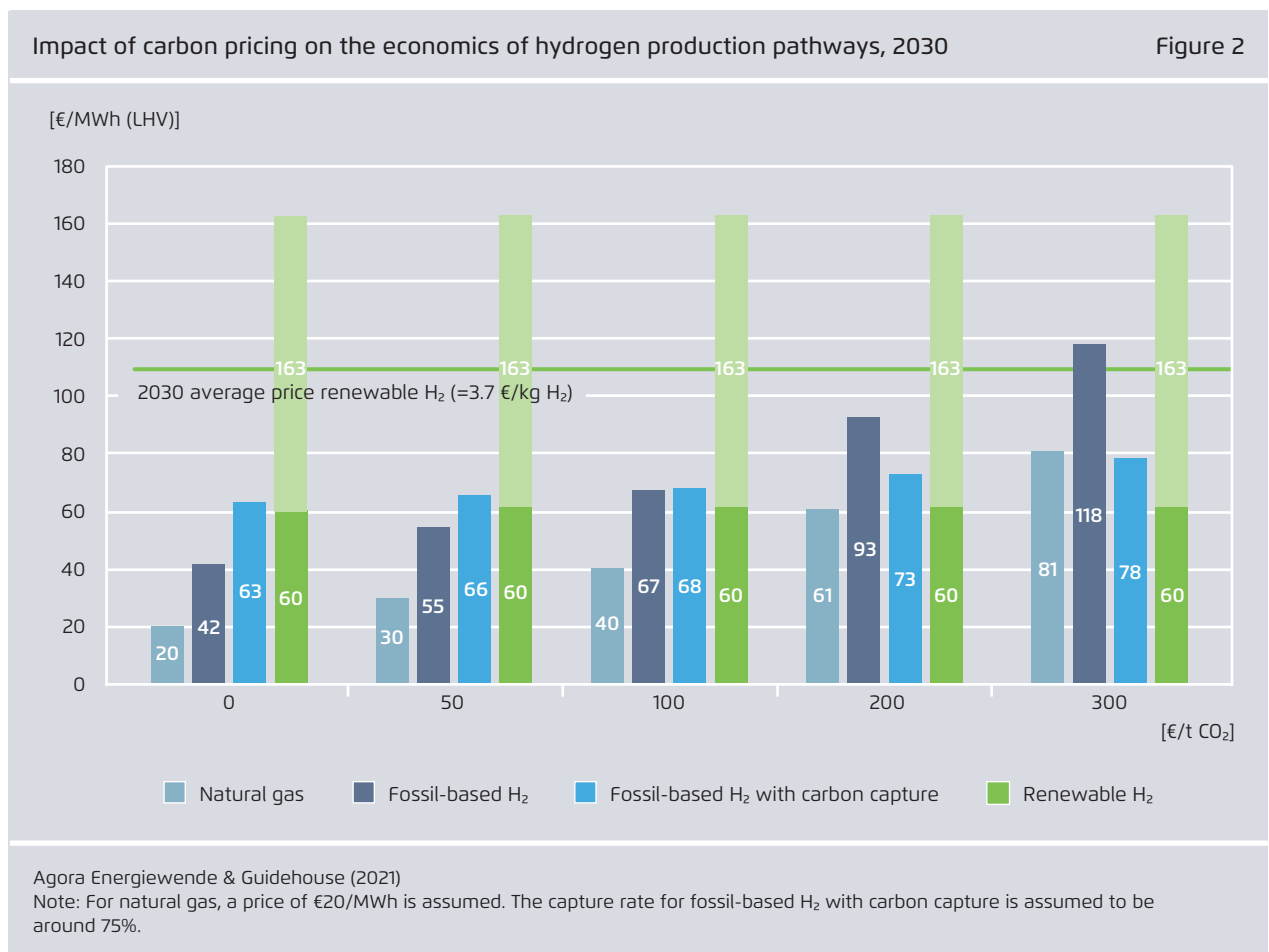
... and brings an opportunity cost

Producing renewable hydrogen requires substantial renewable electricity input, as illustrated by the global net-zero energy scenarios in Figure 3. Due to 30 percent energy losses incurred during hydrogen production and other energy losses during use, hydrogen can be as much as 84 percent less efficient than heat pumps in delivering like-for-like energy than direct electrification in the residential sector, or as much as 60 percent less efficient than battery electric vehicles in the transport sector.⁸ This means that for the same final energy use as direct

electrification, renewable hydrogen requires 2-4 times as much renewable energy capacity and, by extension, a larger land/sea area devoted to renewables production.

This efficiency gap will vary across applications, and may be considerably lower in some cases. At any rate, it represents the opportunity cost of diverting renewable electrons towards producing renewable molecules. The opportunity cost – as well as other effects such as land use – must be weighed against the potential of hydrogen for its ease of storage relative to electricity.

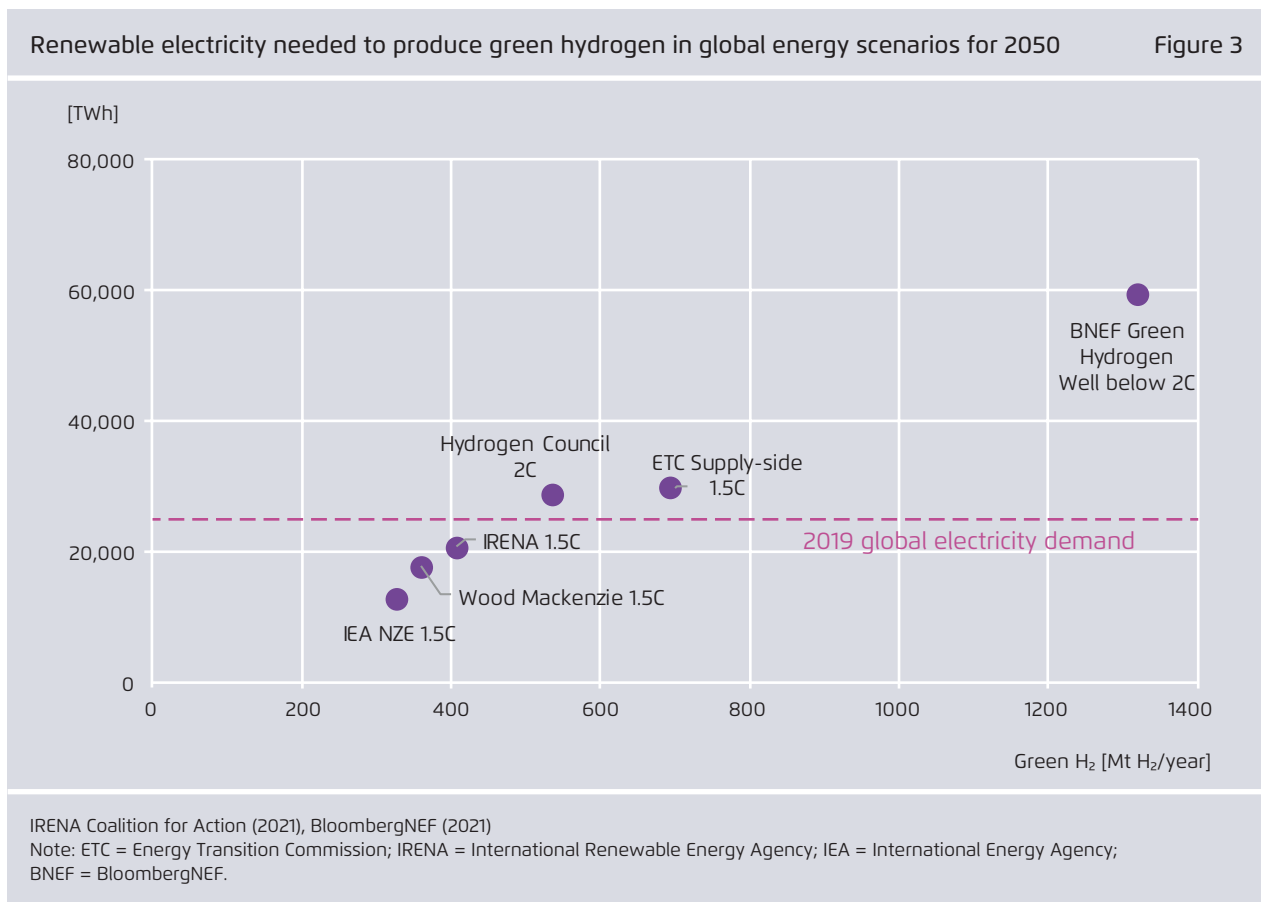
8 See Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018).



Defusing the tensions

Given the trade-offs around hydrogen, there has been much political debate about the amount of early-stage public financial support needed and where to direct it to develop a thriving hydrogen sector. The ongoing uncertainty about how best to proceed risks delaying the necessary infrastructure

rollout, in which case the contribution of hydrogen to decarbonisation will be delayed, and Europe will lose its competitive edge in the hydrogen sector. The following insights aim to cut through the uncertainty by providing actionable, quantitative-based guidance for policymakers.



II 12 Insights on Hydrogen

1

Analysts agree, but not all lobbyists: the role of hydrogen for climate neutrality is crucial but secondary to direct electrification

Since scaling renewable hydrogen in Europe will require significant public financial support – with EU taxpayers footing most of the bill – it is important to minimise the risk of misallocation by identifying areas where hydrogen use is crucial, i.e. inescapable, for achieving climate neutrality.

A clear set of no-regret hydrogen applications

To find out where future hydrogen demand is inescapable, we can draw on several EU-focused scenarios consistent with 1.5 degrees pathways that include hydrogen modelling. International organisations, notably the European Commission,⁹ have also presented several hydrogen-flavoured pathways for achieving global net-zero emissions by 2050. The scenarios have their own macroeconomic and technological assumptions, but that is precisely why it's interesting to compare them and see whether they draw the same conclusions.¹⁰ Figure 4 groups applications from net-zero scenarios into those that:

- figure across most scenarios ("no regret")
- show large variation across scenarios ("controversial")
- appear in few if any of the scenarios ("bad idea")

Hydrogen will supply 14–25 percent of final energy

In European scenarios, hydrogen accounts for 16–25 percent of final energy demand, while global scenarios see a 14–22 percent share of hydrogen in the final energy total. Thus, in a 1.5 degrees world, rather than a hydrogen economy what we see is hydrogen complementing large-scale electrification and reduced energy use with wind and solar, firmed with geothermal, nuclear, hydro and storage.

Everyone agrees hydrogen is key to industrial decarbonisation

European and global scenarios (Figure 5 and Figure 6) agree that industry will be among the most important consumers of hydrogen. Hydrogen demand from the industrial sector will be largely driven by the necessity to shift to the decarbonised production of steel and chemicals, including plastics, where hydrogen is either a reagent or a feedstock.¹¹ Some scenarios also assign hydrogen for decarbonising high temperature industrial heat, but the demand for this application varies across scenarios due to the existence of alternatives such as direct electrification.





9 COM (2020).

10 In the case of the ETC, their scenario is based on work of the IEA and the BloombergNEF, so a certain bias is baked in, but the scenario is notable for being supply-side only and for relying less on behavioural changes.

11 Indeed, the upcoming RED II revision mandates a 50 % use of renewable fuels of non-biological origin by 2030 in industry (excluding refineries). See COM (2021c).

Need for molecules in addition to green electrons

Figure 4

Green molecules needed?	Industry 	Transport 	Power sector 	Buildings 
No-regret	<ul style="list-style-type: none"> · Reaction agents (DRI steel) · Feedstock (ammonia, chemicals) 	<ul style="list-style-type: none"> · Long-haul aviation · Maritime shipping 	<ul style="list-style-type: none"> · Renewable energy back-up depending on wind and solar share and seasonal demand structure 	<ul style="list-style-type: none"> · Heating grids (residual heat load *)
Controversial	<ul style="list-style-type: none"> · High-temperature heat 	<ul style="list-style-type: none"> · Trucks and buses ** · Short-haul aviation and shipping · Trains *** 	<ul style="list-style-type: none"> · Absolute size of need given other flexibility and storage options 	
Bad idea	<ul style="list-style-type: none"> · Low-temperature heat 	<ul style="list-style-type: none"> · Cars · Light-duty vehicles 		<ul style="list-style-type: none"> · Building-level heating

* After using renewable energy, ambient and waste heat as much as possible. Especially relevant for large existing district heating systems with high flow temperatures. Note that according to the UNFCCC Common Reporting Format, district heating is classified as being part of the power sector.

** Series production currently more advanced on electric than on hydrogen for heavy duty vehicles and buses. Hydrogen heavy duty to be deployed at this point in time only in locations with synergies (ports, industry clusters).

*** Depending on distance, frequency and energy supply options

More recent global scenarios see less hydrogen in transport than foreseen by EU studies

There is good agreement across European and global scenarios regarding the role of hydrogen-based fuels in long-haul aviation and maritime freight. There is more disagreement and uncertainty regarding estimates of hydrogen demand from trucks and buses and from short-haul aviation and shipping, which compete to varying degrees with battery-electric technologies. Global scenarios envision less demand in transport as well, and with much less variability than in European scenarios. The difference stems from global scenarios, which see markedly less deployment of fuel-cell vehicles in ground transport. This may be driven by more recent data on fuel cell vs. battery economics and consumer uptake.¹² In several scenarios, sub-sectors including cars and light-duty vehicles envision no hydrogen demand whatsoever.

Hydrogen is vital for firming a renewables-based power system

The big variable across all the scenarios is the power sector. Demand in this sector is the most difficult to forecast since the competitive landscape is even more complicated than the choices in the heat and transport sectors (boilers vs. heat pumps and FCEVs vs. BEVs, respectively). For instance, in the power sector numerous long duration storage technologies besides hydrogen are under development, including liquid air, compressed air, advanced geothermal, new battery chemistries, flow batteries and thermal storage,¹³ as

well as balancing alternatives such as load shaping and interconnection. However, hydrogen may be more scalable than any other technology given its many applications outside the power sector. A notable example of a maximised hydrogen scenario for the power sector is the BloombergNEF Green Climate scenario (2021). This scenario assumes that wind and solar will dominate the future energy landscape, firmed largely with hydrogen during periods of *kalte Dunkelflaute*.¹⁴ In this scenario, hydrogen demand in the power sector is larger than all other uses combined.

Net-zero scenarios see limited hydrogen use in buildings

Of all the hydrogen applications envisioned by European and global scenarios, heating makes up the smallest share, with less than 10 percent of overall hydrogen demand in 2050. This is especially true for households, although hydrogen can be useful for covering the residual heat load¹⁵ at combined heat and power plants generating district heat.

12 Most European scenarios date back to 2018 or 2017, while most of the global scenarios are from 2021.

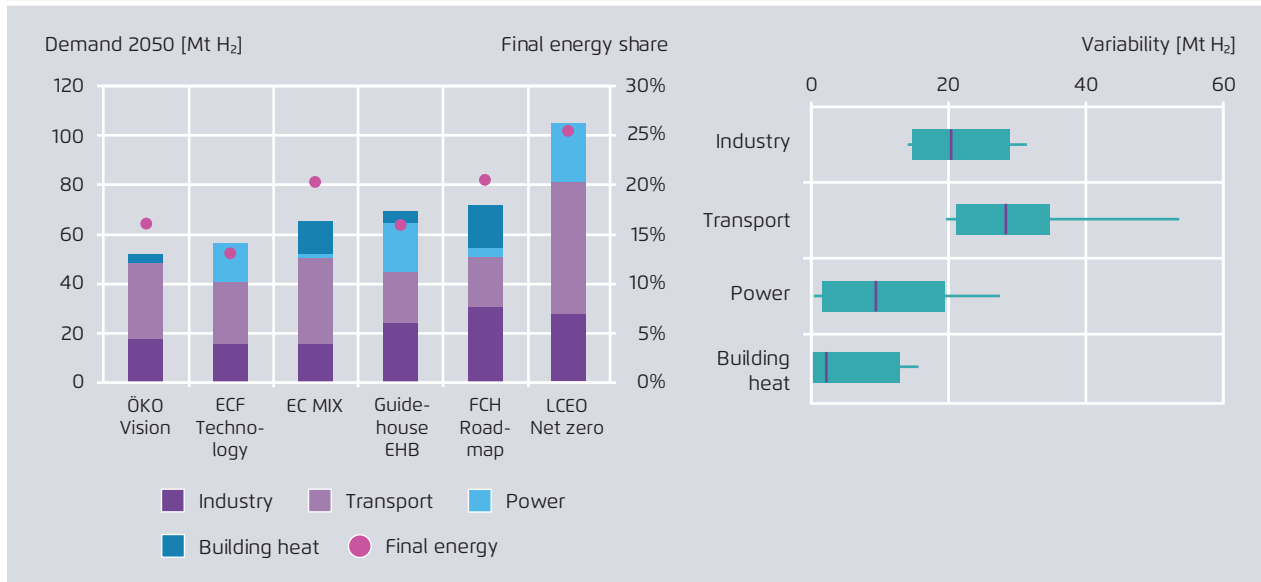
13 See Canary Media (2021); Vox (2020); and J. Jenkins et al. (2021).

14 This is the common industrial term in Germany for "dark doldrums," i.e. prolonged simultaneous lulls in wind and solar generation.

15 The residual heat load in district heating is what remains after all other sources of renewable heat and recycled waste heat have been tapped. In the long run, the most important contribution will come from large-scale heat pumps (Prognos et al. 2021).

Estimates of EU27+UK H₂ demand in European net-zero scenarios for 2050

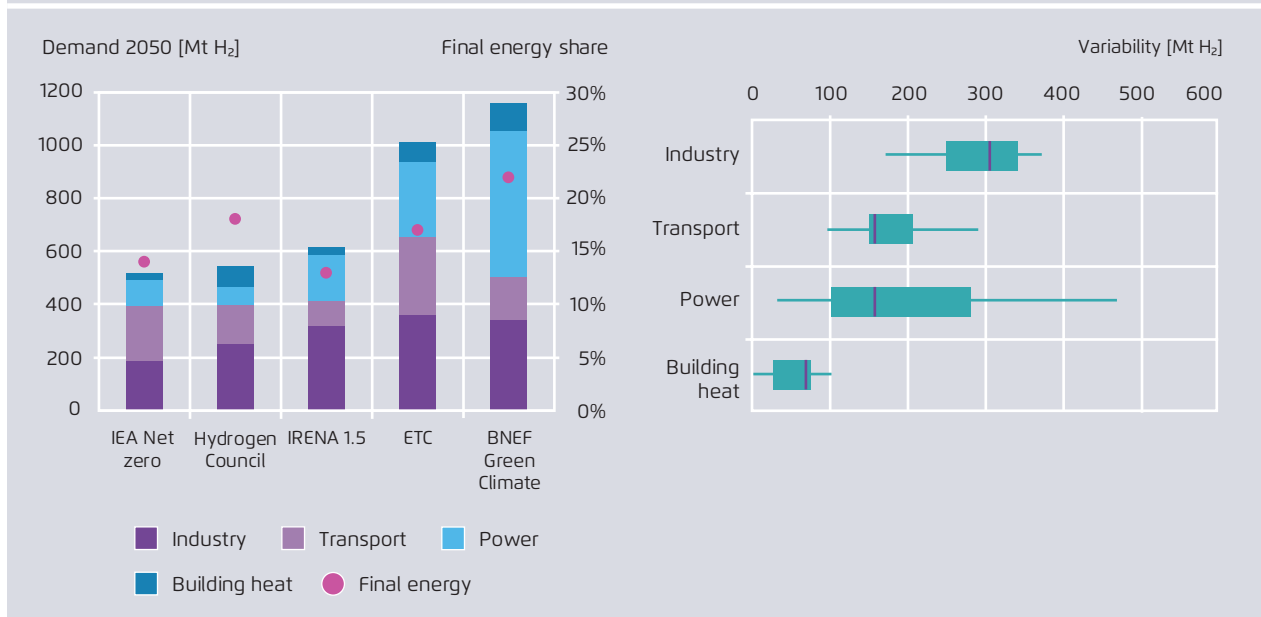
Figure 5



JRC (2020), Guidehouse (2021a), COM (2020)
 Note: EC MIX = European Commission, Impact Assessment SWD (2020); Öko Vision = Öko-Institute; FCH Roadmap = Fuel Cell and Hydrogen Joint Undertaking 1.5C scenario; ECF Technology = European Climate Foundation "Net Zero by 2050"; Guidehouse EHB = Gas for Climate "European Hydrogen Backbone"; LCEO Net Zero = Joint Research Centre "Low Carbon Energy Observatory". Final energy share is calculated by subtracting non-energy demand, adjusting transport to 75% of demand and power to 40% of demand.

Estimates of global hydrogen demand in 2050 by selected scenarios

Figure 6



ETC (2021), BloombergNEF (2021a), IEA (2021a), IRENA (2021a) Hydrogen Council (2017)
 Note: Final energy does not include feedstocks and other non-energy use; ETC=Energy Transition Commission; BNEF= BloombergNEF; IRENA = International Renewable Energy Agency; IEA = International Energy Agency. Final energy figures taken from respective sources.

2

We should anchor hydrogen infrastructure around no-regret industrial and power demand and ensure infrastructure planning that takes projected industry demand as the starting point

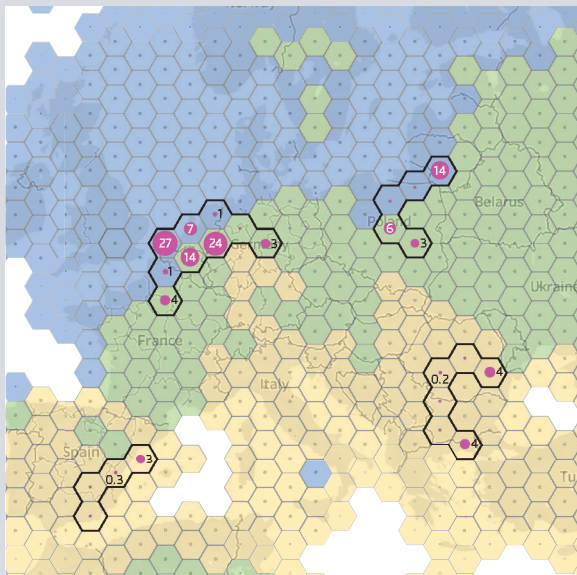
Until now, the deployment of low-carbon hydrogen technologies has suffered from the -chicken-and-the-egg problem: without reliable demand, there's no supply, and without reliable supply there is no demand. We cannot blame technology availability, because there are several clean hydrogen production choices and a host of applications. The issue boils down to a lack of hydrogen infrastructure for connecting and balancing supply and demand and an underlying failure to integrate industry mapping and energy infrastructure planning.

The solutions are to de-risk infrastructure investment, which can be achieved by anchoring early infrastructure around no-regret hydrogen demand and by adopting processes that make sure that energy infrastructure planning is firmly reflective and anticipative of industry needs and renewables production site planning. At the EU level, this would require, say, that the JRC Industry and Renewables Geography Lab set up as part of the revised 2021 clean industry strategy is woven into the Trans-European Network planning procedures. The lab will facilitate

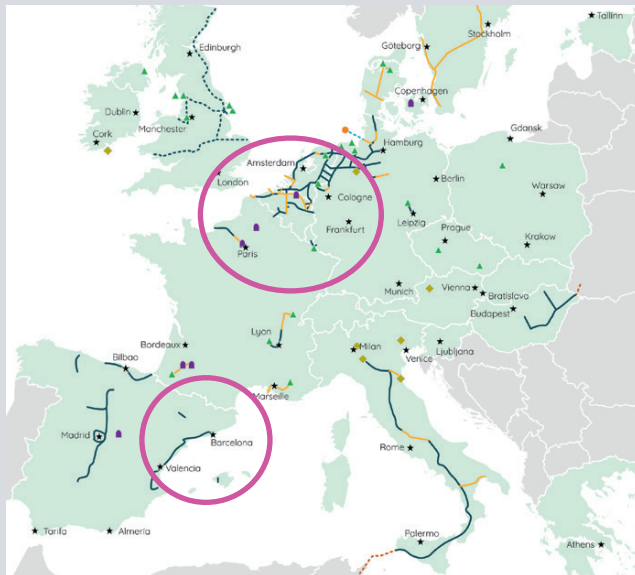
No-regret corridors for 2030 based on industrial hydrogen demand

Figure 7

Agora/AFRY vision for no-regret hydrogen corridors



European hydrogen backbone 2030



Best LCOH 2050 Hybrid Solar Wind Industrial hydrogen demand 2050 in TWh per year

Agora Energiewende & AFRY (2021), Guidehouse (2021b)

Note: Only those hydrogen pipelines that are resilient to the future levels of hydrogen demand and the technology assumptions used here have been considered to be "no-regret".

the development of renewable infrastructure by providing geospatial information on the availability of renewable energy sources, energy infrastructures and industrial demand centres and hence can also identify no-regret locations for hydrogen.

Identifying and planning for no-regret hydrogen uses

The European chemical industry today already consumes large amounts of hydrogen – 8.7 megatonnes¹⁶ – and the supply is currently unabated. Meanwhile, apart from a switch to scrap-based steelmaking, hydrogen is the only other option for decarbonising the current coal-based capacity of the European steel industry, of which 68 percent needs to be replaced by 2030 during the upcoming investment cycle.¹⁷ Based on demand forecasts, these industries can drive large offtake volumes of hydrogen at a minimal risk of stranding assets or betting on the wrong technology. Additionally, the demand profile of industrial hydrogen remains practically constant throughout the year, ensuring volume certainty. By contrast, future hydrogen demand from the power & heat sectors is much more seasonal. The industrial sector is therefore an ideal no-regret sector for anchoring early hydrogen infrastructure by 2030.

Using no-regret hydrogen demand as an anchor, we have identified four opportunities for early hydrogen corridors with a view to 2030. These are shown on the left-hand side of Figure 7. On the right-hand side is the European Hydrogen Backbone 2030 (EHB)¹⁸ for comparison. Though the EHB plan considers various anchors for hydrogen, including a substantial amount of riskier demand, we have found a strong overlap between our no-regret approach and two regions

within the EHB plan – in Northwest Europe and in Spain,¹⁹ as highlighted on the right-hand side of Figure 7.

Hydrogen is not a must for industrial heat ...

Around 40 percent of natural gas demand in EU industry today is used for low temperature heat. In low temperature applications, electric heating, especially heat pumps, offer better energetic performance than any gas technology. When it comes to decarbonising medium- and high-temperature heat, however, the lines are blurrier. Some modelling scenarios employ hydrogen to decarbonise high-temperature industrial heat on the premise that high temperature heat cannot be electrified. This is a common myth, and Figure 8 shows that various temperature electric technologies exist and perform more efficiently than hydrogen heating, which means that less renewable energy input is required.

... but in niche cases uptake could be driven by co-benefits, not efficiency

At industrial sites where hydrogen is already required for non-energy use, the lower efficiency of hydrogen heating than that of heat pumps might be less important than the co-benefits of hydrogen. For instance, given the energy intensity of heavy industry, hydrogen may improve system flexibility by shifting some of the energy demand from the power grids to the gas network. What is more, adding hydrogen for industrial heat use to existing feedstock demand improves economies of scale, translating to a lower cost per unit. Therefore, where feedstock demand is already inescapable, the addition of hydrogen heating could help lower unit hydrogen costs while benefitting system flexibility.

16 Petrochemicals Europe (2021)

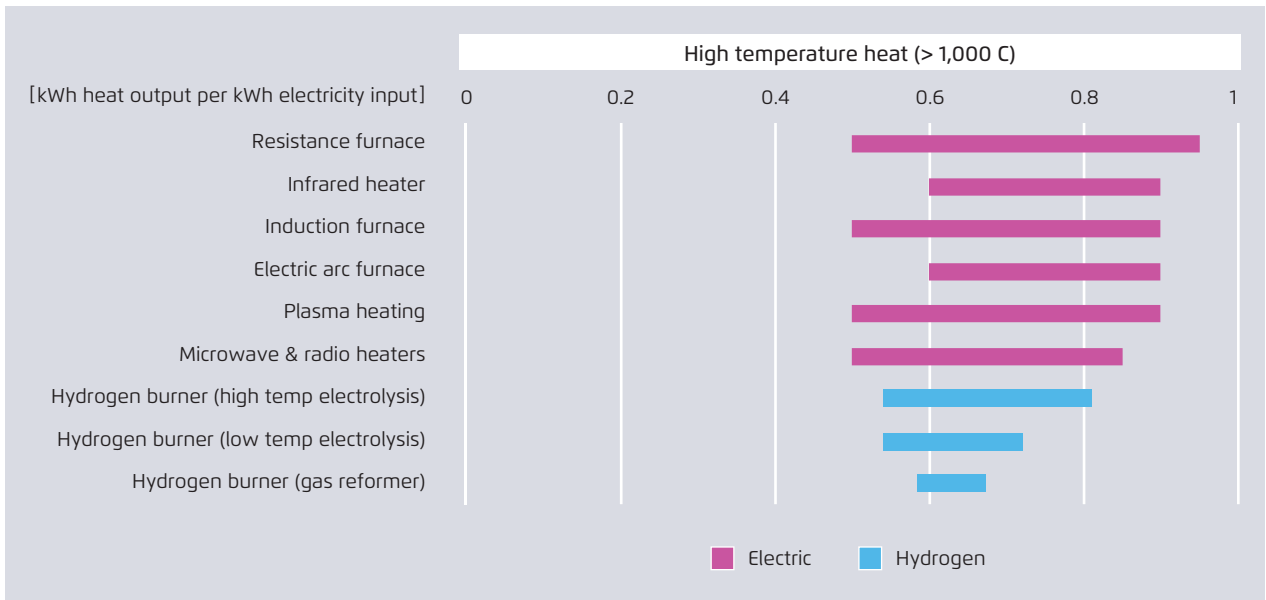
17 See Agora Energiewende & Wuppertal Institut (2021).

18 See The European Hydrogen Backbone initiative consists of European gas infrastructure companies, Guidehouse (2021b).

19 See Agora Energiewende & AFRY (2021).

Performance factors of industrial heat decarbonisation technologies

Figure 8



Agora Energiewende & AFRY (2021)

Note: "Values" refer to lower heating values. The hydrogen burner efficiency is 90%. Efficiencies do not consider midstream losses. Hydrogen produced by gas reforming has gas as its energy input.

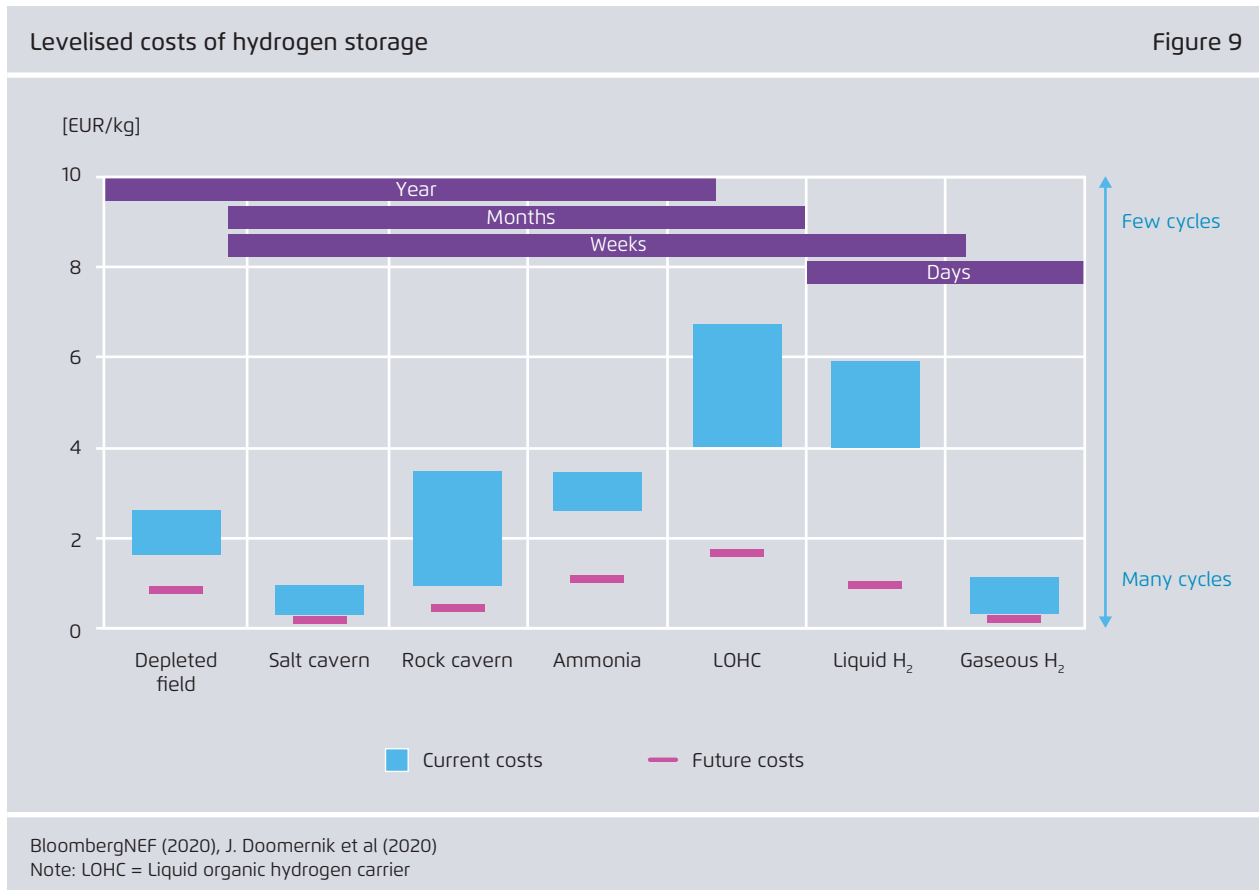
3 We need significantly greater amounts of geological hydrogen storage

In addition to meeting industrial demand, hydrogen will be urgently needed in the combined power and heat sector to firm up a renewables-led system – performing a very different role from that of fossil gas today, which provides the bulk of supply. This is another reason why hydrogen storage should be included in Trans-European Network for Energy planning. Seasonal hydrogen storage will be critical because renewable generation from solar peaks in the summer, while overall energy demand in the Northern Hemisphere typically peaks in the winter. Wind generation profiles are better matched to winter, but it's not uncommon to encounter weeks-long periods in which wind is low. Industrial users

also need a constant supply of hydrogen irrespective of season, and storage will be critical to buffering variable production of renewable hydrogen to their needs.

Geological storage is the cheapest form of large-scale hydrogen storage

There are several options available for seasonal storage, but geological formations, particularly salt caverns, have the lowest costs, as illustrated in Figure 9. Another advantage of salt caverns is that they have a relatively high cycling rate compared with depleted

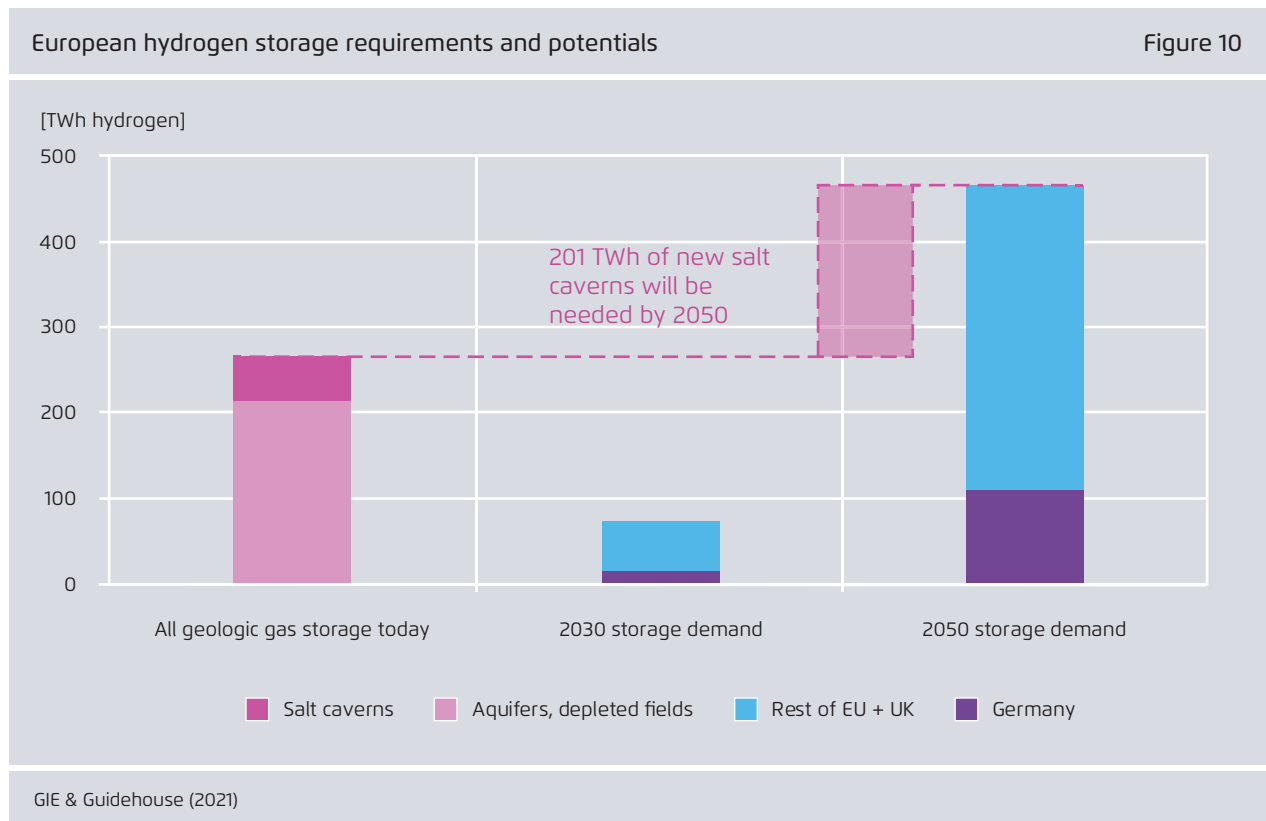


fields or aquifers, meaning that they can add more system flexibility. In the future, rock caverns may become similarly cheap, but there's still much uncertainty about this technology. Europe should pursue geological storage because it has expertise in developing storage facilities, plenty of existing storage sites that can be repurposed and the right geology to develop more sites, particularly in central Europe.

fields and hard rock caverns. However, by 2050, even that would not suffice, as shown in Figure 10. In the long run, therefore, more greenfield storage will need to be developed, or existing storage will need to be expanded. Because it takes 5–10 years to develop new storage projects, planning must begin now.

Start planning for new facilities

If all current gas salt cavern storage were repurposed to hydrogen, Europe would still have a hydrogen storage shortfall by 2030. The shortfall could be made up by repurposing more expensive aquifers, depleted



4

Policy instruments for supporting renewable hydrogen in no-regret applications

Since carbon pricing alone will not be enough in the 2020s to ramp up renewable hydrogen market and cover the cost gap against alternative hydrogen pathways, there is a need for other targeted policy instruments supporting renewable hydrogen specifically²⁰:

1. Carbon contracts for difference (CCfD) will enable European industry to start the transition to climate-neutral production. By offsetting the additional operating costs of breakthrough technologies such as hydrogen-based production of Direct Reduced Iron for primary steel making, CCfDs de-risk long-term investment and allow industry to take advantage of natural re-investment cycles as they build the climate-neutral industrial hubs of the future.

2. A power-to-liquid (PtL) quota in aviation of 10 percent by 2030 would deliver clear market signals that Europe intends to import considerable volumes of liquid e-fuels. Today's fossil-oil exporters should go beyond hydrogen and deliver liquid e-fuels with carbon from sustainable sources. The earlier they start, the better they will be prepared for the disruption awaiting petroleum markets.²¹

3. Gas power plants need to be 100 percent H₂-ready to back up renewables and meet residual heat load in district heating. To have the required hydrogen power plant capacities in place by 2030, a dedicated support instrument will be needed to encourage

switching to renewable hydrogen in a situation where fossil gas remains cheaper.²²

4. Scalable green lead markets would help create a business case for renewable H₂. In the short run, CO₂ performance labelling and public procurement can be valuable for creating lead markets. To be effective, the diverse demand-side instruments must be compatible with the CCfD as an insurance mechanism for supply-side investment.

5. H₂ supply contracts can enable competition between production in the EU and abroad. Ideally, the instrument will let those locations compete against each other and against different modes of transport, be it liquified or compressed hydrogen, ammonia or liquid organic hydrogen carriers, in addition to the less costly hydrogen transport via pipeline.

Figure 11 summarises the policy instruments and a proposed timeline for their implementation. The required policy support for CCfDs and the PtL quota in aviation for renewable hydrogen at the EU level is anticipated to cost 10–24 EUR bn p.a. Beyond 2030, direct support for new renewable H₂ production or consumption should be phased out. In the next decade, the cost gap will be much smaller, and consumers and markets should increasingly shoulder the financing burden.

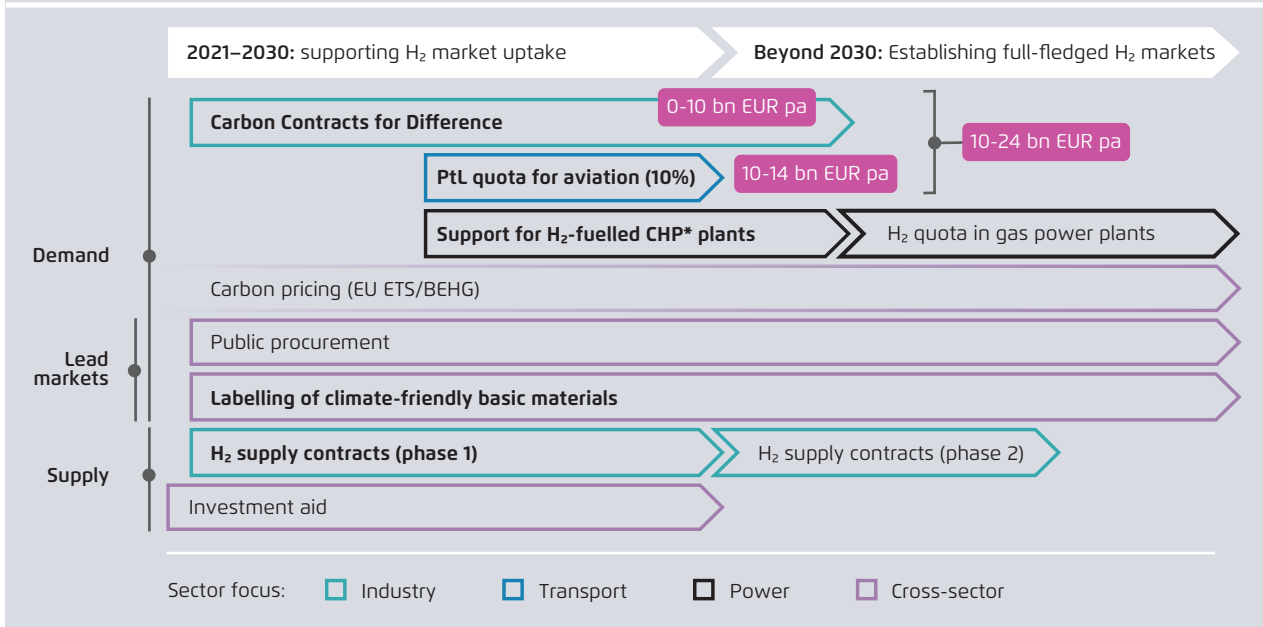
²⁰ See Agora Energiewende and Guidehouse (2021).

²¹ Note that there are also significant non-CO₂ effects of aviation on climate change that e-fuels alone will not be able to mitigate. According to current knowledge, those effects represent at least half of the total climate change effect of aviation. They would need to be offset via negative emissions to achieve climate neutrality (Prognos et al. 2021).

²² In Germany, for example, a fixed feed-in premium for renewable H₂-fuelled CHP plants could be tendered under the existing Combined Heat and Power Act.

Support instruments for renewable hydrogen and costs of support for CCfDs and the PtL quota in the European Union

Figure 11



Agora Energiewende and Guidehouse (2021)
 Note that the PtL quota increase further after 2030. Also, Guidehouse assumes an aviation quota of only 5% by 2030.

5 There is no credible financing strategy for hydrogen use in households

If hydrogen were to assume the role of gas in residential heating, then an aggressive blending strategy would be needed. Most experts agree that a 20 percent share of blending by volume is possible without a major overhaul of the gas grid or household appliances. However, there is a lack of advanced scenarios on how a ramp-up to 100 percent hydrogen can be achieved in such blending scenarios.

Blending is insufficient to meet EU climate targets

A 20 percent renewable hydrogen blend by volume would raise the price of wholesale gas by around 33 percent but reduce emissions only by 7 percent, as illustrated in Figure 12. To be consistent with European Commission's updated goals, an emissions reduction in the residential sector must reach -42 percent by 2030 relative to 2015.²³ Meeting this target would require more investment in the gas grid and a tripling of the wholesale gas price merely for the production cost of clean hydrogen. The 2030 abatement costs of this measure are high – 80–100 EUR/tCO₂²⁴ for fossil-based hydrogen with carbon capture and up to 400 EUR/tCO₂ for renewable hydrogen.²⁵

23 This is illustrated in insight #5.

24 The numbers are from Figure 2.

25 This assumes a 65 percent hydrogen blend for a 42 percent reduction. With an average renewable hydrogen costs of 94 EUR/MWh H₂ (HHV) → 0.65 * 94, the cost component of green hydrogen alone totals 61 EUR/MWh.

Carbon pricing and quotas for hydrogen heating are unrealistic

One option for covering the abatement cost gap would be for governments to raise the CO₂ tax in heating to 100–400 EUR/tCO₂. A mandatory blending quota would be the alternative way to force customers to pay for the extra cost of hydrogen in residential heating. But doing so would triple wholesale gas prices in addition to the costs of upgrading distribution and metering infrastructure and appliances inside homes.²⁶

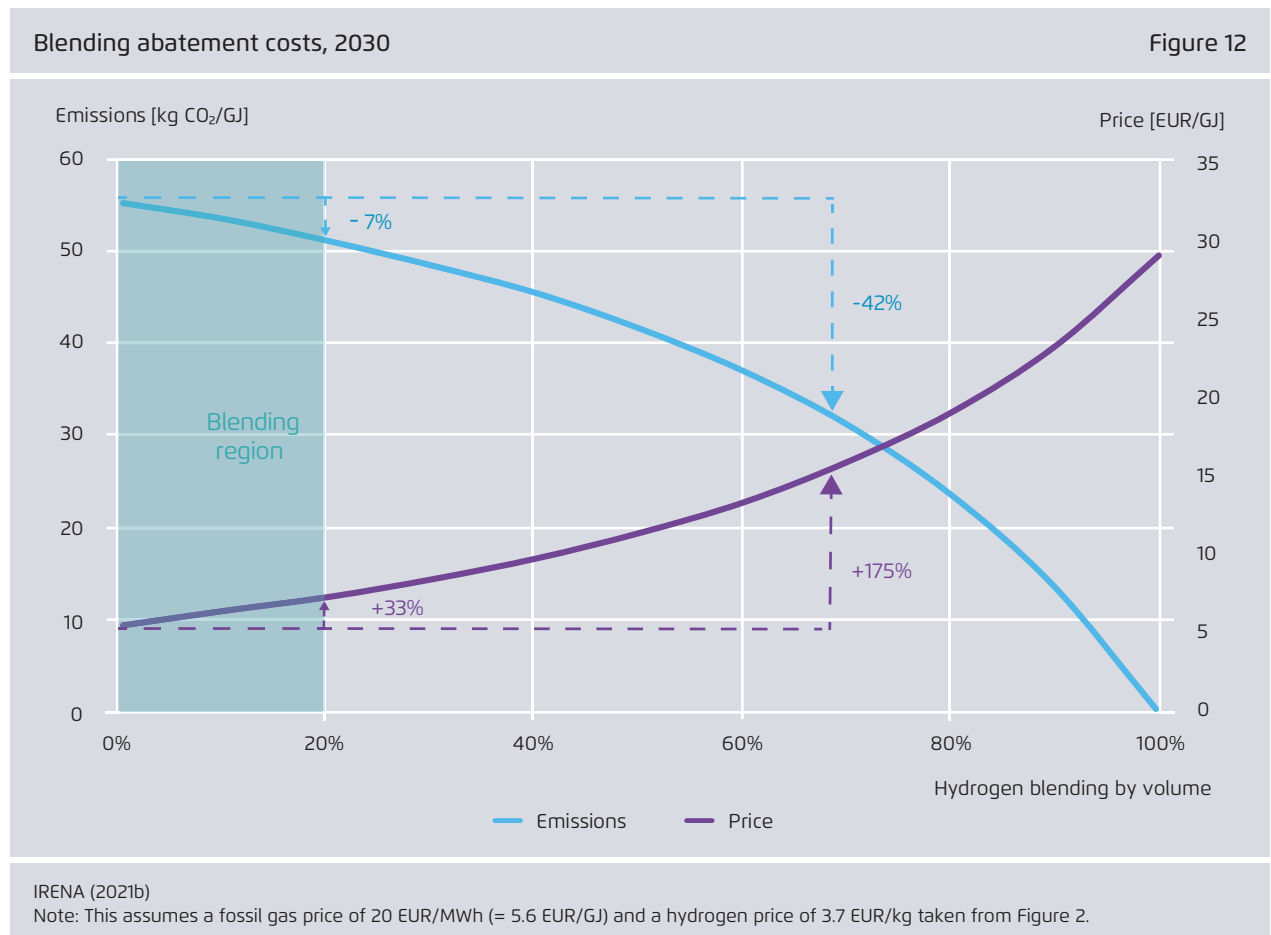
Given the already heated debate on the social effects of moderate CO₂ prices, it is very unrealistic to assume that politicians will increase CO₂ prices to the level where clean hydrogen is marketable or force a tripling of gas prices on customers to deliver the CO₂ reductions required by the new EU (and German) climate targets. Notably, higher gas prices would most likely lead to a higher heat pump uptake since this option would become cheaper than gas or oil. As a result, the remaining gas customers – those least able to adapt due to the lack of capital or rental accommodation – would be stranded with even higher gas bills, effectively footing the bill for gas infrastructure and hydrogen deployment.

26 Such a quota would encourage the physical blending of hydrogen with natural gas, which some industries oppose, as they require pure hydrogen. For instance, the industry dialogue "Gas 2030", hosted by the German Ministry of Economic Affairs and Energy, stressed the importance of gas quality, and identified risks for the industrial demand side arising from blending (BMW 2019).

This is not a growth song

The third option would be a continuous multi-billion EUR government subsidy for hydrogen in the gas grid and related infrastructure development – but there is little justification for using taxpayer money to that end while there is a strong risk of lock-in of assets and energy poverty, given that heat pumps and heat grids are already technologically mature and more cost-effective options. Subsidies for hydrogen in the

residential sector stand in stark contrast to subsidies for hydrogen in the industrial sector: The latter operate in a context where no other decarbonisation option is available and would secure jobs and help decarbonise Europe's industry. Hence, there is no credible route where hydrogen enters the residential heating sector.



6

Gas distribution grids need to prepare for a disruptive end of their business model

To stay on track for 1.5 degrees we need to reduce the consumption of natural gas in buildings by 42 percent over the next decade

According to European Commission modelling, the total demand for natural gas in 2030 will need to have decreased by 34 percent relative to 2015, as shown in Figure 13. The phase-out will have to be even more pronounced in the buildings sector, decreasing by 42 percent by 2030 relative to 2015 and by 68 percent by 2050 – leaving 37 mtoe of gas demand overall. By 2050, all the gas flowing through distribution networks needs to be either clean hydrogen, synthetic methane produced from decarbonised hydrogen, or biomethane.²⁷ But it's already clear now that in the future there will be far less gas than today, and distribution grids will have a hard time attracting new investment, particularly over the next two decades, when heat pumps will offer a much better deal.

Also with a view to ensuring the overall ambition of the Fit-for-55 package and the EU climate law, it is clear that if gas use in buildings is not reduced as much, another sector will have to shoulder the difference and provide more savings. As we have seen above, that would require sectors with fewer alternative decarbonisation options than home heating to reduce even faster.

27 Note that the residual use of any fossil gas would need to be offset by negative emissions in order to be fully climate neutral.

Consumers have stronger financial incentive to switch to heat pumps

While some studies project renewable hydrogen production costs as low as 1 EUR/kg H₂ in 2040, the equilibrium price is closer to 1.5–2 EUR/kg H₂.²⁸ The lower cost limit strongly depends on the availability of cheap imports via pipeline from countries neighbouring the EU. The delivered costs must also include transmission and storage, which would add around 0.43 EUR/kg H₂ over a pipeline transport of more than 3,000 km (the distance from Morocco to Northwest Europe²⁹), and another 0.17 EUR/kg for salt cavern hydrogen storage.³⁰ Finally, the delivered price must also factor in distribution costs, which based on the EU27 average added 2ct/kWh for households in 2020.³¹ Assuming the same relationship holds true for hydrogen, network tariffs would add 0.8 EUR/kg H₂ on average. The delivered retail price in 2040 would amount to 3–3.5 EUR/kg H₂, with transmission, storage and distribution costs accounting for nearly half of the costs of hydrogen delivered to households, as seen in Figure 14.

As Figure 15 indicates, even unrenovated households switching to heat pumps during the 2030s would be approximately 20,000 EUR better off than those on hydrogen boilers after 20 years, with the difference rising to 30,000 for households that combine heat pumps with deep renovation. It would take a delivered hydrogen price of 2.5 EUR/kg to make

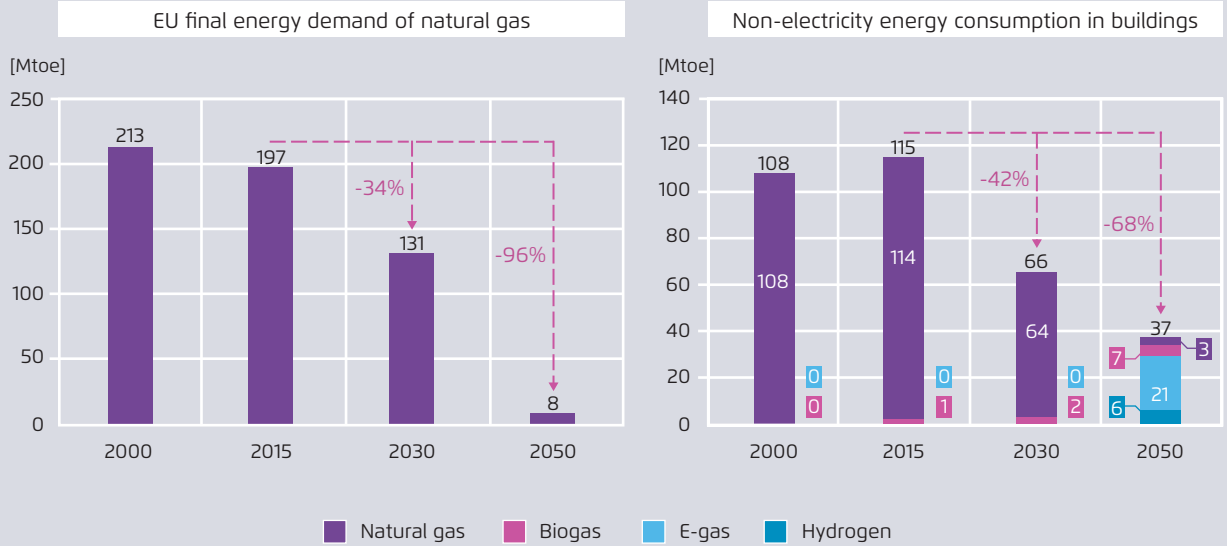
28 The numbers are from Fig 24.

29 Hydrogen Council (2021) assumes a 75 percent share of repurposed pipelines and a 25 percent share of new pipelines.

30 See BloombergNEF (2020). BloombergNEF also assumes a benchmark for salt cavern costs.

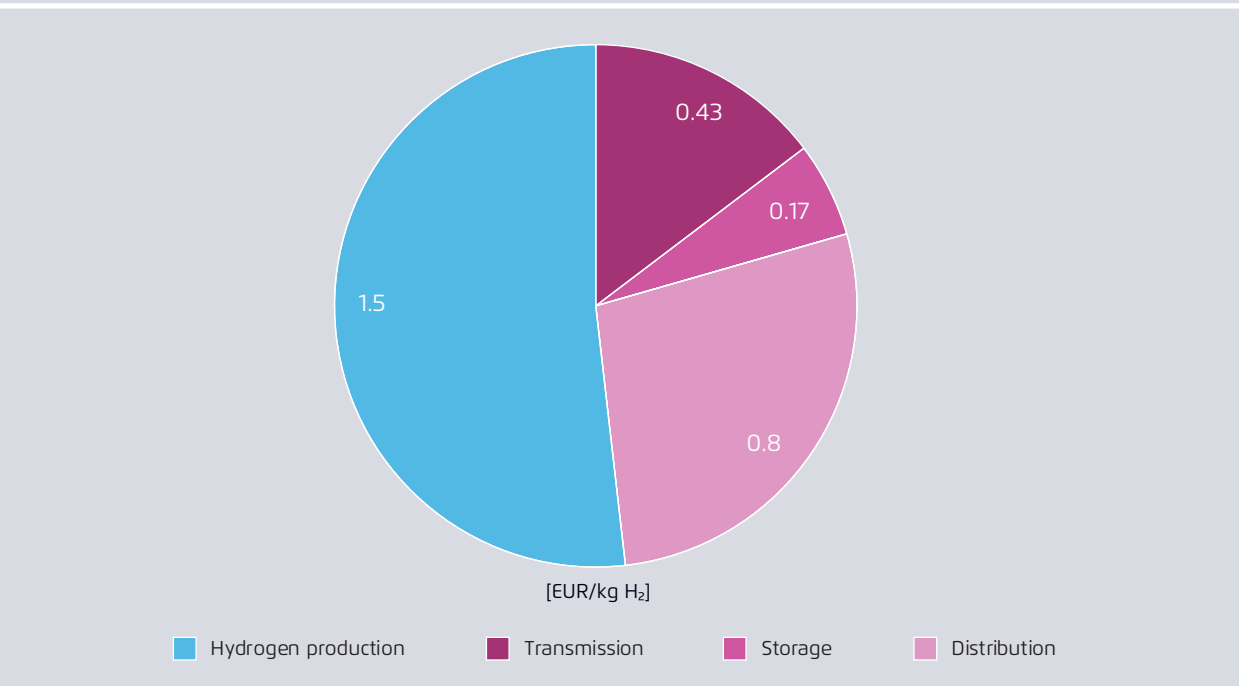
31 See DG Energy (2020).

Total consumption of gases and of gases in buildings in the European Commission's MIX scenario **Figure 13**



COM (2020): Climate Target Plan Impact Assessment

Breakdown of hydrogen price delivered to households in 2040 **Figure 14**



DG Energy (2020) and calculations by Agora Energiewende
 Note: The figure assumes an equilibrium price of 1.5 EUR/kg H₂ in 2040 and a transmission distance of 3,000 km.

hydrogen boilers competitive with a heat pump in an unrenovated flat, but such prices are unlikely to materialise until the mid-2040s. Note that Member States still need to correct the imbalance between charges and taxes for gas vs electricity. The revised Energy Taxation Directive should be the minimum level to start from.

Residential hydrogen boilers have the lowest system efficiency of all heating options

Even in terms of the most efficient use of renewable energy from a system perspective, hydrogen boilers are the worst option. In Figure 16 we considered three different heating scenarios. In the first scenario, hydrogen is generated from renewable electricity, transported to a centralised storage site, and then distributed through a pipeline system to households. Given 100 kWh of renewable energy input, 61 kWh is delivered as heat.

In the second scenario, hydrogen is also generated from renewable electricity and transported to a centralised storage site. However, this hydrogen is then delivered to a combined cycle hydrogen turbine. This scenario is conceivable as a response to a prolonged period of low renewables production, due to a *Dunkelflaute* ("dark doldrums"). The system would then access hydrogen storage and use turbines to generate power, which would be sent to households and consumed by heat pumps to generate heat. Depending on the outside temperature, the heat pump will be more or less efficient at generating heat. In the worst-case scenario – that is, given sub-zero temperatures during a dark winter day – a *kalte Dunkelflaute* – every 100 kWh of renewable energy can be converted to 63 kWh of heat, which is still 2 kWh more than with a boiler. However, averaged throughout the entire year, a typical heat pump performs twice as well, meaning that for every 100 kWh of renewable energy, 125 kWh of heat is produced.

In the final scenario we envisage a period of abundant wind and solar generation and the direct transfer of power to the heat pump, without intermediate storage. Under such circumstances, and again depending on ambient temperatures, heat pumps supply between 135 and 270 kWh of heat for every 100 kWh of renewable generation. This is 2 to 4 times the output of the hydrogen boiler.

Hydrogen heating for households will be a niche solution

There are some challenges still standing in the way of a total heat pump rollout. The most notable are poor insulation in old dwellings,³² financing, difference in charges and taxes between gas and electricity as well as continued fossil heating subsidies, grid constraints, lack of space, particularly for urban dwellings, and a shortage of trained and experienced workers. Yet for densely populated urban areas, heat pumps don't have to be fitted to every building. Utility-scale heat pumps will be the largest contributor to district heating.³³

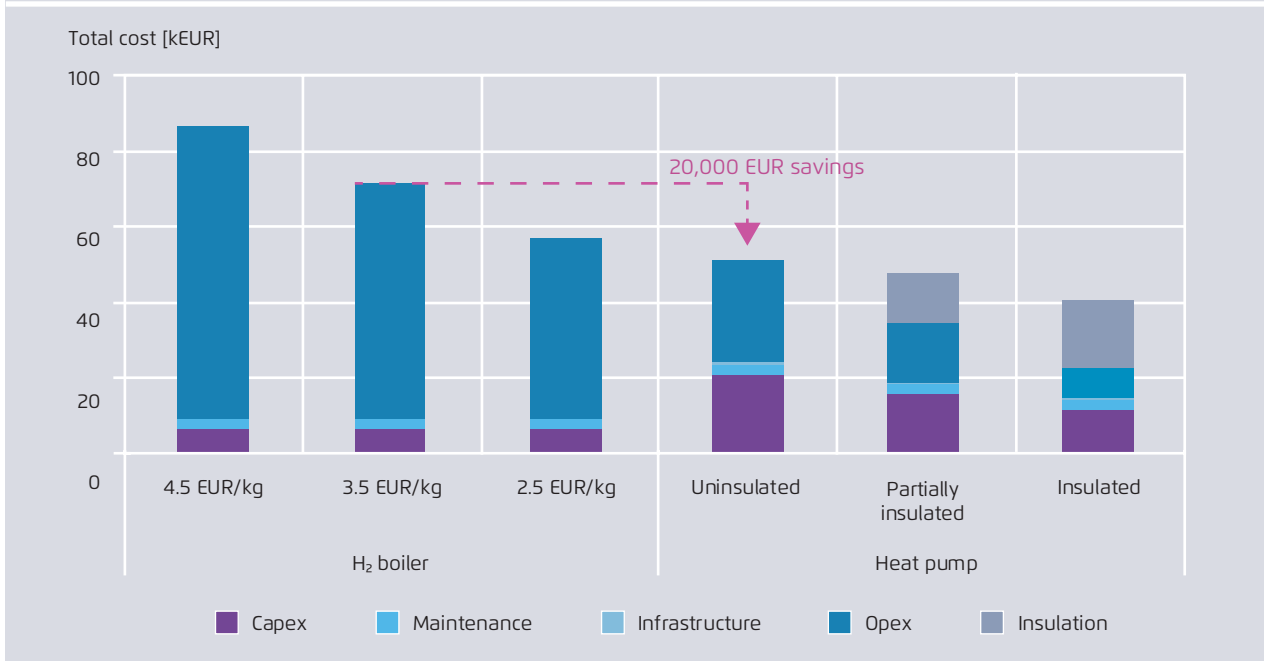
Nonetheless, some heat networks with high temperatures may have residual heat loads requiring hydrogen back-up (also see Figure 4). We should also account for those who might prefer sticking with their boiler instead of carrying out major work, even if it ultimately saves thousands of euros. Niche opportunities for hydrogen heating like these may arise, but most distribution networks must prepare for a phase-out of their low-pressure gas assets.

32 In Germany, France and Italy, the share of buildings built before 1946 is 24.3 percent, 28.7 percent, and 20.7 percent, respectively. See Eurostat (2011). On the other hand, there are still considerable myths about the use of heat pumps in the existing building stock that have been addressed recently, see Fraunhofer-ISE (2021).

33 See Prognos et al. (2021) for the case of Germany.

Net present value comparison between an unrenovated single-family house with hydrogen heat supply and a building renovation including an air heat pump in 2025

Figure 15

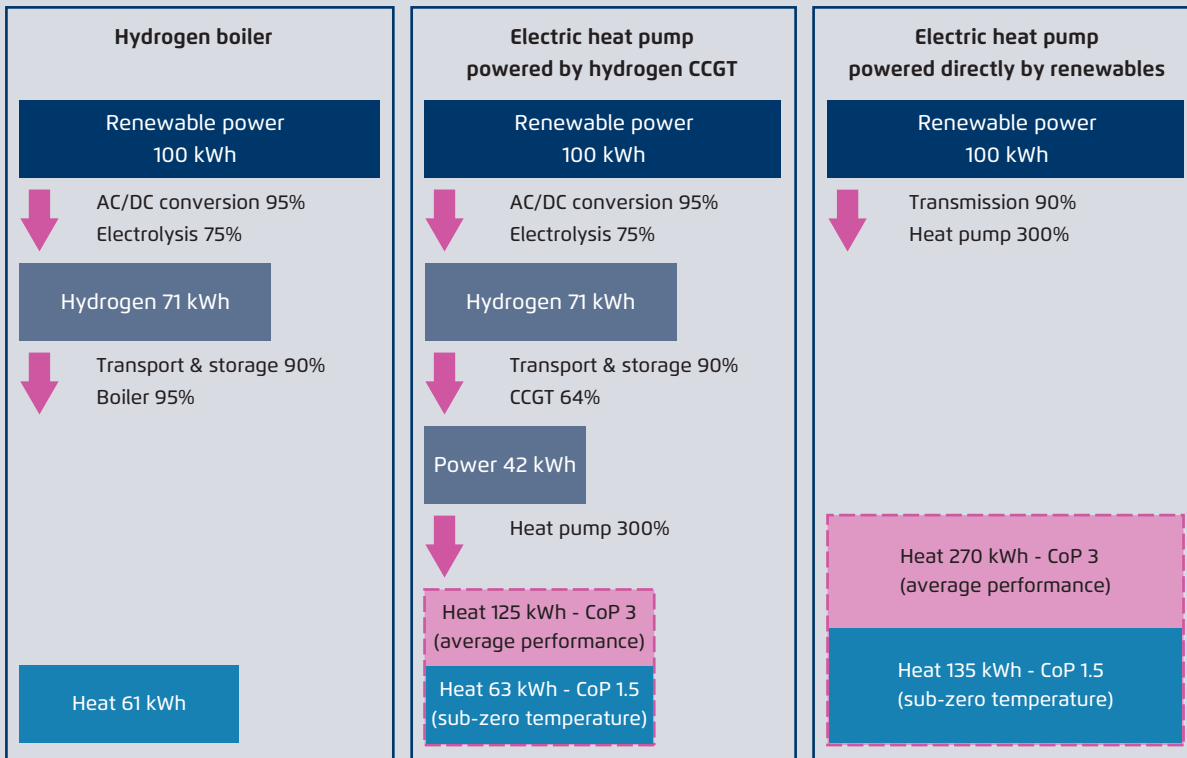


Öko-Institut (2021)

Notes: Heat pump costs decrease by 20% until 2025. The electricity price follows price path 3 from figure 2–3 in Öko-Institut (2021), i.e. from 21 ct/kWh (2020) to ~15 ct/kWh (2025) and 14 ct/kWh (post 2030). This is based on the assumption of an EEG surcharge phase-out by 2025, which would decrease the electricity tax to an EU minimum in 2030, and of a heat pump tariff, all without VAT.

Efficiency comparison of different heating systems starting from renewable electricity

Figure 16



Own calculations based on LETI (2021) and Fraunhofer ISE (2011)

Note: Heat pump performance varies based on external temperature. Heat pump coefficient of performance (CoP) were chosen based on average seasonal performance (CoP = 3) and performance under sub-zero temperatures typical of winter months (CoP = 1.5)

7 The potential future market for hydrogen vehicles is shrinking daily

Dude, where is my fuel-cell car?

Just a decade ago, fuel-cell electric cars seemed to be the future of the automotive industry. Today, the dream is over: as illustrated in Figure 17, battery-electric cars have come to completely dominate the electric vehicle market.

Hydrogen-fuelled transport will remain niche

Ultimately, some hydrogen vehicles are likely to hit the market, but they will be few in number, and their applications will be limited to long-range and specialist vehicles in, say, long-range freight, construction or mining. Even in the freight sector, there is good reason to believe that battery-electric trucks will be used for most trips, as Figure 18 illustrates. This is because around 80 percent of the daily driving distance is less than 400km, well within the range of battery technology. Additionally, research continues into more efficient batteries, such as solid state or lithium sulphur, which would extend the current advantage of battery electric trucks and buses, further shrinking the case for hydrogen.

But hydrogen-based power-to-liquids will capture shipping and aviation markets

As for other transport modes, such as long-range shipping and aviation, liquid fuels have many advantages over hydrogen, most significantly improved energy density, and power-to-liquid makes for a stronger fuel than pure hydrogen. Yet there is still a question mark hanging over short-haul aviation and marine, where the density of liquid fuels is

not as important, but the weight of batteries is still prohibitive. As batteries continue improving, however, they might chip away at the short-haul maritime and aviation hydrogen markets through improved innovation and scale.

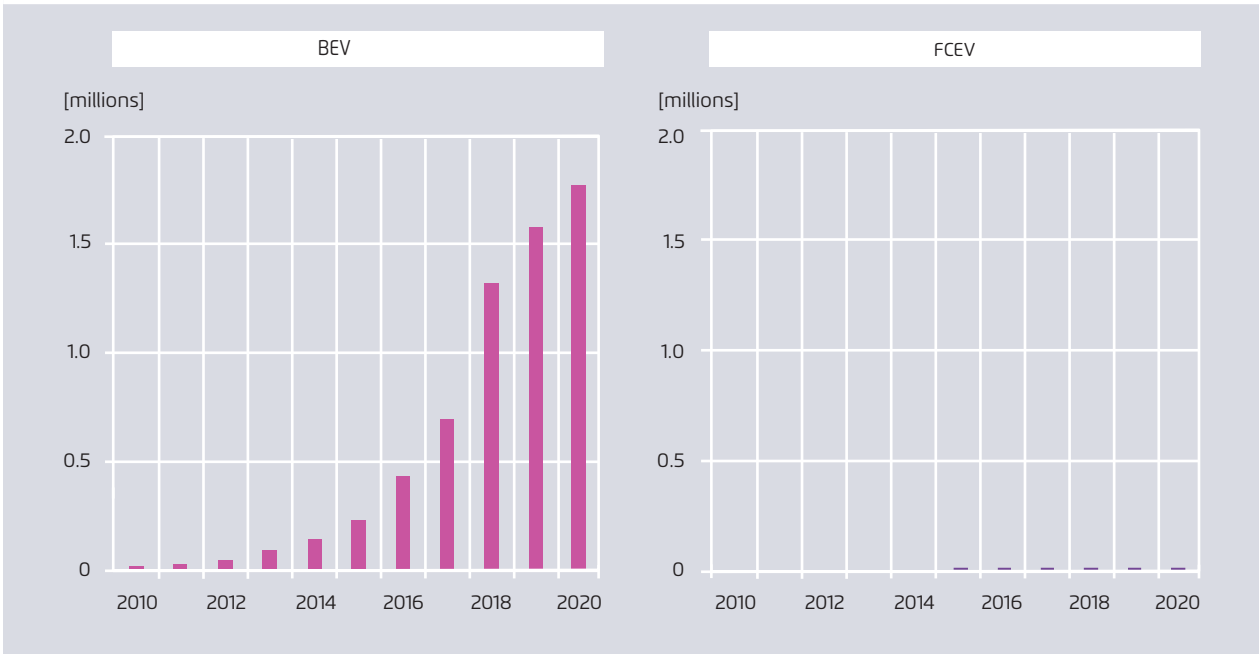
Ports will be a hotspot for a hydrogen refuelling infrastructure and a meeting place for industry users and offshore renewables

Despite a shrinking pool of mobility applications, there is still a case to be made for a limited deployment of hydrogen refuelling infrastructure in certain locations. For instance, situating hydrogen refuelling and storage infrastructure at ports could provide the impetus for decarbonising the maritime sector, which suffers from the same chicken and egg problem as hydrogen in ground mobility. Ports are often home to clusters of energy-intensive industries that would make the deployment of local hydrogen networks worthwhile. Moreover, the ports of the future will receive the production of offshore wind. The maritime sector is also a less risky bet on hydrogen or hydrogen-based fuels because heavy loads and long trips are likely to remain challenging for batteries.

Sharing refuelling across port operations, including maritime, drayage, and other commercial vehicles, would further diversify application-specific risk. For instance, if a refuelling station at a port becomes stranded through battery competition, the associated storage could be repurposed for local industrial use or power-to-liquid production.

BEV vs. FCEV annual sales

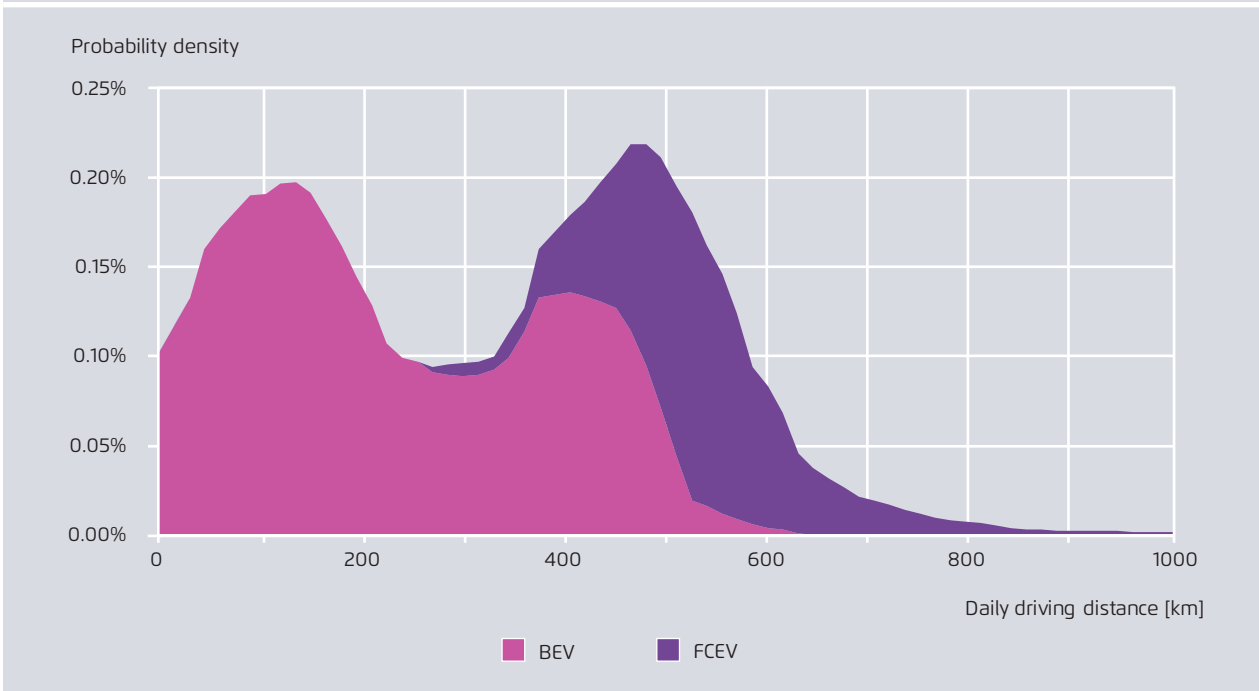
Figure 17



BloombergNEF (2021b)

Distribution of heavy trucks by daily driving distance, 2050

Figure 18



IEA (2021a)

8

Each GW electrolysis must come with 1–4 GW of additional renewables, located so that they do not exacerbate grid bottlenecks

Additional renewable capacity depends on generation technology

Any new electrolysis for hydrogen production must spur additional renewable power production to fully cover its electricity consumption. 4,000 full-load hours for electrolysis means that 1 GW of electrolysis requires 4,000 GWh of renewable electricity per year, which could be provided with either 1 GW of wind offshore, 2 GW of wind onshore, 4 GW of solar PV³⁴ or an equivalent combination.³⁵ Figure 19 shows that, at good sites, higher full-load hours could be achieved for each technology, decreasing the renewables capacity that would need to be deployed.

Providing support, avoiding congestion

It is important that the siting of electrolyzers does not aggravate grid bottlenecks and, ideally, even assist the network. If H₂ production and renewable electricity production are geographically separate, electrolysis may end up running on local fossil-based generation. Otherwise, the large distances between H₂ production and renewable electricity production will increase

new grid congestion across Europe. In Germany, this would add to the risk of a bidding zone split, with increasing electricity prices in the South and decreasing prices in the North. While bidding zones generally reflect current structural congestion in the grid, it is advisable to specify areas suitable for H₂ production,³⁶ so as to avoid the creation of more grid congestion in the future.

Electrolysers connected to the grid will also need to operate flexibly to match periods of high renewable energy share and low GHG intensity in the grid. In terms of electrolyser running costs, this makes sense because electricity prices tend to be low in times of high renewable generation. But electrolysers will compete with other demand-side flexibilities such as battery-electric vehicles and heat pumps so that their effective use of low-priced electricity will be limited.³⁷

34 These are simplified values. At good sites, offshore wind in Europe may achieve more than 4,000 full-load hours (FLH); onshore wind, more than 2,000 FLH; and solar PV, more than 1,000 FLH. Mixing different renewable energy sources is another option (Agora Energiewende and AFRY Management Consulting 2021).

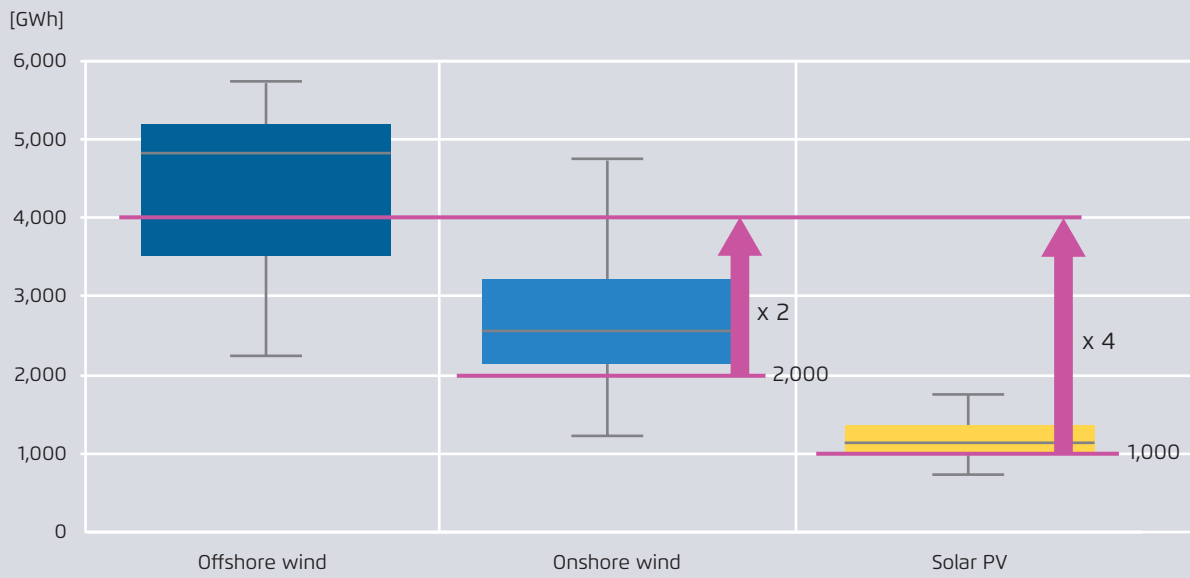
35 Distributing the investment costs of electrolysers over many annual operating hours lowers the overall cost of hydrogen production. This basic mechanism has its limits, however. If electrolysers use grid electricity and operate based on market prices for H₂ and electricity, operating costs would increase disproportionately at higher operating hours (Agora Energiewende & Guidehouse 2021).

36 Consequently, electrolysers could be developed in areas with already abundant renewable energy generation, while additional renewable energy assets could be placed in areas with low renewable energy penetration where imports are affected by grid congestion. Such approaches would be particularly relevant for Germany.

37 For example, the average number of full-load hours in the scenario for a climate-neutral Germany by 2045 would amount to 1,800–1,900 hours between 2030 and 2045 (Prognos et al. 2021).

GWh electricity produced by 1 GW of renewable technology per year

Figure 19



Agora Energiewende based on AFRY Management Consulting (2021)

Note: The underlying box plots represent key statistics of average full-load hours, multiplied by 1 GW at the level of hexagons in Europe with an approximate size of 50,000km². They do not represent the total potential volume of renewable electricity that can be generated.

9

Hydrogen trade will be regional: shipping hydrogen is more expensive than pipes or cables

Global hydrogen markets and import/export opportunities have been much discussed in recent years. But hydrogen is tricky to store, and therefore tricky to transport. The available transport options fall into three groups: pipelines, cables or ships.

Retrofitted pipelines, where available, are the cheapest

Consuming hydrogen close to production with favourable renewables will always be the cheapest option since transport costs can be significant, as shown in Figure 20. However, if the hydrogen needs to be sent elsewhere – over 3,000 km, say, the theoretical route from Morocco to Northwest Europe – repurposed pipelines are the lowest-cost transport option for connecting hydrogen supply with import demand. Over long distances, ultra- and high-voltage DC cables start becoming competitive with newly built pipelines. Nonetheless, the competitiveness of local production improves over time because 2050 grids will have far more curtailed, zero-cost electricity.

Figure 20 also shows that when the end-use molecule is hydrogen, shipping from faraway lands such as Chile or Australia works out to be more expensive than if the hydrogen was produced locally in Germany, even with average renewables. Shipping is also roughly twice as expensive as importing hydrogen by pipeline or importing electricity via cable from Morocco for electrolysis in Northwest Europe.

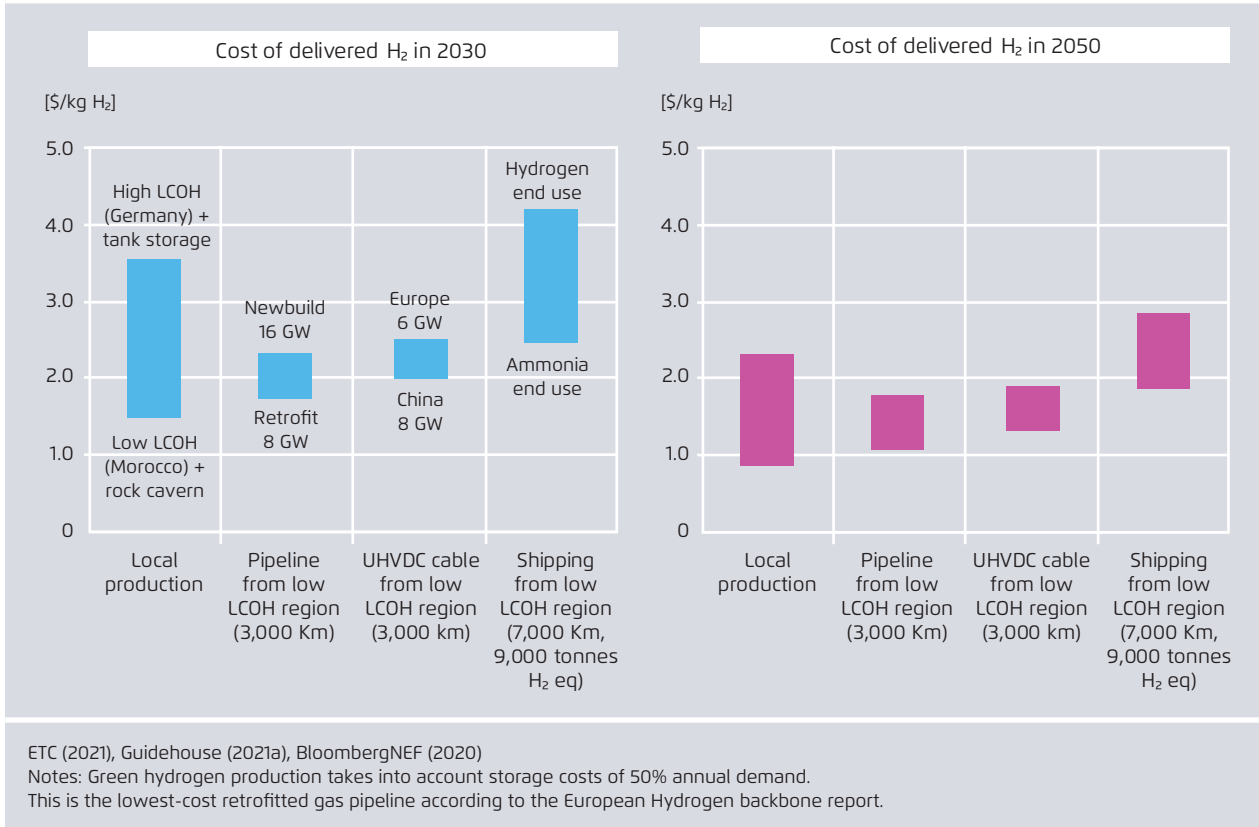
Ship-based trade lends itself better to hydrogen-based products or where pipelines are not feasible

However, instead of cracking shipped ammonia back to hydrogen, using ammonia directly as a fuel could be cheaper than the local production of hydrogen, even in 2050. This would require a new set of power plants instead of just a retrofit of existing assets. Moreover, in places where salt strata are available for mass hydrogen storage such as Europe or the US, the case for ammonia in electricity generation would become much weaker, because salt caverns store hydrogen markedly cheaper than ammonia. (See Figure 9.)

In practice, then, opportunities for ship-based hydrogen trade will be limited to instances where pipelines are not ready or unfeasible due to, say, public opposition or distance (as in Japan) or politics. Another opportunity for ship-based trade are markets where the final demand consists of energy-intensive hydrogen-based products, such as ammonia, methanol, and other high-value chemicals.

Economics of delivered hydrogen

Figure 20



10

Actively securing public acceptance is crucial for Europe to reach its full hydrogen potential

Based on the median hydrogen demand in European scenarios compatible with 1.5 degrees of global warming,³⁸ only the region comprising Germany, Netherlands and Belgium would have a technical deficit of regionally produced renewable hydrogen to meet their needs, as shown in Figure 21. As a whole, however, the EU27+UK have more technical production potential than estimated demand. One could conclude that with appropriate hydrogen transport infrastructure, the EU could become self-sufficient in terms of its hydrogen needs.

Reaching Europe's renewable hydrogen potential will require a significant ramp-up of renewable deployment

Technical potential does not guarantee that the appropriate production facilities will be built. There is always the risk that the practical supply will be far less due to factors such as the public or even local acceptance of large-scale infrastructure or land-use competition.³⁹

Meeting estimated hydrogen demand in the EU purely with wind and solar would require eight times as much electricity to be produced from these sources by 2050 than was produced in 2020. Over half of that electricity would be dedicated towards hydrogen production, as seen in the left-hand graph in Figure 22.

In terms of deployment rates, meeting EU's 2030 target of 10 megatonnes of renewable hydrogen would require doubling the historical rate of deployment of wind and solar achieved in 2010–2020, as seen in right-hand graph in Figure 22. The doubling

is driven by hydrogen demand. The next two decades would require doubling the rate of deployment again, with twice as much electricity flowing towards hydrogen production as towards direct electrification.

Given that already today we are seeing signs of local opposition to further renewable expansion in the EU, the challenge of ramping up deployment further is not to be ignored.

Increasing circularity can help, but on its own is unlikely to close the renewable supply gap entirely

One of the most materially efficient things that we can do to bridge the renewable supply gap is to increase circularity. Doing so would halve the 2050 hydrogen demand from steel, plastics and ammonia sectors as per Figure 23. This would translate into a reduction in renewable energy demand for hydrogen of around 10 percent by 2050. Though it is worth pursuing, circularity alone would be unlikely to close the renewable electricity supply gap should the EU fall short of ramping up renewable deployment by a factor of 4 by 2030.

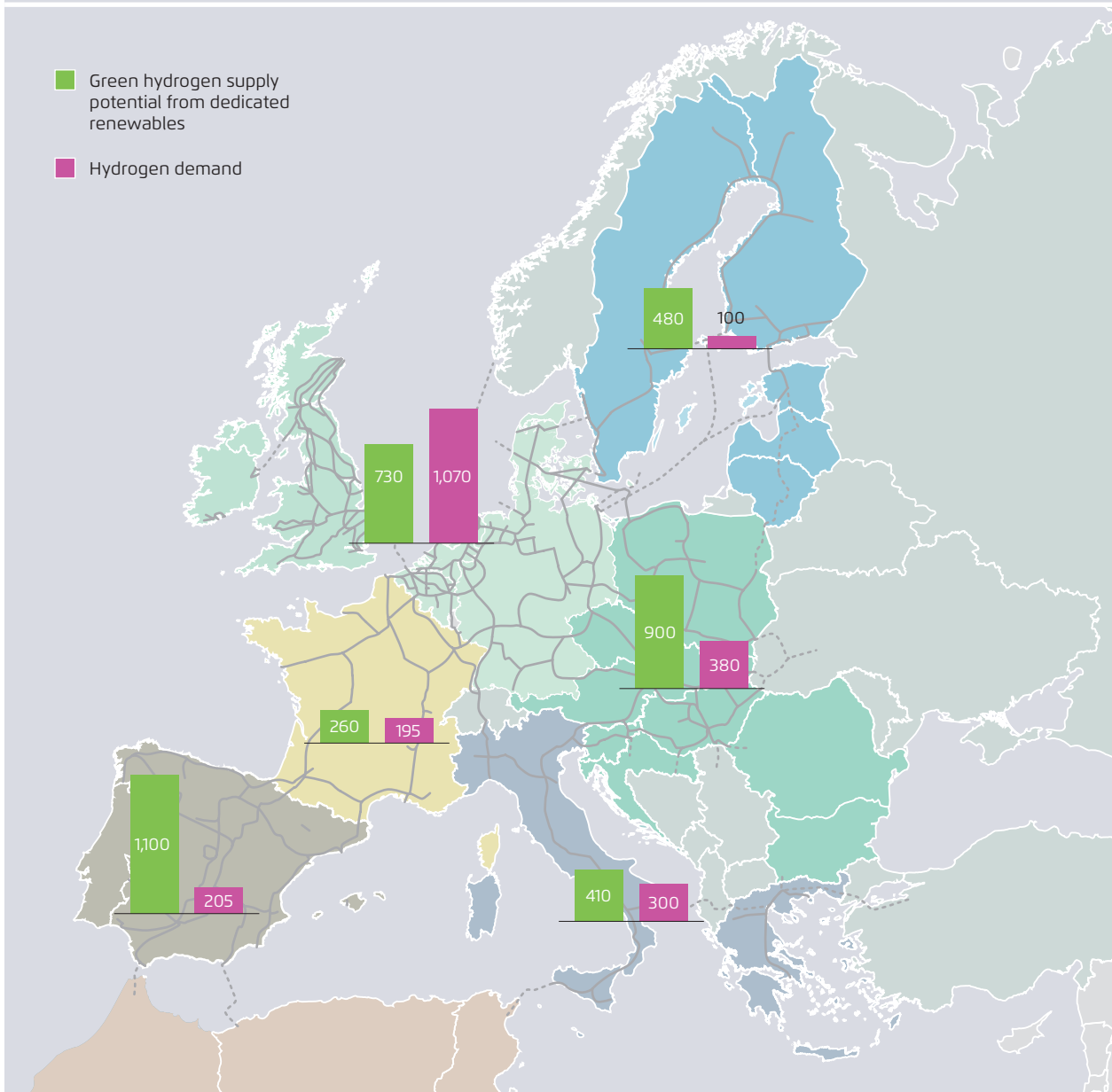
To fully hedge against the risk of insufficient domestic renewable deployment, together with increasing circularity, the EU has the option of importing clean hydrogen from abroad, or producing it from gas with carbon capture locally.

38 See Figure 5 from insight #1.

39 See page 4 of Fraunhofer IEE (2021).

EU hydrogen demand and supply potentials (TWh)

Figure 21

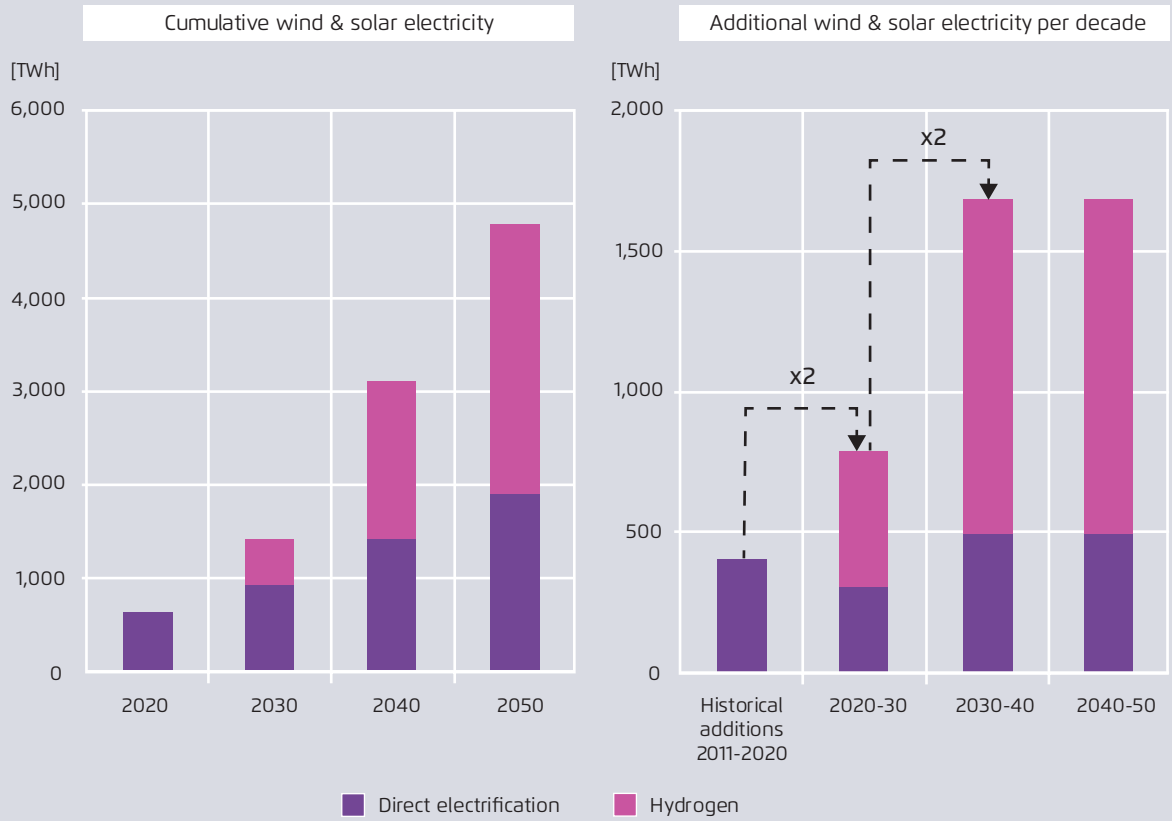


Guidehouse (2021a)

Note: EU countries and UK are grouped into 6 regions based on geographical and supply/demand characteristics: North Sea, Baltic Sea, Central & Eastern Europe, South East Europe, Portugal & Spain, and France.

Electricity requirements to meet European hydrogen demand projections and renewable supply gap

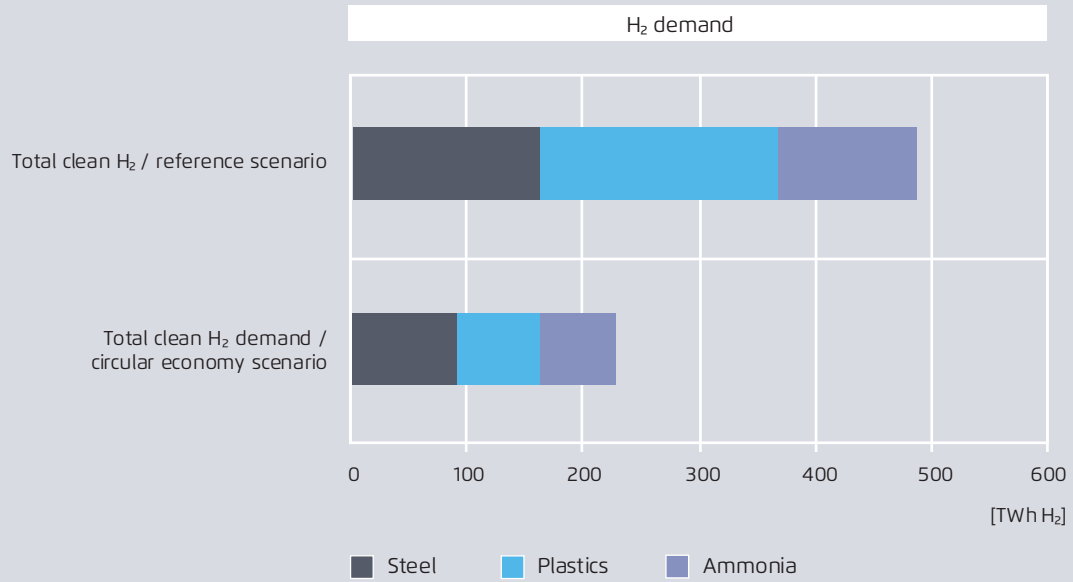
Figure 22



Guidehouse (2021a), COM (2020) and Agora Energiewende & Ember (2021)
 Note: Assumed electrolyser efficiency of 70% for 2020–2030 and 80% for period 2030–2050.

EU industrial potential for hydrogen savings through circularity

Figure 23



Agora Energiewende based on Material Economics (2018)

11

To keep its industry competitive, the EU should access cheap hydrogen from its neighbours while importing renewable hydrogen-based synthetic fuels from the global market

The issue of public acceptance is not the only reason why EU should look beyond its borders for sustainable hydrogen. Countries with better renewables than the EU will be able to produce cheaper hydrogen, creating opportunities for technology transfer, employment and export revenues. But the advantages of hydrogen imports must be weighed against the transport costs.

Hydrogen pipelines will keep European industry in business and ensure a firm power market

The current focus on – expensive – hydrogen imports from Chile, Australia or the Arab region, as outlined in insight 9, risks driving hydrogen-dependent industries out of Europe to countries with cheap hydrogen.

In order to keep European industry competitive globally and to ensure enough hydrogen to back up a renewable-led power system, the EU should look domestically and towards neighbours with whom pipeline links are feasible, and ideally already existing. Depending on the pace of progress on a pan-European hydrogen pipeline network, by 2030s the EU could be importing cheap renewable hydrogen from North Africa and from Ukraine, as seen in Figure 24. By 2050, North Africa, owing to its excellent solar potential, could be supplying just under half of EU's hydrogen demand at prices well below the European average – and at low transport costs due to pipelines. There is also space for Ukraine to supply similarly low-cost hydrogen to the EU. There are even more options in the Southeast provided new pipeline or cable infrastructures can be agreed upon.

The EU should foster international power-to-X markets for sustainable chemicals and for sustainable maritime and aviation fuels

Sustainable fuels for maritime transport and aviation are easy to transport but require a source of sustainable carbon to be climate neutral. In the future, direct air capture will be the source for sustainable carbon,⁴⁰ and it will be a highly energy-intensive process. Countries that have an advantage due to large quantities of cheap renewable resources, such as Argentina, Australia, Chile, the Arab region, Morocco and South Africa, will be the places to produce sustainable fuels for the world.

The same holds also for some chemicals, such as ammonia and methanol. Importing sustainable methanol or synthetic fuels from places with cheap renewables is more cost-effective than producing them in Germany, as shown in Figure 25. The European chemical industry will, therefore, need to devise a strategy to keep most of the high-value chemical production in Europe while at the same time tapping cheap sustainable basic chemical production in other world regions. It is urgent that this process starts soon.

40 Some countries also have significant biocarbon potential. For instance, one possibility for obtaining sustainable CO₂ is by capturing the gas generated in the process of the sugar and ethanol industry, a major sector in the Brazilian economy. A study conducted by Silva et al. (2018) maps the main distilleries in Brazil and calculates a yield of 15 Mt CO₂/year. Because the CO₂ from the process is pure, the cost of capture is quite low (around US\$ 11/t CO₂).

Marginal cost curves of hydrogen supply for Europe

Figure 24



Guidehouse (2021a)

Exports based on renewable hydrogen aren't the only game in town

Russia's recent hydrogen strategy⁴¹ leans heavily towards fossil-based hydrogen with carbon capture and storage (CCS), with a secondary role for nuclear-sourced hydrogen, and a minor role for renewable hydrogen with a single 'hydrogen cluster' until 2035. Norway and the UK also want to enter the European hydrogen market at the beginning of the ramp-up, primarily with fossil-based hydrogen with CCS.

41 See the Government of the Russian Federation (2021).

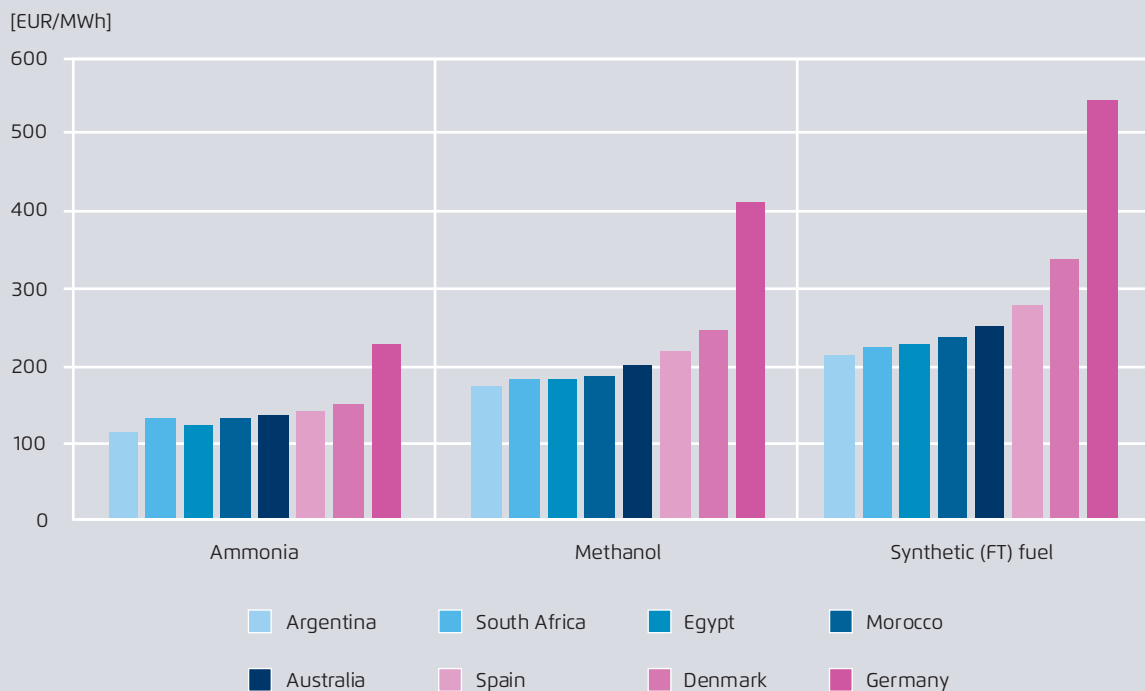
For all suppliers with existing pipeline links, Europe must send a signal that hydrogen imports will need to conform to EU sustainability norms,⁴² which they currently do not.⁴³ In parallel, the EU should start discussing potential imports of renewable sourced hydrogen. Any discussion on potential imports of nuclear sourced hydrogen could only follow after the EU has clarified its domestic approach to the issue of nuclear sourced hydrogen.

42 See insight #12 for detailed suggestions on sustainability criteria.

43 See Figure 26 from insight #12. When sending fossil gas over distances greater than 5,000 km, methane leakage alone could be enough to cross the sustainability threshold.

Cost of energy delivered through hydrogen-based products to Germany, 2030

Figure 25



J. Hampp et. al (2021)
 Note: 10% Weighted average cost of capital

12

We should remain open to the idea of (blue) hydrogen from processes involving carbon capture, but combine it with strict safeguards

Fossil-based hydrogen with carbon capture is not 100 percent carbon free – but it could play a role in a pathway to net-zero emissions

Figure 26 shows how different fossil-based hydrogen configurations with and without carbon capture stack up against each other and against renewable hydrogen in 2050. By 2050, emissions from renewable hydrogen fall to zero because the energy used to produce the hardware is assumed to be fully decarbonised. It's also worth noting that due to leakage from the transport and storage system, fossil-based hydrogen causes more emissions the further the fossil gas has to travel. A particularly bad case would result if methane travelled 5,000 km from extraction deep inside Russia to be reformed into hydrogen close to EU borders. Current gas exporters have an incentive to do so, as it would minimise the need for pipeline retrofits.

Blue hydrogen produced from fossil gas with carbon capture will not be part of a fully decarbonised energy system for two reasons. First, there will always be upstream emissions related to leakage from methane production and transport; and second, gas reforming technologies such as steam methane reforming (SMR) or autothermal reforming (ATR) cannot fully capture process CO₂ – leading industry sources put the maximum practical capture at 98 percent.⁴⁴ Thus, if blue hydrogen is to contribute to decarbonisation, a solid regulatory framework will be needed to ensure that the carbon capture and control of fugitive emissions improve significantly. This implies additional criteria on top of those set out under the Taxonomy on Sustainable Finance. Ideally, the new

⁴⁴ See Rechargenews (2021).

criteria will be included in the second Fit-for-55 package scheduled for December 2021.

Controlling methane leakage of hydrogen is critical

Due to its stronger global warming effect relative to CO₂, methane leakage has a proportionately greater influence on the final carbon footprint of CCS hydrogen. For instance, at a 1.5 percent leakage rate, considered the global average by the IEA today,⁴⁵ even a carbon capture rate of 98 percent, considered the world's best, would make the lifecycle footprint exceed the threshold defined in the European Commission's Sustainable Finance Taxonomy,⁴⁶ as illustrated by Figure 27. Assuming an even higher methane leakage rate of 3.5 percent, which was recently proposed by Robert Howarth and Mark Jacobson, makes fossil-based hydrogen with carbon capture around 20 percent less polluting than its unabated counterpart on the basis of a 20-year global warming potential (GWP 20) for methane.⁴⁷ Controlling methane leakage is therefore the most important aspect to get right in order to ensure that fossil-based hydrogen with carbon capture is consistent with net-zero emissions in 2050 criteria.

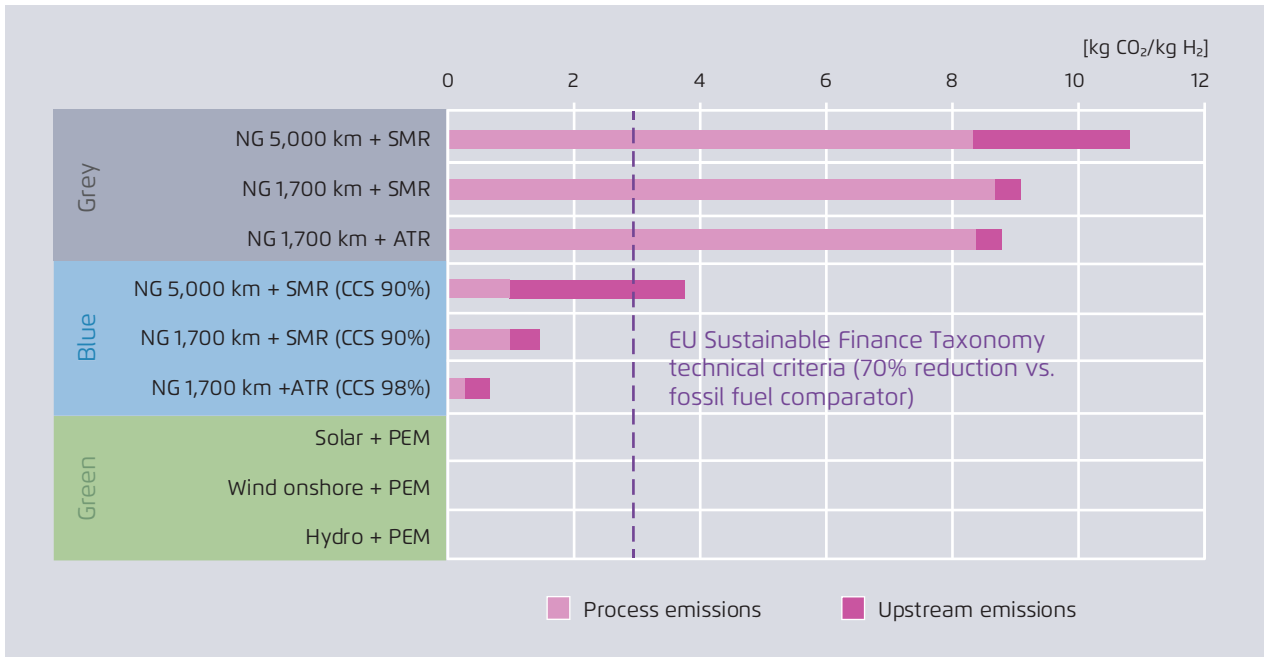
⁴⁵ See IEA (2021b).

⁴⁶ See COM (2021b).

⁴⁷ Note that the most commonly used GWP is GWP100. With GWP100, the GHG effect of fugitive methane emissions would become less than half of what it is under GWP20.

Lifecycle GHG emissions of hydrogen production pathways on a GWP 20 basis, 2050

Figure 26



ETC (2021), Hydrogen Council & LBST (2021), COM (2021a)

Note: The energy production includes upstream methane emissions and has leakage rates of 0.15–1.2% based on fossil gas source and transport distance. H₂ production refers to process emissions from SMR/ATR. GHG emissions for capex are due to carbon emissions associated with grid electricity used to manufacture equipment. Embedded emissions in renewables are assumed to be zero due to the complete decarbonisation of production process, including electricity, steel and concrete. NG = Fossil gas; ATR = Autothermal reforming; SMR = Steam methane reforming; PEM = Polymer electrolyte membrane electrolysis. A GHG emissions factor of 84 is used to reflect the global warming potential of methane over 20 years. OGCI = Oil and Gas Climate Initiative.

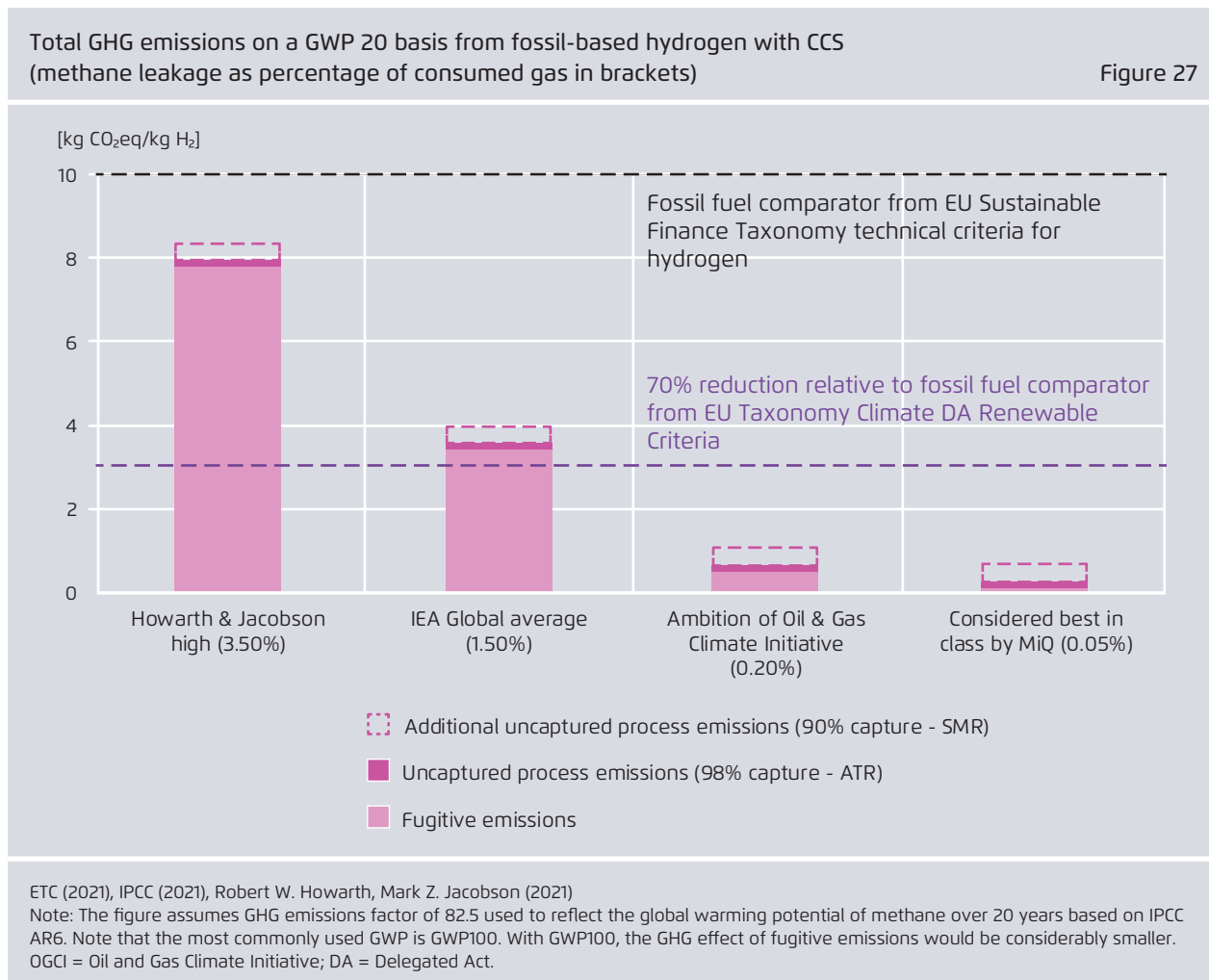
Gas-based hydrogen with carbon capture has co-benefits

Meeting the EU power sector’s ambitious 2030 targets while promoting the uptake of hydrogen in sectors that cannot otherwise be decarbonised represents a major challenge. Fossil gas-based hydrogen with carbon capture can provide some assistance at an environmental cost comparable to grid-connected electrolysis with a grid intensity of 100g CO₂/kWh, as shown in Figure 28⁴⁸.

Effectively, hydrogen from gas reforming with carbon capture can act as a sort of capacity reserve for the hydrogen market in times when variable renewable energy sources would not produce enough hydrogen. This is of strategic importance for the transformation of industrial processes such as the production of ammonia and DRI steel production. While these sites are an ideal anchor for the use of renewable hydrogen, their operation cannot be constrained by the limited availability of renewable electricity and low numbers of full-load hours for electrolyser operation.

Moreover, fossil-based hydrogen with carbon capture would necessarily lead to the creation of a carbon capture and storage infrastructure, which could be used to decarbonise other sectors, notably cement. The CCS infrastructure will also be needed

48 Effectively, the lifecycle assessments are sensitive to a number of inputs and can vary dramatically. There are also several other bio and waste based routes for producing hydrogen with varying carbon footprints. For more, see ICCT (2021)



for Direct Air Carbon Capture & Storage (DACCS) or Bioenergy Carbon Capture and Storage (BECCS), which will be crucial for attaining climate targets⁴⁹ and net-negative emissions, which according to the IPCC will be required to stay below 1.5 degrees. The benefits of BECCS can also be achieved by swapping fossil feedstock for biomethane because the carbon capture element turns it into negative emissions technology.

What's required from regulation

Because fossil-based hydrogen with carbon capture is not climate neutral, it needs strict regulation to keep emissions to an absolute minimum. An often unappreciated fact is that while some countries might reject blue hydrogen, not all will. What's the outcome when regulation is left to those with the least incentive to do so? That's why Europe must lead the stringent regulatory charge and lock in standards. Here is what is needed as part of the upcoming Fit-for-55 gas decarbonisation package in order to ensure that hydrogen production performance is compatible with a net-zero pathway and does not risk creating

49 On the role of negative emissions in a carbon-neutral Germany, see Prognos et al (2021).

additional emissions or veering too close to tipping points:

1. A definition of the requirements for increasing stringency to ensure that

- fugitive and upstream methane emissions do not exceed 0.20 percent for production within Europe and outside Europe as of 2025, in line with the target set by the Oil & Gas Climate initiative and with the goal of decreasing the threshold to 0.05 percent⁵⁰ in the long run; and that
- the carbon capture and storage process does not fall below 90 percent for retrofits of existing facilities, while any new/additional capacity captures a minimum of 98 percent of process CO₂ emissions as of 2025.

2. Transport and storage leakage must be minimised by locating CCS close to methane extraction, providing another strong argument against generalised blending and in favour of the full integration of industry demand projections and renewables production planning into energy infrastructure planning. Ideally, this should be introduced in the ongoing negotiations regarding the revised TEN-E regulations.

3. A monitoring and liability regime must be introduced for carbon storage. The regime should include strong standards on carbon storage sites, monitoring and verification of the carbon storage sites by independently accredited companies, no conflicts of interest for the monitoring and verification institutions (such as third-party funding), open-source data, and a liability regime that holds companies and countries accountable for carbon leakage, including the capture of any leaked carbon from the atmosphere.

50 This is today's lowest methane leakage rate according to MiQ's independent methane emissions certification. See MiQ (2021).

The alternative to verification by private companies is verification by the state.⁵¹ For instance, Norway, a pioneer in the field, will take on full responsibility for carbon reservoirs after a 10-year monitoring period.⁵² When reservoirs are tightly regulated and monitored, the risk of carbon leakage is very low. The peer-reviewed studies used by the Norwegian government for their Northern Lights carbon storage project estimate a 95 percent probability that the leakage from an offshore reservoir will be below 0.09 percent over a 100-year horizon.⁵³ Assuming a cost of 250 EUR/tCO₂ for DAC⁵⁴ after 2030, every kilogram of hydrogen produced would then impose an extra clean-up insurance cost of 0.2 cents/kg H₂. For regulated onshore storage with a leakage of 0.358 percent over 100 years, the clean-up insurance would add 0.80 cents/kg H₂.

The development of innovative strategies of carbon capture and use requires regulatory support, not subsidies

According to Figure 2, fossil-based hydrogen with carbon capture becomes competitive with unabated hydrogen when the carbon price enters the range of 50–100 EUR/tCO₂. Given recent carbon prices in Europe of 60 EUR/tCO₂, with expectations of 100 EUR/tCO₂ by the end of decade, direct subsidies for fossil hydrogen with carbon capture are unnecessary.

While the carbon capture and storage of carbon in geological storage sites has already reached the demo stage and is in the process of being upscaled for

51 Clearly, the state also has a major role to play in CCS infrastructure development, including storage, which is why carbon transport and storage should also be included in the TEN-E regulation. See Agora Energiewende (2021).

52 Norwegian Ministry of Petroleum and Energy (2020), chapter 4.3

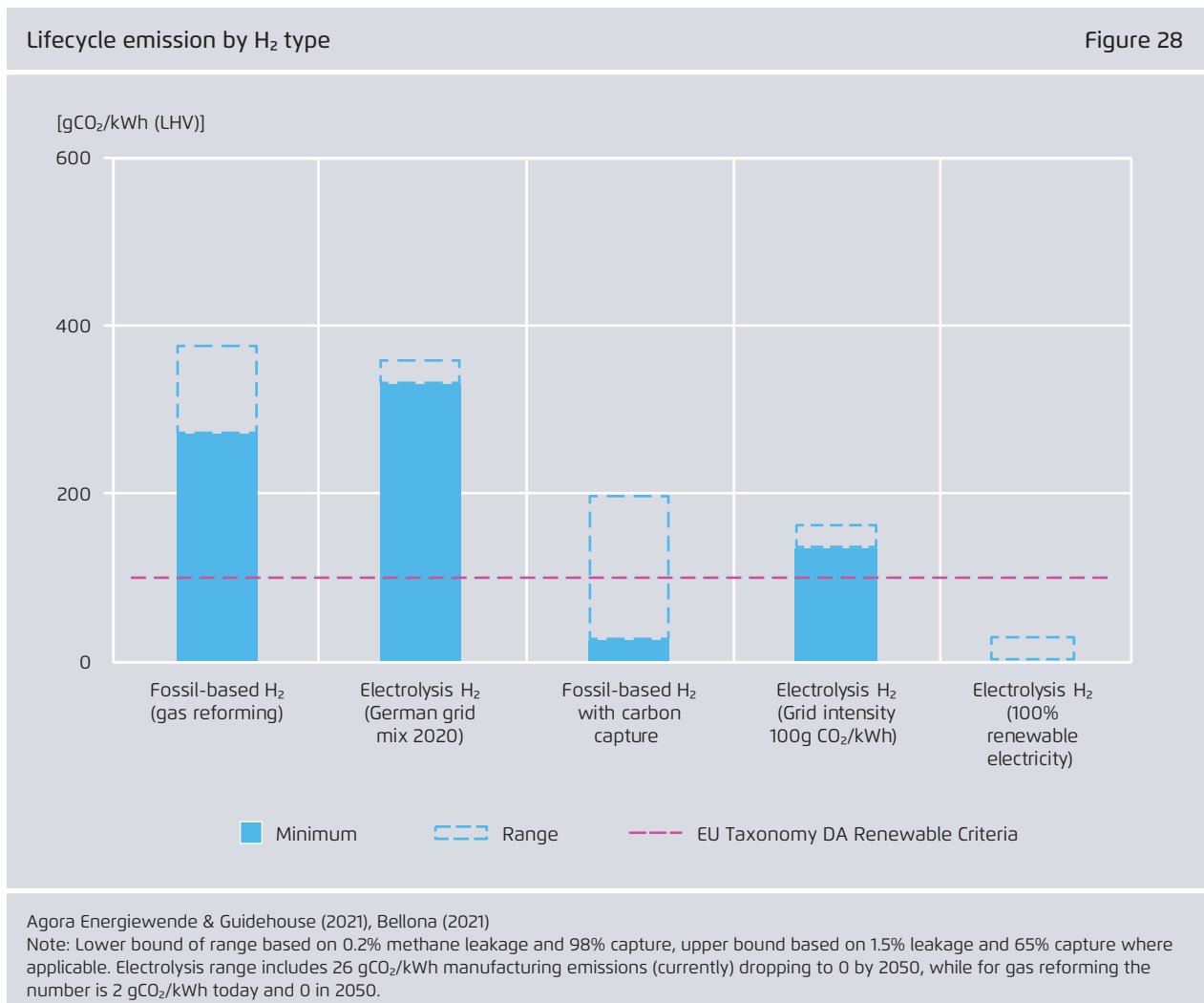
53 See J. Alcade et al (2018).

54 See Prognos et. Al (2021).

commercial use, there are other promising CCS strategies that still require support for their applied development. Some examples include the pyrolysis of fossil gas and biomethane as a pathway to produce hydrogen and elementary carbon, and the mineralisation of cement and concrete or other fossil and synthetic minerals. Moreover, there is a broad set of strategies that use carbon or CO₂ as feedstock (Carbon Capture and Use/ CCU) to produce chemical products with long lifetimes that may have great potential as long-term carbon sinks.

The EU Commission's proposal for a revision of the ETS Directive⁵⁵ has acknowledged the importance of these strategies by establishing that no ETS surrender obligations will be made for CO₂ emissions that are “permanently chemically bound in a product so that they do not enter the atmosphere under normal use”. The Commission should be empowered to adopt acts specifying the conditions under which greenhouse gases meet these criteria and when a carbon removal certificate may be obtained in view of the current regulations.

55 See COM (2021b).



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