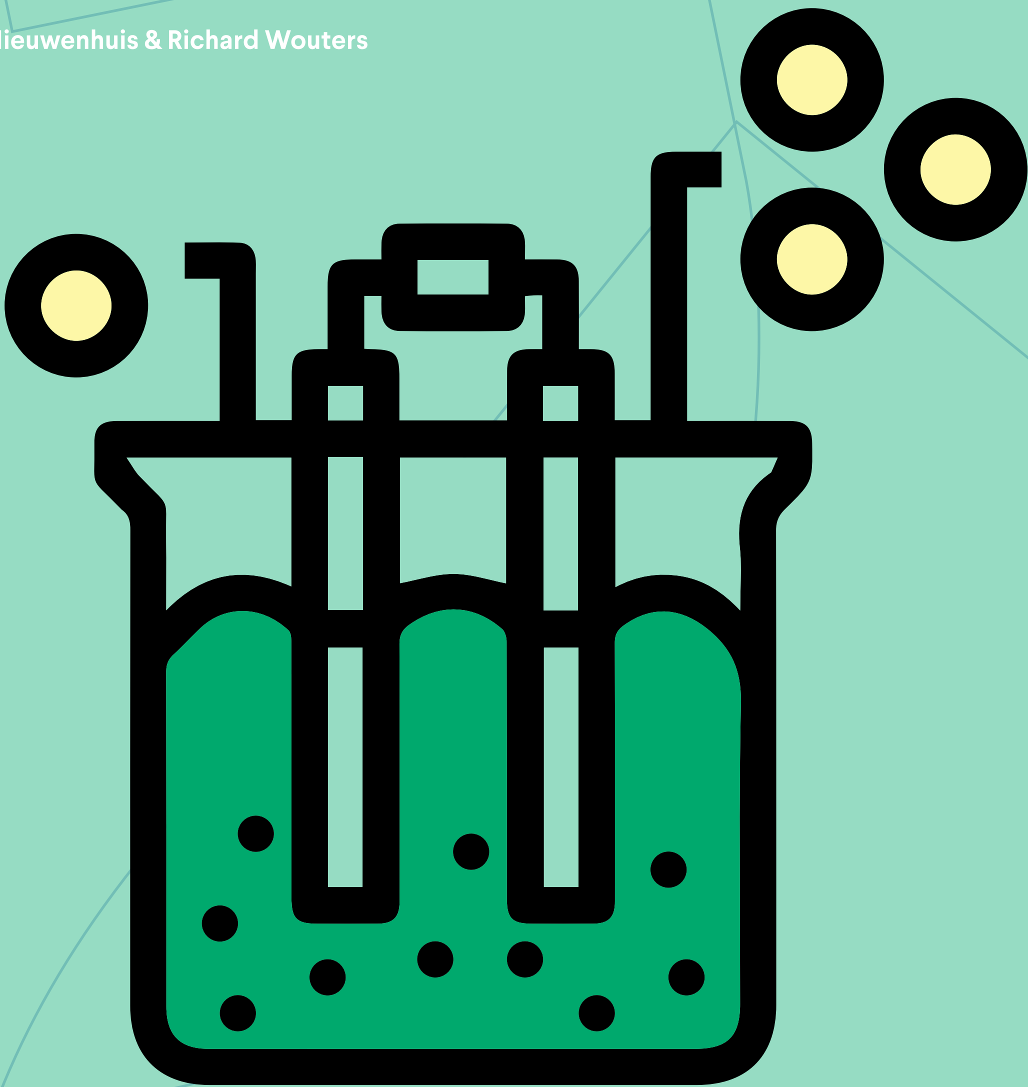
Greening Hydrogen
Big issues around a small molecule

Evert Nieuwenhuis & Richard Wouters



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Greening Hydrogen: Big issues around a small molecule

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GREEN EUROPEAN FOUNDATION

The **Green European Foundation** (GEF) is a European-level political foundation whose mission is to contribute to a lively European sphere of debate and to foster greater involvement by citizens in European politics. GEF strives to mainstream discussions on European policies and politics both within and beyond the Green political family. The foundation acts as a laboratory for new ideas and offers cross-border political education and a platform for cooperation and exchange at the European level.

WETENSCHAPPELIJK BUREAU GROENLINKS
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Wetenschappelijk Bureau GroenLinks (WBGL) is an independent think tank affiliated with GroenLinks, the Dutch Green party. WBGL works to deepen and expand progressive and green thinking. Ecological challenges, inequality, and human rights violations require green, social, and progressive answers. WBGL operates at the intersection of science, society, and policy to develop long-term solutions to these issues.

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Introduction

Europe is heading towards the Green Age, an era defined by climate neutrality and the circular economy. There is broad agreement on the need for this transition, reflected by the global Paris Agreement and the European Green Deal. But in order to bring in this new age, green policies must be rapidly introduced. Further delay could prove perilous. Governments must therefore firmly take the helm and steer our societies towards a swift and far-reaching transition. For industry to become climate-neutral and circular, a green industrial policy is essential.[1] Green hydrogen is a key element of such a policy.

The Green Age will herald the end of oil, natural gas, and coal. Green hydrogen can play a crucial role in the transition away from these fossil fuels.[2] It is produced emission-free using renewable electricity. It can be used as both an energy carrier and a feedstock, replacing fossil inputs. When used for energy, in a fuel cell or a burner, it releases no CO_2. Water is its only or main by-product. Hydrogen can also be used as a buffer in a green energy system: renewable energy can be converted into hydrogen during high-production periods and then converted back into electricity at times when renewable electricity production falls short. Furthermore, given its ability to function as both an energy carrier and feedstock, hydrogen opens up the possibility of exchange between these applications. This allows the integration of the energy and materials systems, thus strengthening their resilience and flexibility.[3] Green hydrogen can drive forward the energy and circular transitions that will lead us into the Green Age.

But green hydrogen also has its drawbacks. First and foremost, its production, through electrolysis using renewable electricity, is extremely energy-intensive. In order to meet the European Commission's 10-million-tonne hydrogen target for 2030, nearly 500 terawatt-hours of renewable electricity will be needed. This roughly equals the total electricity consumption of Germany (558 terawatt-hours) or France (474 terawatt-hours) in 2019. In other words, in approximately eight years' time we will have to be capable of producing an additional quantity of renewable electricity that is comparable to the total current electricity use of the largest member states of the European Union.[4] This will be a mammoth and difficult task requiring vast swathes of land for wind turbines, solar panels, and other renewable energy installations, as well as large quantities of scarce minerals. The high electricity input of green hydrogen production is partly due to the fact that large amounts of energy are lost during the conversion of electricity into hydrogen. This is also the case when using hydrogen to generate electricity. Whereas the overall energy efficiency ("well to wheel") of electric cars is about 77 per cent, the figure for hydrogen-powered cars is only 33 per cent.[5] In short, green hydrogen is effective, versatile, and can be produced sustainably. However, it is also expensive to produce, energy inefficient, and in short supply: electrolysis currently accounts for less than 1 per cent of hydrogen production in the EU.

Hydrogen is firmly in the spotlight today. Governments and industry are launching plans for its production, use, and transportation.[6] This focus on hydrogen could be good news for the planet, but it doesn't mean that we can simply sit back and expect that it will automatically bring the Green Age closer. Fossil energy companies are among those interested in producing and selling (more) hydrogen, but their offer explicitly includes hydrogen from fossil fuels. While hydrogen in any form can be seen as helpful in creating a hydrogen market and accelerating its uptake, such investments could serve to lock us into the fossil age and thus hamper the fight against extreme climate disruption.

1 Wetenschappelijk Bureau GroenLinks, *Groene industriepolitiek – Bouwen aan de Groene Eeuw*, 2021 www.wbgl.nl/gip and Green European Foundation, *Blockers and Enablers for Decarbonising the Dutch Chemistry, Refinery and Basic Metals Industries*, 2020. https://gef.eu/publication/blockers-and-enablers-for-decarbonising-the-dutch-chemistry-refinery-and-basic-metals-industries/

2 Raad voor de Leefomgeving en infrastructuur, *Waterstof, de ontbrekende schakel,* 2021. https://www.rli.nl/publicaties/2021/advies/waterstof-de-ontbrekende-schakel

3 Natuur & Milieu, *Waterstofverkenning*, 2020.

4 Keith Whiriskey & Marta Lovisolo, 'Additionality: the key to turn the hydrogen buzz into a renewable boom', *euractiv.com,* 14 October 2021. https://www.euractiv.com/section/energy/opinion/additionality-the-key-to-turn-the-hydrogen-buzz-into-a-renewable-boom/

5 Transport & Environment, *Electrofuels? Yes, we can ... if we're efficient. Decarbonising the EU's transport sector with renewable electricity and electrofuels*, 2020, p. 29. https://www.transportenvironment.org/discover/electrofuels-yes-we-can-if-were-efficient/

6 For instance, more than 750 industrial projects have signed up to the European Clean Hydrogen Alliance. European Commission, 'Hydrogen: Europe's Industry rolling out hydrogen projects on massive scale', *ec.europa.eu*, 30 November 2021. https://ec.europa.eu/info/news/hydrogen-europes-industry-rolling-out-hydrogen-projects-massive-scale-2021-nov-30_en

The introduction of hydrogen to our energy and materials systems clearly raises a number of pressing questions that are of relevance to the work of Green parties in Europe. This report aims to give a brief overview of the most controversial issues surrounding hydrogen from a green perspective in order to facilitate debate on this matter.

In chapter 1 we discuss the properties, availability, and production of hydrogen and the role it could play in the energy transition. Chapter 2 gives an overview of the challenges to be overcome if we wish to move to the large-scale production and use of green hydrogen. Chapters 3, 4 and 5 present three responses to the current shortage of green hydrogen and examine their relative advantages and disadvantages.

The first is **blue hydrogen**, derived from the methane in natural gas. While carbon dioxide is a by-product of the production process, most of this is captured and stored underground, for example under the North Sea. Blue hydrogen could play a useful role within a transition phase, but how do we avoid a lock-in that slows down the emergence of green hydrogen?

The second response, the **hydrogen ladder**, allows us to determine which green hydrogen applications should have priority under a shortage scenario. Applications for which there are sustainable alternatives are lower down the hydrogen ladder.

The third response is to **import hydrogen** from solar- or wind-rich countries outside the EU, where production is more efficient and cheaper. This offers both opportunities and threats. How do we ensure that the people in these countries (including Namibia, Chile, and Saudi Arabia) actually benefit from the hydrogen trade? And how do we mitigate the geopolitical risks of reliance on hydrogen imports, as experienced with oil and natural gas?

The report concludes with a chapter presenting our political recommendations.

1. Hydrogen and the green transition

Hydrogen (H) is the smallest and lightest element on Earth. It is a colourless, odourless, tasteless, non-toxic gas made up of molecules consisting of a pair of identical atoms (H_2). It is highly flammable, lighter than air, and only becomes liquid at a temperature of minus 253 degrees Celsius. Hydrogen is the most abundant element in the universe: more than 90 per cent of the atoms in the universe are hydrogen atoms.[7] It is also common on Earth, with around two thirds of all molecules containing one or more hydrogen atoms, including water (H_2O) and methane (CH_4).

While there is technically no scarcity of hydrogen on Earth, it hardly ever occurs in its isolated form (H_2). However, it is in precisely this form that hydrogen can play a role in the energy transition. Whoever wants to use hydrogen must therefore produce it. There are a variety of production methods.[8] Of primary interest to this report is electrolysis, which uses electricity to split water into hydrogen and oxygen. If that electricity is generated using renewable sources, the hydrogen produced is considered to be "green". Neither its production nor its use – via a burner or a fuel cell, the two ways of extracting energy from hydrogen – emits CO_2. Note that hydrogen is not an energy source (like coal or oil), but an energy carrier: it takes energy to make hydrogen and when it is oxidised, energy is released. Hydrogen is also used as a feedstock in several industrial processes. The demand for this application will rise as industry decarbonises. The fact that hydrogen is both an energy carrier and a feedstock that can be used without emitting CO_2 makes it indispensable to building the Green Age.

Uses of hydrogen, now and in the future

As previously stated, hydrogen plays three important roles in our current and future economy: as an energy carrier, a feedstock, and a buffer within the energy system. These diverse functions allow it to act as a connector between the energy and materials systems: the possibility to convert electrons into molecules and vice versa provides flexibility and security of supply. The table below lists the different applications of hydrogen by sector[9] and is followed by further details on these applications.[10]

Economic sector	Hydrogen application opportunities
Industrial sector	High-temperature heat Feedstock for materials
Energy sector	Flexible energy storage and transportation
Transport and mobility sector	Fuel for means of transport
Built environment sector	Heating Hot water

High-temperature heat: The burning of hydrogen allows the chemicals and steel industries, for example, to generate the high-temperature heat required for manufacturing processes without releasing CO_2.

Feedstock for materials: Hydrogen, in combination with other raw materials, is used in the manufacturing processes of a variety of products, including fertilisers, steel, plastics, and fossil transport fuels. It is also an ingredient of synthetic fuels for shipping and aviation that might replace conventional fuels.

Flexible storage and transportation of energy: Hydrogen can be used in the electricity system to store (large) surpluses of electricity, accommodate peak demand and long-term shortages, and transport energy over long distances.

Fuel for means of transport: In the transport and mobility sector, hydrogen is an alternative to CO_2-emitting fuels such as petrol, diesel, and kerosene. For example, heavy goods vehicles can be equipped with fuel cells that (re)convert hydrogen into electricity to power the motor. In addition, both ammonia and synthetic fuels can be produced using hydrogen.[11] The first is the most promising option for shipping over longer distances, the latter for long-distance air travel.

Heating and hot water in the built environment sector: Hydrogen can be used to power central heating systems and to heat tap water, primarily as a replacement for natural gas.

If we wish to ensure a quick and equitable energy transition while also taking long-term considerations into account, not all of these applications are equally desirable. For example, hydrogen is not the most efficient option for

7 N.N., 'Hydrogen', wikipedia.org. https://en.wikipedia.org/wiki/Hydrogen

8 See "The production of hydrogen" below for a brief overview.

9 Raad voor de Leefomgeving en Infrastructuur, *Waterstof: de ontbrekende schakel*, 2021, p. 23. https://www.rli.nl/publicaties/2021/advies/waterstof-de-ontbrekende-schakel

10 This overview is an adaptation of Raad voor de Leefomgeving en Infrastructuur, *Waterstof: de ontbrekende schakel*, 2021, pp. 29-30. https://www.rli.nl/publicaties/2021/advies/waterstof-de-ontbrekende-schakel

11 See "Feedstock for materials" above.

heating houses or powering cars. We will look at this in more detail in chapter 4 on the hydrogen ladder.

The production of hydrogen

As mentioned previously, hydrogen is rarely found in its pure form on Earth. This is because hydrogen molecules quickly and easily bond with other molecules in the atmosphere, such as oxygen (the atom O, which creates H_2O, or water) or carbon (the atom C, which creates CH_4, methane). Pure hydrogen must therefore be chemically produced by separating it from other atoms such as oxygen and carbon. This process requires energy.

There are a range of ways to produce hydrogen, which are often ascribed colours. The most important of these are the following:[12]

Grey hydrogen: Fossil fuels such as natural gas or coal are decomposed into carbon and hydrogen by means of a chemical process. This requires fossil fuels, and releases CO_2 into the atmosphere, thus contributing to global warming. Around 95 per cent of the hydrogen produced in the world today is grey.

Blue hydrogen: Uses the same production process as grey hydrogen, but most of the CO_2 is captured and stored, for example in depleted gas and oil fields.

Green hydrogen: Through electrolysis, pure water (H_2O) is split into pure hydrogen (H_2) and pure oxygen (O_2). No CO_2 is released in this process. Electrolysis requires electricity, and if this is from renewable sources which also produce no CO_2, the resulting hydrogen is considered to be "green". Hydrogen produced via electrolysis has a higher degree of purity than grey and blue hydrogen; it can be used immediately in fuel cells.

Purple hydrogen: Nuclear reactors provide energy and heat that is used for electrolysis or chemical decomposition, with hydrogen as the product.[13]

Turquoise hydrogen: Produced from natural gas using "methane pyrolysis", also known as methane cracking. Under this process, the methane in the natural gas is converted into hydrogen and solid carbon through oxygen-free heating. The solid carbon can be stored to prevent it from entering the atmosphere.

Transportation and storage of hydrogen

Hydrogen can be transported in various ways.[14] For small volumes (e.g. 50 litres), transportation in cylinders as a compressed gas is the logical choice. Slightly larger volumes (up to 1 tonne) can be liquefied by cooling the gas to below minus 253 degrees Celsius and transported in specially designed cryogenic tankers.

For higher volumes, pipelines are the most obvious option. There are already 1,500 kilometres of hydrogen pipelines in the EU, predominantly in countries with heavy industrial hydrogen use, such as the Netherlands, Belgium and Germany. Hydrogen can also be transported using natural gas infrastructure, on the condition that certain modifications are made.[15] A consortium of 23 European gas infrastructure companies is developing plans for a European hydrogen pipeline network. By 2040, 39,700 kilometres of hydrogen pipelines should be in place, including connections to North Africa.[16]

If there are no pipes, long-distance transport of hydrogen can be done by ship. Liquefaction is one way of increasing the energy density of the compressed gas and thus the economic attractiveness of transporting it. Another is to temporarily bind hydrogen to other molecules, physically or chemically, in order to reduce its volume. For example, hydrogen can be converted into ammonia (NH_3), using nitrogen (N_2) from the air. Both liquefaction and conversion are energy-intensive and expensive.

Hydrogen can also be stored in several ways.[17] One way is to liquefy it, as for transportation. It may also be possible to store sizeable quantities of hydrogen in depleted natural gas fields, although extensive research still needs to be done before it is certain that this is safe. Storage in salt caverns is possible too; this is already in operation in the United States and the United Kingdom.

12 This overview is based on *The World of Hydrogen*. https://www.theworldofhydrogen.com/

13 Nuclear-produced hydrogen can also be referred to as pink or red hydrogen.

14 This paragraph is partly based on *The World of Hydrogen*. https://www.theworldofhydrogen.com/gasunie/infrastructure/

15 DNV GL, *Verkenning waterstofinfrastructuur*, 2017. https://www.topsectorenergie.nl/sites/default/files/uploads/TKI%20Gas/publicaties/DNVGL%20rapport%20verkenning%20waterstofinfrastructuur_rev2.pdf?UA-142619432-2

16 Guidehouse, Enagás, Energinet, Fluxys Belgium, Gasunie, GRTgaz, Net4GAS, OGE, ONTRAS, Snam, Swedegas & Teréga, *European Hydrogen Backbone*, 2020. https://gasforclimate2050.eu/ehb/

17 *The World of Hydrogen*. https://www.theworldofhydrogen.com/

2. Challenges of green hydrogen

Whereas the energy from sun and wind is nearly infinite, hydrogen produced from these renewable sources is not. As detailed in the introduction to this report, the production of green hydrogen uses large amounts of renewable electricity. This in turn requires wind turbines, solar panels, and other renewable power installations. Lots of them. To get an idea of what it would take to move to a green hydrogen economy, we can look to the European Commission's hydrogen strategy. Its intermediate production target of 10 million tonnes of green hydrogen by 2030 slightly exceeds the EU's current grey hydrogen production.[18] This would require an additional renewable electricity input almost equal to the bloc's total wind and solar power in 2020.[19]

The main reason for the high energy demand of green hydrogen production is the need to match the huge quantities of energy condensed in the fossil fuels that green hydrogen is planned to replace. But it also stems from the low conversion rate of electrolysers: at their current stage of development, around 30 per cent of the total energy is lost in the conversion of electrons into molecules. The lost energy takes the form of residual heat. It depends on the location of the electrolysers whether this heat can find a useful application, for instance in district heating networks.

As increasing numbers of EU member states publish their own hydrogen strategies, including targets and support measures for boosting electrolyser capacity, the goal of 10 million tonnes of green hydrogen by 2030 seems attainable. Nonetheless, scaling up both green hydrogen production and renewable electricity poses considerable challenges in various areas including land use, materials, infrastructure, safety, and costs. Matching green hydrogen production with a sufficient renewable energy supply is a particularly thorny issue.

Need for space

While renewable electricity generation is currently experiencing rapid growth and needs to grow even faster, it will never be infinite, if only because it takes up space. Solar and wind energy is more dispersed than the energy in fossil fuels, and needs to be harvested over a large area. It was not for nothing that Germany's new governing coalition, which took office at the end of 2021, has reserved 2 per cent of the country's land surface for wind turbines.[20] Plans for new wind and solar farms, as well as high-voltage power lines, often lead to conflicts over their impact on the landscape, biodiversity, or the health of nearby residents. Wind farms at sea spark protests from the fishing industry, among others.

Need for materials

Renewable energy infrastructure, including wind turbines, solar panels, and power lines, requires materials – especially metals. The energy transition implies a shift from a fossil-based to a metals-based energy system. The growth of renewables is pushing up demand for iron, aluminium, copper, zinc, chromium, manganese, and rare earths, to name only a few.[21] However, metal ores are finite resources. For some ores, such as copper, depletion is on the horizon. Whereas in the late 19th century the average ore grade of copper was between 10 and 20 per cent, it has since dropped to 0.5 per cent.[22] If the ore grade continues to drop, there will come a time when copper extraction will require too much energy, water, materials, or land, or will cause unacceptable damage to nature and the environment. Metals mining is already responsible for significant biodiversity loss, waste, and pollution, especially in the Global South. On top of this, human rights violations are rife in the mining sector. The EU is strongly reliant on imports for most of the metals it uses. This creates supply risks that may slow down the energy transition, especially if we don't get better at

18 European Commission, *A hydrogen strategy for a climate-neutral Europe*, 2020, p. 6. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301

19 Assuming a conversion efficiency of 70 per cent, 10 million tonnes of green hydrogen would require 476 terawatt-hours of electricity. EU solar and wind produced 540 terawatt-hours in 2020.

20 SPD, Bündnis 90/Die Grünen & FDP, *Mehr Fortschritt wagen. Bündnis für Freiheit, Gerechtigkeit und Nachhaltigkeit*, 24 November 2021, p. 57. https://www.gruene.de/artikel/koalitionsvertrag-mehr-fortschritt-wagen

21 International Energy Agency, *The role of critical minerals in clean energy transitions*, 2021, p. 5. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

22 Theo Henckens & Ernst Worrell, 'Reviewing the availability of copper and nickel for future generations. The balance between production growth, sustainability and recycling rates', *Journal of Cleaner Production* 264, 2020. https://doi.org/10.1016/j.jclepro.2020.121460

recycling metals and sourcing the virgin metals that we really need in a responsible way.[23]

With green hydrogen comes an additional demand for metals for use in applications including electrolysers, fuel cells and hydrogen pipelines. Among those needed for electrolysers are nickel, zirconium, and platinum group metals.[24] Within the platinum group, iridium in particular stands out. It is one of the rarest metals, with only around 7 tonnes mined each year, mostly in South Africa. Yet it is indispensable for the catalytic reaction that splits water into hydrogen and oxygen in the type of electrolyser that is most able to deal with a fluctuating supply of renewable electricity.[25] If this becomes the dominant form of electrolysis, the EU might need more iridium for its 2030 hydrogen target than is currently being extracted globally.[26] The material efficiency of electrolysers is expected to increase in the coming years, meaning that smaller quantities of rare metals will be needed to achieve the same capacity. Still, iridium scarcity may well become a bottleneck for green hydrogen production.

In addition to metals, the production of green hydrogen via electrolysis requires demineralised fresh water. Nine litres of water are needed to produce 1 kilogramme of hydrogen.[27] In solar-rich regions that are well suited to hydrogen production, fresh water is often scarce. It will become even scarcer due to the effects of climate change. Under these conditions, green hydrogen producers would do well to establish themselves in places where they can use seawater. The desalination process increases the electricity demand of green hydrogen, but only by about 0.1 per cent.[28] The waste product of desalination, brine, needs to be treated responsibly – preferably by converting it into useful chemicals.

Need for infrastructure

Forecasts of how much green hydrogen the EU will ultimately need vary widely. Some scenarios suggest that the 10 million tonnes the European Commission wants to see produced by 2030 will be enough to satisfy EU demand.[29] Others foresee demand rising much further, up to almost 70 million tonnes by 2050.[30]

This lack of consensus makes it difficult for governments and private operators to plan the infrastructure needed for the green hydrogen transition. Where should new hydrogen pipelines be installed on top of the 1500 kilometres that are already in place? And where should the storage facilities that balance supply and demand be located? Which parts of the power grid need to be reinforced, to get enough electricity to the electrolysers? This uncertainty extends to possible locations for green hydrogen production. Electrolysers can be installed on land, but also integrated into offshore wind turbines or farms. Furthermore, green hydrogen can be produced domestically or imported from abroad. Other unknowns include the likely location of large consumers – although some industries on the route to decarbonisation have no other option than green hydrogen – and the form in which hydrogen will be transported over large distances. Since gaseous hydrogen has a large volume, sea transport will probably require liquefaction or conversion into ammonia.[31] Would pipelines for ammonia be needed for onward transport?

The roll-out of infrastructure for a green hydrogen transition must nevertheless begin early. Creating the infrastructural conditions for defossilisation is an indispensable element of a green industrial policy.[32] If governments wait for certainty or leave it to the private sector, they risk a repeat of the power grid congestion drama. In several

23 Green European Foundation, *Metals for a Green and Digital Europe*, 2021, section 1 & 2. https://gef.eu/publication/metals-for-a-green-and-digital-europe-an-agenda-for-action/

24 International Energy Agency, *The Role of Critical Minerals in Clean Energy Transitions*, 2021, pp. 111-113. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

25 Polymer electrolyte membrane (PEM) electrolyser, also known as proton-exchange membrane electrolyser. See Sachverständigenrat für Umweltfragen, *Wasserstoff im Klimaschutz: Klasse statt Masse*, 2021, p. 18. https://www.umweltrat.de/SharedDocs/Downloads/DE/04_Stellungnahmen/2020_2024/2021_06_stellungnahme_wasserstoff_im_klimaschutz.html

26 This calculation is based on data provided by the International Renewable Energy Agency. IRENA, *Green hydrogen cost reduction. Scaling up electrolysers to meet the 1.5 °C climate goal*, 2020, p. 68. https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction

27 With 8 kilogrammes of oxygen as a by-product.

28 Transport & Environment, *Electrofuels? Yes, we can … if we're efficient. Decarbonising the EU's transport sector with renewable electricity and electrofuels*, 2020, p. 26. https://www.transportenvironment.org/discover/electrofuels-yes-we-can-if-were-efficient/

29 See the overview of projections in Bellona, *Cannibalising the Energiewende? 27 Shades of Green Hydrogen*, 2021, p. 5. https://bellona.org/publication/will-hydrogen-cannibalise-the-energiewende

30 Fuel Cells and Hydrogen Joint Undertaking, *Hydrogen roadmap Europe. A sustainable pathway for the European energy transition*, pp. 49-50. https://www.fch.europa.eu/news/hydrogen-roadmap-europe-sustainable-pathway-european-energy-transition

31 See chapter 1.

32 Green European Foundation, *Blockers and enablers for decarbonising the Dutch chemistry, refinery and basic metals industries*, 2020, p. 16. https://gef.eu/publication/blockers-and-enablers-for-decarbonising-the-dutch-chemistry-refinery-and-basic-metals-industries/

EU countries, insufficient grid capacity has caused delays in the construction and connection of much-needed renewable energy installations. Governments would do well to start with the hydrogen infrastructure that they are least likely to regret building, connecting probable electrolyser sites with clusters of industries that have no alternatives to green hydrogen. In many cases, existing natural gas pipelines can be retrofitted to transport hydrogen, thus lowering costs.[33] Blending natural gas with hydrogen in pipelines should be avoided. After separation, the hydrogen would not be pure enough for use in fuel cells. If no separation takes place, meaning that end users receive a mix of natural gas and hydrogen, it becomes almost impossible to set priorities for the use of green hydrogen.[34]

Safety standards

Hydrogen is a highly flammable gas. It has a lower ignition temperature than natural gas and burns faster, with a poorly visible flame. Like natural gas, hydrogen is odourless. As it is 14 times lighter than air, hydrogen will rise and disperse swiftly when released, which is a safety advantage in the open air but a risk in enclosed spaces.[35] The expansion of hydrogen production, transport, storage, and use beyond current industrial settings would therefore require new safety standards (including the addition of an odorant) as well as monitoring and verification systems, lest the reputation of green hydrogen be tarnished by accidents. The European Commission recognises that such standards are "critical" and their development is underway.[36]

Costs and subsidies

As previously mentioned, green hydrogen is currently only produced in very small quantities, with electrolysis accounting for less than 1 per cent of hydrogen production in the EU. This is primarily due to the costs involved. According to the International Energy Agency, green hydrogen is between two and 16 times more expensive than grey hydrogen produced from natural gas, depending on the prices of gas and renewable electricity.[37] This is due to a number of factors, including the low rate of production and modest capacity of electrolysers, the need for further developments in the field of electrolyser technology, and the higher price of renewable electricity. However, there may well be a steep decline in costs on the horizon, as witnessed with solar panels and batteries. Electrolysers are projected to become cheaper due to economies of scale and the more efficient use of scarce materials, conversion rates will go up, and, most importantly, renewable electricity will become cheaper. With such a fall in costs, green hydrogen may be able to compete with fossil-based hydrogen as soon as 2030, especially in solar-rich regions.[38]

The speed at which green hydrogen will become cost-competitive depends at least partly on governments. To be more precise: on the boldness and breadth of their green industrial policies. National governments must develop the necessary infrastructure in a timely manner. The EU can bring a green hydrogen breakthrough closer by putting a high price on CO_2 emissions[39] and by creating a guaranteed demand. The European Commission's Fit for 55 legislative package on climate policy, for example, proposes an obligation to use green hydrogen and green hydrogen-based fuels in certain industrial and transport applications.[40] In a similar way, the EU could impose an obligation on steel buyers, such as the car industry, to use an increasing proportion of fossil-free steel in their products. This would boost steel production with green hydrogen and/or green electricity instead of coal.

Subsidies are another instrument to increase the supply of and demand for green hydrogen. Governments are already providing support for the development and production of electrolysers. So-called "carbon contracts for difference" (CCfDs) can accelerate the take-up of green hydrogen in the steel and chemicals sectors. Under such a scheme, companies would be compensated for the cost disadvantage of using green hydrogen as opposed to fossil-based fuels or feedstock. This type of state aid reduces the risk of over-subsidisation.

Public and private investments in green hydrogen can help the EU become climate-neutral, but may also deliver an additional reward: world leadership in electrolyser production. The EU already has more than 60 per cent of the global electrolysis manufacturing capacity.[41]

33 Agora Energiewende, *No-regret hydrogen. Charting early steps for H2 infrastructure in Europe*, 2021. https://www.agora-energiewende.de/en/publications/no-regret-hydrogen/

34 See chapter 4.

35 Raad voor de Leefomgeving en Infrastructuur, *Waterstof: de ontbrekende schakel*, 2021, pp. 113-114. https://www.rli.nl/publicaties/2021/advies/waterstof-de-ontbrekende-schakel

36 European Commission, 'Questions and answers: A Hydrogen Strategy for a climate neutral Europe', *ec.europa.eu*, 8 July 2020. https://ec.europa.eu/commission/presscorner/detail/en/qanda_20_1257

37 International Energy Agency, *Global Hydrogen Review 2021*, p. 113. https://www.iea.org/reports/global-hydrogen-review-2021

38 Ibid, p. 114.

39 See chapter 3.

40 European Commission, *Fit for 55*, 2021. https://ec.europa.eu/commission/presscorner/detail/en/IP_21_3541

41 International Energy Agency, *Global Hydrogen Review 2021*, p. 183. https://www.iea.org/reports/global-hydrogen-review-2021

Matching green hydrogen and green electricity

The bright prospects for the future of green hydrogen should not blind us to the problems of today. One of the thorniest issues is green hydrogen's hunger for electricity. As it currently stands, there are few moments and places where there is an oversupply of renewable electricity. If the renewable electricity for electrolysers were simply bought on the market and taken from the grid, it would be diverted from other power users. Given the current grid electricity mix in most European countries, this additional demand would mostly be met by firing up natural gas or coal power plants. Under these conditions, the production of millions of tonnes of green hydrogen would be unlikely to make much of a contribution to the EU's 2030 climate targets. It could even increase CO_2 emissions compared to grey hydrogen.[42]

The problem of green hydrogen production diverting renewable electricity away from other users could be eased by introducing an additionality requirement.[43] In market zones where the electricity mix is not yet dominated by renewables, increased green hydrogen production should go hand in hand with the accelerated expansion of wind and solar capacity. Companies planning to move into green hydrogen production should be encouraged to give advance notice of this to allow governments and renewable energy developers to anticipate their green energy needs. Power purchase agreements (PPAs) can give wind and solar operators greater certainty that extra investments will pay off. Governments would only be able to subsidise electrolysers if they could demonstrate that the renewable electricity they require would be generated by installations that would not otherwise have been built[44], or only at a later stage.

An acceleration of renewable energy growth, already at exponential levels, is essential to limit global warming to 1.5 degrees while taking responsibility for Europe's large share of historical greenhouse gas emissions. In order to do so, the EU would have to become climate-neutral by 2040.[45] A further acceleration to enable the production of truly green hydrogen, however desirable, may well encounter obstacles such as bottlenecks in the power grid, metals shortages, a lack of skilled workers, conflicts over land, and lengthy administrative procedures.

There is a clear need for and interest in green hydrogen, but this is accompanied by sizeable obstacles to scaling-up the currently low output to cover all possible applications. In this context, what are our options? The remainder of this report will focus on three key responses that each have a role to play: the production of blue hydrogen, prioritising hydrogen applications (the hydrogen ladder), and hydrogen imports.

42 Bellona, *Cannibalising the Energiewende? 27 Shades of Green Hydrogen*, 2021, p. 8. https://bellona.org/publication/will-hydrogen-cannibalise-the-energiewende

43 The EU already has such a requirement in place for green hydrogen used in the transport sector. The European Commission is working on a delegated act which is expected to both broaden and soften the requirement. For a critique, see note 42.

44 See the joint contribution from Austria, Denmark, Spain, Ireland, Luxembourg, and Portugal, *Additionality in renewable hydrogen production*, 9 November 2020. https://www.politico.eu/wp-content/uploads/2020/11/2020-11-09-Additionality-in-renewable-hydrogen-production-AT-DK-ES-IE-LU-PT.pdf

45 Greens/EFA Group in the European Parliament, *Fit for 55 in light of IPCC report - Letter to the European Commission*, 13 September 2021. https://www.greens-efa.eu/en/article/document/fit-for-55-in-light-of-ipcc-report

3. Blue hydrogen

Blue hydrogen is produced from natural gas, just like grey hydrogen, but with most (not all) of the resulting CO_2 stored underground instead of being released into the atmosphere. There are currently three blue hydrogen facilities in operation, in Canada and the USA.[46] Blue hydrogen is particularly attractive for large energy companies because it allows them to make use of their fossil-fuel assets for longer.

Most proponents see blue hydrogen as a bridging technology, able to deliver a quick reduction in CO_2 emissions until a solution is found to the insufficient renewables capacity and high costs hampering the development of green hydrogen.[47] It would allow industry to start adapting its installations for the move away from natural gas, oil, and coal immediately, rather than wait for green hydrogen to become available and affordable. According to this view, blue hydrogen can pave the way for true defossilisation using green hydrogen.

Shades of blue hydrogen

As tempting as it may seem, the use of blue hydrogen is accompanied by a range of drawbacks and risks. First, like green hydrogen, the production of blue hydrogen involves higher energy consumption than the direct use of natural gas in industry. Fossil-based hydrogen is mostly produced through steam methane reforming. This process involves natural gas not only as a feedstock, but also as a fuel to produce the necessary heat, implying an additional gas use of 3 to 20 per cent.[48] Capturing, transporting, and storing CO_2 also entails additional energy consumption of 3 to 10 per cent.[49] This includes electricity, which may also be generated by the combustion of natural gas.

This extra demand for natural gas makes the climate advantage of blue hydrogen far less obvious. For how would any additional European gas demand be met? Most likely by imports from Russia, which is already by far the EU's largest supplier. This raises the issue of methane emissions. Methane is the main component of natural gas. Leakage of methane during gas extraction, transport, and storage is much higher in Russia than in the EU or Norway. While measurements are lacking, estimates of the share of methane leaking into the atmosphere along the Russian gas supply chain range from 0.5 to 5 per cent.[50] These leaks are an important driver of climate change. Methane is a short-lived but extremely powerful greenhouse gas; it has a global warming impact 30 times higher than CO_2 over a century, rising to 83 times higher over a 20-year period. In order to slow the rate of warming in the short run, the world urgently needs to reduce methane emissions, not increase them.[51]

The European Commission is planning to take action against methane leaks from both domestic and imported gas.[52] However, it is doubtful that the EU has enough leverage over the Russian gas industry to make it clean up its act as long as Moscow continues to turn a blind eye, demonstrated by its failure to sign the Global Methane Pledge that was launched at the November 2021 UN climate summit in Glasgow.[53] The tight gas market that sent prices skyrocketing in autumn 2021 might well be a recurring phenomenon over the coming decade,[54] making the EU vulnerable to Russian muscle-flexing. This is one more reason to wean ourselves off fossil gas.

Second, CO_2 capture from steam methane reforming will never achieve 100 per cent efficiency. The CO_2 emitted during the burning of natural gas for heat is particularly difficult to capture, since it is mixed with nitrogen.[55]

46 Global CCS Institute, *Global Status of CCS 2021*, p. 16. https://www.globalccsinstitute.com/resources/global-status-report/

47 See chapter 2.

48 M. Roeb et al., *Wasserstoff als ein Fundament der Energiewende – Teil 1*, p. 21. https://www.dlr.de/content/en/downloads/2020/hydrogen-research-study-part-1.html

49 Sachverständigenrat für Umweltfragen, *Wasserstoff im Klimaschutz: Klasse statt Masse*, 2021, p. 19. https://www.umweltrat.de/SharedDocs/Downloads/DE/04_Stellungnahmen/2020_2024/2021_06_stellungnahme_wasserstoff_im_klimaschutz.html

50 Forum Ökologisch-Soziale Marktwirtschaft, *Implementing a methane pricing model for the EU gas market*, 2021, p. 8. https://crm.foes.de/civicrm/mailing/view?reset=1&id=1443

51 United Nations Environment Programme, 'Global Assessment: Urgent steps must be taken to reduce methane emissions this decade', *unep.org*, 6 May 2021. https://www.unep.org/news-and-stories/press-release/global-assessment-urgent-steps-must-be-taken-reduce-methane

52 European Commission, *EU strategy to reduce methane emissions*, 2020, p. 17. https://ec.europa.eu/commission/presscorner/detail/en/ip_20_1833 For a concrete proposal for a methane import tax on natural gas, see Forum Ökologisch-Soziale Marktwirtschaft, *Implementing a methane pricing model for the EU gas market*, 2021. https://crm.foes.de/civicrm/mailing/view?reset=1&id=1443

53 The Global Methane Pledge has been signed by the USA, the EU, and over 100 other countries. https://www.globalmethanepledge.org/

54 The Hague Centre for Strategic Studies, *De afnemende leveringszekerheid van aardgas in Nederland*, 2021, p. 15. https://hcss.nl/report/afnemende-leveringszekerheid-aardgas-nl/

55 CE Delft, *Feasibility study into blue hydrogen*, 2018, p. 10. https://cedelft.eu/publications/feasibility-study-into-blue-hydrogen/

The higher the rate of carbon capture, the more energy it requires. Whereas the current capture rate is around 60 per cent,[56] the European Commission considers 90 per cent to be the maximum.[57] As such, a percentage of the CO_2 generated during blue hydrogen production will still end up in the atmosphere.

A third issue with blue hydrogen is the fact that the success of carbon capture and storage (CCS) depends on the availability of reliable geological sequestration sites. Since the possibility of CO_2 leakage – which would threaten the environment and public health – cannot be completely excluded, storage in depleted offshore gas and oil fields is the most feasible option. However, the European storage sites that are currently in operation (off the Norwegian coast) or under development (in British, Irish, Norwegian, and Dutch waters) have limited annual capacity. They would not even be capable of receiving half of the CO_2 emitted by current grey hydrogen production in Europe.[58] Meanwhile, the construction of new storage facilities requires a long lead time. This narrows the scope for blue hydrogen. Moreover, suitable storage sites are "a scarce resource in Europe"[59] that we must be careful not to deplete. It would be wise to keep ample space under the seabed available for negative emissions – the removal of CO_2 from the atmosphere in the event that climate policies fail to rein in greenhouse gas emissions in time to avoid disastrous climate change.

A fourth issue with blue hydrogen is that CCS projects have a high failure rate. In 2007, the European Council called on the Commission to support 12 commercial-scale CCS demonstration plants in the EU by 2015. None of these materialised.[60] Globally, of all planned large-scale pilot and demonstration plants, 78 per cent have been cancelled or put on hold due to an "imbalance between risk and return".[61] The current rising CO_2 price in the EU's emission trading system (EU ETS) promises higher returns, and the growing involvement of governments in CCS projects may also lead to a higher success rate. But there is still a chance that blue hydrogen ventures will end up producing grey hydrogen for lack of a complete carbon storage infrastructure.

Fifth, the lifespan of new blue hydrogen facilities – at least 30 years – is at odds with the EU's goal of becoming climate-neutral by 2050. This deadline will have to be brought forward if we want the EU to do its fair share in limiting global warming to 1.5 degrees.[62] Installations that are yet to be built risk becoming stranded assets or may lock us into fossil fuel use and CO_2 emissions for longer than our climate can endure. These risks also apply to alternative methods for blue hydrogen production that use no additional gas for heating and promise a high CO_2 capture rate.[63] In the event that they require the construction of new plants, the time window for such investments seems already closed.

Finally, the volatility of natural gas prices is a threat to blue hydrogen, rendering its cost advantage illusory. In autumn 2021, when gas prices spiked, both grey and blue hydrogen became more costly to produce than green hydrogen from renewable electricity bought under power purchase agreements (which offer stable prices).[64] Furthermore, some factories in Europe scaled back their fossil hydrogen production in order to cut losses, undermining the argument that blue hydrogen provides more security of supply than green hydrogen.

Turning grey hydrogen blue

Blue hydrogen is not climate-neutral. The carbon in natural gas can never be stored as safely and completely as it was before it was pumped up. Governments should

56 UK Committee on Climate Change, *Hydrogen in a low-carbon economy*, 2018, p. 67. https://www.theccc.org.uk/publication/hydrogen-in-a-low-carbon-economy/

57 European Commission, *A hydrogen strategy for a climate-neutral Europe*, 2020, p. 4. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301 Same estimate in Intergovernmental Panel on Climate Change, *Global warming of 1.5 °C*, p. 124. https://www.ipcc.ch/sr15/

58 Sachverständigenrat für Umweltfragen, *Wasserstoff im Klimaschutz: Klasse statt Masse*, 2021, p. 20. https://www.umweltrat.de/SharedDocs/Downloads/DE/04_Stellungnahmen/2020_2024/2021_06_stellungnahme_wasserstoff_im_klimaschutz.html

59 E3G, *European CCS: learning from failure or failing to learn?*, 2020, p. 9. https://www.e3g.org/publications/european-ccs-learning-from-failure-or-failing-to-learn-summary/

60 European Court of Auditors, *Demonstrating carbon capture and storage and innovative renewables at commercial scale in the EU: intended progress not achieved in the past decade*, 2018, p. 20. https://op.europa.eu/webpub/eca/special-reports/climate-action-24-2018/en/

61 Nan Wang et al., 'What went wrong? Learning from three decades of carbon capture, utilization and sequestration (CCUS) pilot and demonstration projects', *Energy Policy* 158, 2021, pp. 2 & 6. https://doi.org/10.1016/j.enpol.2021.112546

62 See chapter 2.

63 Autothermal reforming with CCS, for instance. CE Delft, *Feasibility study into blue hydrogen*, 2018, pp. 10-11. https://cedelft.eu/publications/feasibility-study-into-blue-hydrogen/

64 Leigh Collins, 'Green hydrogen now cheaper to produce than grey H_2 across Europe due to high fossil gas prices', *rechargenews.com*, 12 November 2021. https://www.rechargenews.com/energy-transition/green-hydrogen-now-cheaper-to-produce-than-grey-h2-across-europe-due-to-high-fossil-gas-prices/2-1-1098104

promote blue hydrogen only when the immediate benefits of its use outweigh the drawbacks and risks – for instance to replace grey hydrogen in places where renewable electricity production cannot be scaled up rapidly enough to produce sufficient quantities of green hydrogen.[65] There is also a case for blue hydrogen production if industrial waste gases are used as a feedstock instead of natural gas. This approach largely avoids creating extra demand for (Russian) natural gas and driving up CO_2 emissions in the event that CCS fails to materialise. Furthermore, the "bluing" of existing grey hydrogen plants carries a lower risk of lock-in.

Even with this cautious approach, surplus blue hydrogen could be available for new industrial applications, paving the way for green hydrogen. After all, one of the main current applications of grey hydrogen, the production of fossil transport fuels, will decline due to the electrification of the car fleet. Another application, synthetic nitrogen fertiliser, can also be expected to shrink as governments aim to close nutrient cycles in agriculture and the European Commission pushes for organic farming on at least 25 per cent of the EU's agricultural land by 2030.[66]

If governments decide to provide subsidies for the conversion of grey hydrogen facilities to blue, they should require a 90 per cent carbon capture rate and as many guarantees as possible against methane leaks in the supply and production chains. Subsidies should also be time-limited; it would, however, be preferable if they became redundant due to a high carbon price. That is mainly in the hands of EU legislators. According to the European Commission, "carbon prices in the range of 55 to 90 euros per tonne of CO_2 would be needed to make fossil-based hydrogen with carbon capture competitive with fossil-based hydrogen today". The price for emitting a tonne of CO_2 in the EU Emissions Trading System (EU ETS) hit 90 euros at the end of 2021, but this peak is unlikely to last. The carbon price is projected to be between 85 and 100 euros by 2030 if the revision of the ETS directive that the Commission tabled in its Fit for 55 legislative package is adopted by the European Parliament and the Council of Ministers.[67] The co-legislators could boost the CO_2 price by deciding a steeper descent of the emissions ceiling and/or a minimum carbon floor price[68] within the ETS. Accelerating the phase-out of free CO_2 allowances and the phase-in of carbon pricing for imported products such as fertilisers[69] would also help bring about the switch from grey to blue hydrogen without subsidies. Such a tightening of climate policy would bring the era of green hydrogen closer as well.

National governments would still have a role to play in the development of blue hydrogen, by providing the necessary CCS infrastructure if they consider it safe enough and feasible to do so. The associated pipelines, compressor stations, and storage locations should be seen as public infrastructure, if only to prevent private monopolies.[70] Hydrogen plant owners would pay the public operator for every tonne of CO_2 that is transported and stored under the seabed. Government ownership can lead to a higher rate of success for CCS projects.[71] It also allows governments to block access to CCS for industries that already have a fossil-free alternative, such as direct electrification with renewable power.[72] Green industrial policy needs to prioritise forward-looking investments over stop-gap measures. With a public CCS infrastructure, it may also be possible to reduce the climate impact of industries in which the production of CO_2 during chemical processes is currently unavoidable, especially the cement sector. Moreover, the development of an effective CCS infrastructure would lay the ground for negative emissions.[73] Alas, it is highly likely that in order to limit global warming to 1.5 degrees, we will need to deploy a range

65 The European Commission speaks of retrofitting half of the existing hydrogen plants with CCS. European Commission, *A hydrogen strategy for a climate-neutral Europe*, 2020, p. 7. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301

66 European Commission, *A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system*, 2020, pp. 8-9. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0381

67 Frédéric Simon, 'Analyst: EU carbon price on track to reach € 90 by 2030', *euractiv.com*, 19 July 2021. https://www.euractiv.com/section/emissions-trading-scheme/interview/analyst-eu-carbon-price-on-track-to-reach-e90-by-2030/

68 Greens/EFA Group in the European Parliament, *Letter to the European Commission*, 30 June 2021, p. 2. http://extranet.greens-efa-service.eu/public/media/file/1/7142

69 Under the proposed Carbon Border Adjustment Mechanism. See https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_3661

70 Natuur & Milieu, *Transitievisie CCS*, 2021, p. 7. https://www.natuurenmilieu.nl/themas/kenniscentrum/transitievisie-ccs-waterstof/

71 Nan Wang et al., 'What went wrong? Learning from three decades of carbon capture, utilization and sequestration (CCUS) pilot and demonstration projects', *Energy Policy* 158, 2021, p. 7. https://doi.org/10.1016/j.enpol.2021.112546.

72 See chapter 4.

73 Or carbon dioxide removal (CDR). In the 2018 special report by the Intergovernmental Panel on Climate Change (IPCC), "all analysed pathways limiting warming to 1.5°C with no or limited overshoot use CDR to some extent to neutralize emissions from sources for which no mitigation measures have been identified and, in most cases, also to achieve net negative emissions to return global warming to 1.5°C following a peak." IPCC, *Global warming of 1.5°C*, 2018, p. 96. https://www.ipcc.ch/sr15/

of methods, both tech- and nature-based, that draw excess CO_2 out of the atmosphere.[74]

Turquoise hydrogen

An alternative to blue hydrogen which may also eventually lead to negative emissions via CCS is turquoise hydrogen. This production process also creates hydrogen from natural gas but via methane pyrolysis instead of steam methane reforming. During this process, oxygen-free heating splits the methane in the natural gas into hydrogen and solid carbon. The latter can be used as an additive or stored to prevent it from entering the atmosphere.

Turquoise hydrogen is not yet commercially available, but could become so by 2030.[75] Its late arrival carries the risk that the associated installations will either become stranded assets or lock us into natural gas use. However, the development of methane pyrolysis on a modest scale may still make sense. The technology could play a role in a fossil-free Europe on the condition that biogas replaces natural gas as a feedstock. Like natural gas, biogas consists mainly of methane, but it can be produced from organic waste streams such as sewage sludge. Its limited supply will be in high demand in a climate-neutral Europe, but part of it will likely be processed into carbon for materials; even fossil-free steel needs carbon as an additive.

If necessary, the use of biogas to produce hydrogen could also serve to reduce atmospheric CO_2. As the carbon in biogas is ultimately derived from plants that have taken CO_2 out of the air, storing this carbon in solid form after pyrolysis would represent negative emissions, without the leakage risk associated with CO_2 that is tucked away underground. Even the use of the resulting biocarbon in products could be counted as negative emissions once we have a circular economy where discarded materials are not burned but recycled.[76]

Green over blue hydrogen

In order to reach its production target of 10 million tonnes of green hydrogen by 2030, the European Commission has proposed obliging national governments to ensure that, by 2030, at least 50 per cent of the hydrogen used by industry is green.[77] This provision from the Fit for 55 package, if approved by the EU's legislators, will prevent an overreliance on blue or turquoise hydrogen.[78] It should also lead to the steering of public funds towards green hydrogen, and hopefully accelerate the deployment of wind and solar power. But it might also trigger a dash for green hydrogen from countries as far away as Chile, Namibia, and Oman. Or has that race already begun? This is the subject of chapter 5.

74 For an overview of negative emissions technologies, see Sara Budinis, 'Going carbon negative: What are the technology options?', *iea.org*, 31 January 2020. https://www.iea.org/commentaries/going-carbon-negative-what-are-the-technology-options

75 TNO, 'Ember methane pyrolysis technology produces hydrogen without CO_2 emissions', *tno.nl*. https://www.tno.nl/en/focus-areas/energy-transition/roadmaps/towards-co$_2$-neutral-industry/hydrogen-for-a-sustainable-energy-supply/optimising-production-hydrogen/ember-methane-pyrolysis/

76 Our present economy is only 9 per cent circular, on a global scale. Circle Economy, 'The circularity gap report 2021'. https://www.circularity-gap.world/2021

77 Hydrogen used for the production of fossil transport fuels is excluded from the obligation. European Commission, *Proposal to amend Directive 2018/2001 as regards the promotion of energy from renewable sources*, 2021, article 1(11). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0557

78 Alex Kaat, 'Waterstofdoel uit 'Fit for 55' zet Nederlands beleid op zijn kop', *energeia.nl*, 7 September 2021. https://energeia.nl/trilemma/40097210/waterstofdoel-uit-fit-for-55-zet-nederlands-beleid-op-zijn-kop

4. Hydrogen ladder

"Green hydrogen is the champagne among energy carriers", explains Thijs Van de Graaf, a researcher at Ghent University and a consultant to the International Renewable Energy Agency (IRENA). "It's a fantastic resource, but very expensive. Only for special occasions."[79]

This comparison hits the nail on the head. Like champagne, green hydrogen is in short supply and expensive. The green electricity needed to produce it is anything but abundant, and this will remain the case well into the coming decade. In a country like the Netherlands, even the straightforward substitution of grey by green hydrogen would require twice as much renewable electricity as the country currently produces, and may well slow the greening of the electricity mix.[80]

As mentioned before, green hydrogen's high electricity use is partly due to the loss of a significant percentage of energy in the conversion of electricity to hydrogen and vice versa.[81] For example, the overall energy efficiency of electric cars is more than twice as high as that of hydrogen-powered cars.[82]

In another similarity to champagne, green hydrogen is also highly sought after. A fast-growing number of companies are announcing their plans to start working with green hydrogen, which finds remarkably diverse applications from green steel to hydrogen bikes. For example, the first vehicle made of green steel, a truck made by Volvo using steel produced with green hydrogen by Scandinavian steel manufacturer SSAB, rolled off the production line in mid-2021.[83] Other steel manufacturers are also betting on green hydrogen. Furthermore, large aircraft manufacturers such as Airbus are presenting plans to fly aircraft on hydrogen instead of kerosene from 2035,[84] while smaller aircraft manufacturer ZeroAvia wants to fly between Rotterdam and London as early as 2024 with a 19-seater propelled by hydrogen.[85] The built environment is another sector in which hydrogen is eagerly awaited, given the relative ease of substituting hydrogen for natural gas. In the idyllic Dutch village of Graft-De Rijp, for example, an energy cooperative is making plans for the village to become gas-free as early as 2025. This will be achieved with the help of its own hydrogen plant, which runs on locally generated solar power and wind power from offshore wind farms.[86] Meanwhile, hydrogen bikes have been available since 2020 and can be bought for the tidy sum of 7500 euros – excluding the hydrogen filling station.[87]

Why do we need a hydrogen ladder?

These brief examples raise the question of which applications should be prioritised in decision-making over the limited amount of green hydrogen at our disposal. In other words, who gets to drink that precious and delicious champagne? While we generally believe that everyone should be able to drink as much champagne as they want, the purchase of green hydrogen does require some form of regulation.

There are a number of reasons for this. Firstly, green hydrogen comes with trade-offs for society. Green hydrogen and the renewable electricity needed to produce it require a lot of space, scarce materials, and public money (e.g. for building infrastructure[88]). The choices made must therefore serve the public interest as much as possible. It would be unfair for a minority of companies and individuals to reap the benefits of green hydrogen while society at large foots the bill (for instance in the form

79 Caitlin Stooker, 'Waterstof zet de machtsverhoudingen op zijn kop', *Het Financieele Dagblad*, 15 october 2021. https://fd.nl/tech-en-innovatie/1414264/waterstof-zet-de-machtsverhoudingen-op-zijn-kop-mqk1caRl8Ed0

80 See chapter 2.

81 See introduction and chapter 2.

82 Transport & Environment, *Electrofuels? Yes, we can … if we're efficient. Decarbonising the EU's transport sector with renewable electricity and electrofuels*, 2020, p. 29. https://www.transportenvironment.org/discover/electrofuels-yes-we-can-if-were-efficient/

83 Marc Seijlhouwer, 'Dit is hem: het eerste voertuig van groen staal gemaakt van waterstof, gebouwd door Volvo', *change.inc*, 14 October 2021. https://www.change.inc/mobiliteit/dit-is-hem-het-eerste-voertuig-van-groen-staal-gebouwd-door-volvo-37195

84 RTL Nieuws, 'Airbus presenteert concepten voor uitstootvrije vliegtuigen', *rtlnieuws.nl*, 23 September 2020. https://www.rtlnieuws.nl/tech/artikel/5185725/airbus-presenteert-concepten-voor-uitstootvrije-vliegtuigen

85 NOS, 'Luchthavens en vliegtuigbouwer: over 3 jaar op waterstof vliegen naar Londen', *nos.nl*, 27 October 2021. https://nos.nl/index.php/artikel/2403309-luchthavens-en-vliegtuigbouwer-over-3-jaar-op-waterstof-vliegen-naar-londen

86 NH Nieuws, 'De Rijp en Graft in 2025 aan de waterstof?', *nhnieuws.nl*, 15 October 2020. https://www.nhnieuws.nl/nieuws/274580/de-rijp-en-graft-in-2025-aan-de-waterstof

87 N.N., 'Fiets op waterstof vanaf deze zomer te koop in Nederland', *tweewieler.nl*, 4 June 2020. https://www.tweewieler.nl/41948/fiets-op-waterstof-vanaf-deze-zomer-te-koop-in-nederland

88 See chapter 2.

of changes to the landscape due to the construction of large wind farms).

Related to this is an infrastructural consideration. The transition to green hydrogen requires the construction of electrolysis plants, pipelines, and storage facilities, as well as application-specific infrastructure, with a lifespan of several decades or more. Without well-thought-out decisions about which applications should have access to hydrogen, we could lock ourselves into wasteful practices for extended time periods. Suppose we chose to build hydrogen pipelines and fuelling stations for hydrogen-powered passenger cars. The significant cost and effort involved would cause us to be stuck with this choice for decades. Hydrogen cars are certainly less energy efficient than electric cars, this much is already clear.

Finally, there are energetic-atmospheric trade-offs. Rapidly unfolding climate disruption and the need to stay below 1.5 degrees of global warming are forcing us to prioritise the green hydrogen applications that avoid the most CO_2 emissions. This implies once again that we should not resort to hydrogen in cases where there are better alternatives already, such as direct electrification. For instance, electric heat pumps in buildings have a far more favourable energy conversion rate than hydrogen boilers.[89] Replacing fossil fuels by green electricity is the most energy efficient way to decarbonise many industrial processes too.[90]

A ranking of the various applications of hydrogen in terms of priority is known as a "hydrogen ladder". In the section below, we first discuss the considerations which form the basis of hydrogen ladders. This is followed by visual representations of the assessment framework when applied to certain specific examples and the resulting hydrogen ladder (figures 1 & 2).

The assessment framework for a hydrogen ladder

Various hydrogen ladders have been published, each with their own starting points and considerations.[91] In this chapter, we largely follow the hydrogen ladder developed by Dutch environmental organisation Natuur & Milieu.[92] There are various reasons for this. First of all, the Natuur & Milieu hydrogen ladder is informed by key green principles, including the achievement of maximum sustainability both now and in the future, and a thorough consideration of both short- and long-term societal impacts. Second, this version of the hydrogen ladder is dynamic as opposed to static. Instead of a narrow focus on the exact outcome – whether the hydrogen bike should be one rung higher than the hydrogen scooter, for instance – it is the considerations that guide our choices that are of primary importance. Decisions are made using several criteria, and their weighting may differ from country to country. Since we have authored this report with Green parties throughout Europe in mind, we believe it is more important to focus on the underlying criteria (the assessment framework) than on the outcome per se. After all, one of the main reasons for developing a hydrogen ladder is to foster debate as a prerequisite for well-considered choices.

Below we present a three-question assessment framework which we believe forms the basis of a good green hydrogen ladder. If a question receives a "no" response, the application deserves a higher position (greater priority) on the hydrogen ladder. The questions are listed in order of importance: the first criterion (availability of sustainable alternatives in the long term) is more important than the second (energy efficiency), which is more important than the third (costs to society).

1. Is there, or will there be in time, a sustainable alternative available?

If there are no alternatives to hydrogen available for a particular application, it deserves a higher position on the hydrogen ladder. Take steel production, for example. An almost indispensable material, steel is used in myriad applications including the wind turbines and electricity pylons crucial to the Green Age. At present, iron ore is converted into steel using coal, resulting in high CO_2 emissions. Hydrogen is the only serious sustainable alternative for primary steel. Green steel should therefore be given high priority on the ladder.

"In time" refers to the depreciation period of the investments required (including infrastructure) for the switch to hydrogen. In specific cases, if a more sustainable alternative to hydrogen is likely to become available well before full depreciation, it could be preferable to work towards that alternative while making efforts to reduce CO_2 emissions in the meantime. After all,

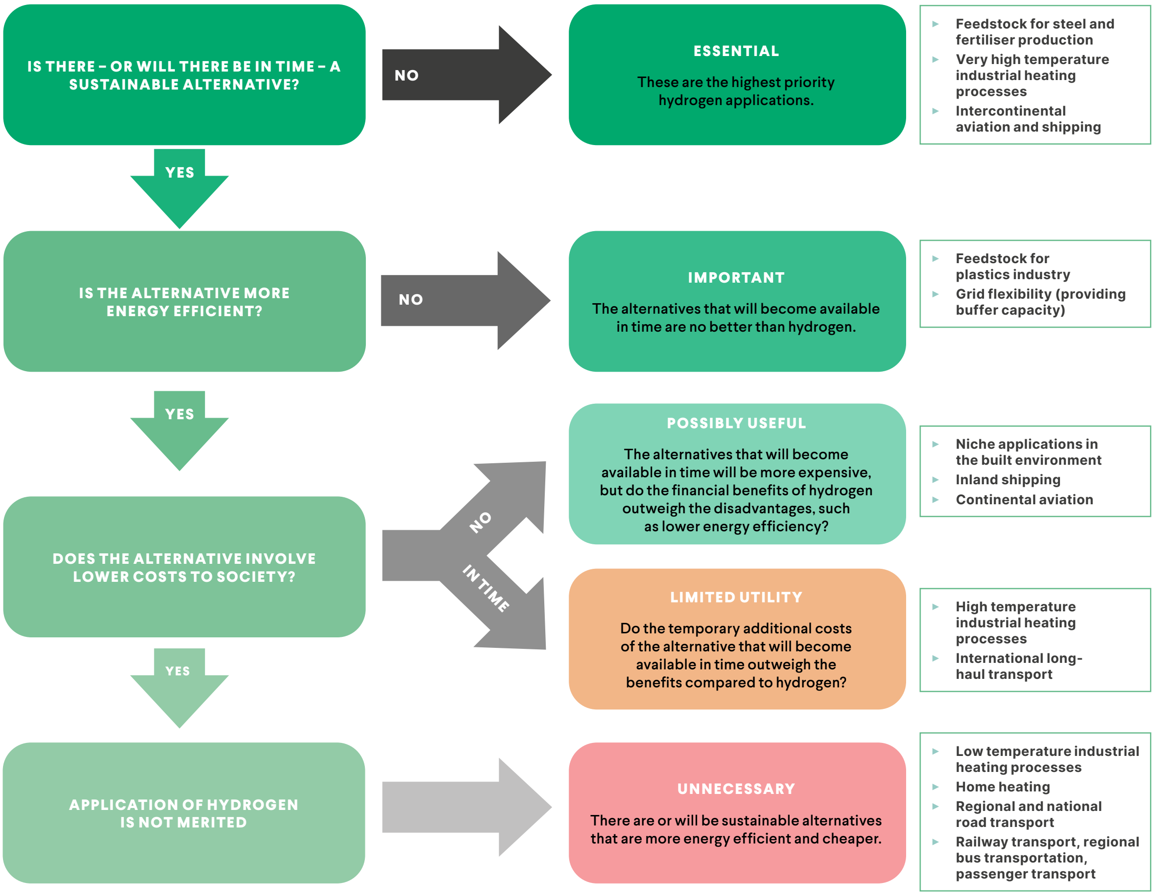
89 "PV-powered heat pumps require 5-6 times less electricity than a boiler running on electrolytic hydrogen to provide the same amount of heating." International Energy Agency, *Global Hydrogen Review 2021*, p. 87. https://www.iea.org/reports/global-hydrogen-review-2021

90 "Given that the performance factor of electric heating is at the very least comparable to and at the very best (...) considerably better than burning hydrogen from electrolysis, power-to-heat technologies should be considered before thinking about producing heat from hydrogen." Agora Energiewende, *No-regret hydrogen. Charting early steps for H2 infrastructure in Europe*, 2021, p. 14. https://www.agora-energiewende.de/en/publications/no-regret-hydrogen/

91 See for instance Zeeuws Energieakkoord, *Dossier: waterstof* https://www.zeeuwsenergieakkoord.nl/bibliotheek/waterstof and Michael Liebreich, 'The Clean Hydrogen Ladder (version 4.1)', *linkedin.com*, 15 August 2021. https://www.linkedin.com/pulse/clean-hydrogen-ladder-v40-michael-liebreich/

92 Natuur & Milieu, 'Waterstof: de waterstofladder', *natuurenmilieu.nl* https://www.natuurenmilieu.nl/themas/energie/projecten-energie/waterstof/waterstof-de-waterstofladder/

Figure 1: The assessment framework for a hydrogen ladder



green hydrogen will remain in short supply for quite some time and the highest-grade applications of hydrogen (where there are no alternatives) deserve to be given priority.

"Sustainable" refers to an analysis of the entire value chain, including social components. For example, burning large quantities of biomass for high-temperature industrial heat would threaten both biodiversity and food security.

2. Is the alternative more energy efficient?

If a particular application can be fulfilled more efficiently using an alternative to hydrogen, it should be given a lower position on the hydrogen ladder. As mentioned earlier, electric cars, bikes, and heat pumps are more energy-efficient than their hydrogen-powered alternatives. The use of hydrogen for private transport and heating within the built environment should therefore be allocated a lower rung on the hydrogen ladder.

3. Would the alternative lead to lower costs to society?

The use of hydrogen, or its alternatives, implies not only economic benefits and burdens but also costs and returns to society. Take the example of the village of Graft-De Rijp. The use of heat pumps would guarantee higher energy efficiency. However, with today's technology, it would also require the thorough insulation of the village's houses, which may spoil its historic appearance. In this case, broader societal considerations may well prevail over energy efficiency, justifying the use of hydrogen.

Below we present schematic representations of the assessment framework (fig. 1) and its output, the hydrogen ladder (fig. 2), using a small number of selected examples. The results should not be considered as exhaustive.[93]

The use of this particular assessment framework leads to the hydrogen ladder detailed in figure 2. It should be noted that, due to the continuous nature of technological innovation, hydrogen ladders are not able to give a definitive ranking of all of the applications of hydrogen; these may move up or down the ladder depending

93 These diagrams are based on Natuur & Milieu's hydrogen ladder. Natuur & Milieu, *Waterstofverkenning*, 2020.

Figure 2: A hydrogen ladder

ESSENTIAL	IMPORTANT	POSSIBLY USEFUL	LIMITED UTILITY	UNNECESSARY
Priority applications for hydrogen, for which no other renewable alternatives are available.	Important applications for hydrogen, which become as suitable as the renewable alternatives.	In time, renewable alternatives are in some cases more suitable than the application of hydrogen.	In time, renewable alternatives are more suitable than the application of hydrogen.	For these applications, renewable alternatives already exist.
Application ① Feedstock for steel production ② Feedstock for fertiliser production ③ Very high temperature industrial heating process ④ Intercontinental aviation and shipping	**Application** ① Feedstock for plastics industry ② Grid flexibility (providing buffering capacity)	**Application** ① Niche applications in the built environment ② Inland shipping ③ Continental aviation	**Application** ① High temperature industrial heating processes ② International long-haul transport	**Application** ① Low temperature industrial heating processes ② Home heating ③ Regional and national road transport ④ Railway transport, regional bus transportation, passenger transport
Possible alternatives ① No alternatives for primary steel ② No alternatives ③ No large-scale alternatives ④ No large-scale alternatives	**Possible alternatives** ① Recycling ② Battery storage; electricity grid reinforcement; flexibility in renewable energy production	**Possible alternatives** ① Electric heating, district heating ② Electric shipping ③ Electric aviation, railway transport	**Possible alternatives** ① High temperature heat pumps ② Electric transportation	**Possible alternatives** ① Electric heating ② Electric heating ③ Electric transportation ④ Electric transportation

on the latest developments. Moreover, the context for hydrogen use can differ from country to country. This means that the application of hydrogen, like the entire energy transition and the Green Age that it heralds, requires customisation. The primary utility of a hydrogen ladder is to serve as a guide for discussion on this issue, pointing the way to well-considered choices.

Implementing a hydrogen ladder

What measures are available to aid us in implementing hydrogen prioritisation? In other words, how do we ensure that the limited supply of green hydrogen is used for applications on the top rungs of the hydrogen ladder (e.g. green steel) and not for those on its bottom rungs (e.g. hydrogen bikes)?

Applications that are low on the ladder do not necessarily need to be banned, but should definitely not be subject to government encouragement. If someone wants to buy a hydrogen bike, then so be it, but they should not receive a single euro from the public coffers to do so. Applications that are high on the ladder, conversely, should be the target of government incentives.

The following policy instruments – which are part of green industrial policies – can play a significant role in implementing a hydrogen ladder:

Subsidies: The hydrogen ladder should be the guiding principle when awarding subsidies. To create a market for green hydrogen, it is advisable for governments to compensate early adopters for the additional costs of green hydrogen over fossil-based fuels and feedstock. This should be available exclusively for applications that are high on the ladder. Subsidies can also be granted for R&D and other development costs. The energy cooperative in the village of Graft-De Rijp, for example, could receive financial assistance with the further development of its plans.

Public infrastructural development: Developing the infrastructure for hydrogen transportation and storage should be a public responsibility.[94] This would allow priorities to be set by governments in accordance with the hydrogen ladder. A steel mill or fertiliser plant that needs hydrogen to become climate-neutral would be connected to the public network, while a new housing development with dreams of hydrogen-based heating may well be advised to think again.

Regulation: Governments could set product requirements that promote the use of green hydrogen, ideally at the European level. An obligation for car manufacturers to phase in the use of fossil-free steel, for example, would create a market for green steel and

94 See chapter 2.

therefore green hydrogen.[95] Such requirements should be developed for products that are high on the hydrogen ladder. These products include fuels for intercontinental shipping and aviation. For maritime transport, the EU should set rules to increase the share of green hydrogen and green hydrogen-based ammonia in the fuel mix. For jet fuel, it should introduce an obligation to blend in e-kerosene made from green hydrogen and CO_2, including an increasing share of CO_2 that is extracted from the atmosphere using direct air capture (DAC).

Public procurement: When buying products or putting construction projects out to tender, governments could attach conditions that promote the use of green hydrogen, provided this is in line with the hydrogen ladder. Examples include green steel for infrastructure and synthetic fuel for the air force.

CO_2 pricing, for example through the European Emissions Trading System (EU ETS), is clearly a valuable tool to stimulate green hydrogen. However, such mechanisms do not distinguish between the different specific applications of hydrogen. It is therefore not possible to use the ETS to prioritise one application of hydrogen over another.

95 Wetenschappelijk Bureau GroenLinks, *Groene industriepolitiek: Bouwen aan de Groene Eeuw*, 2021, www.wbgl.nl/gip and Tomas Wyns, 'Naar een nieuw industriebeleid voor een klimaat- neutrale en competitieve Vlaamse en Belgische industrie', in Sacha Dierckx (ed.), *Klimaat en sociale rechtvaardigheid*, 2019, pp. 257-276.

5. Hydrogen imports

EU production might not be able to meet either short- or long-term demand for green hydrogen, even when accompanied by the limited use of blue hydrogen[96] and a system of prioritisation that discourages the uptake of hydrogen by sectors with better alternatives such as direct electrification.[97] Mindful of this, the European Commission, national governments, and industry are looking into the importation of green hydrogen from sun and/or wind-rich regions outside of the EU that have access to sufficient water of any kind, as well as ports and/or pipelines that could be adapted to its transportation. If EU legislators endorse the Commission's proposal that 50 per cent of the hydrogen used by industry must be green by 2030,[98] this will provide an additional impetus for import plans.[99]

A number of EU countries have already signed deals with third countries wishing to become exporters of green hydrogen. Germany, for example, agreed to establish a hydrogen partnership with Namibia – a vast, sparsely populated former colony that has twice as many sunshine hours as Germany. The German government has entered into similar agreements with Morocco, Tunisia, Chile, and Australia. It is also wooing the United Arab Emirates and Ukraine. Berlin has set aside a budget of 2 billion euros to put flesh on the bones of these deals.[100] The Netherlands and Belgium have also concluded agreements with Namibia and Chile. The latter country has been dubbed "the Saudi Arabia of renewables"[101] (even though Saudi Arabia itself may be looking to claim that title). The focus of the European Commission lies with (North) Africa and Ukraine. In the words of Commission president Ursula von der Leyen: "We will invest with Africa to create a market for green hydrogen that connects the two shores of the Mediterranean."[102]

The large-scale procurement of green hydrogen from third countries could create geopolitical risks for the EU. It may ultimately affect its industrial base. But this chapter is not limited to the possible effects on the EU. The local impacts in exporting countries should also be our concern. The ethical risks of trade in green hydrogen are not unlike those we face today when importing natural gas, oil, coal, metals, soy, palm oil, timber, and wood pellets. The EU must counter these risks if it wants a global hydrogen market that benefits all. This time, we have to get it right from the beginning.

Geopolitics of hydrogen

By opening itself up to green hydrogen imports, does the EU risk repeating the mistake of becoming overly dependent on a few suppliers? Today, only three countries – Russia, Norway, and Algeria – supply two thirds of the natural gas we consume, with a rogue state being the main seller. Would the importation of large volumes of hydrogen once more make the EU vulnerable to price manipulation and political blackmail?

An EU that seeks strategic autonomy would do well to aim for a broad group of hydrogen suppliers.[103] Diversification is certainly conceivable. Whereas geology is fickle with oil and gas reserves, climate and geography are generous with the appropriate conditions for green hydrogen. Many countries around the world have the solar and wind resources to produce hydrogen in large quantities. Hydrogen is a "democratic fuel", according to Belgian Green energy minister Tinne Van der Straeten.[104]

Even the EU's southern member states may well be capable of producing lots of green hydrogen – more than they need for themselves – at a favourable cost. This could then be exported within the bloc. Lisbon and The Hague

96 See chapter 3.

97 See chapter 4.

98 See chapter 3.

99 Planbureau voor de Leefomgeving, *Nederland fit for 55? Mogelijke gevolgen van het voorgestelde EU-klimaatbeleid*, 2021, p. 6. https://www.pbl.nl/publicaties/nederland-fit-for-55

100 Klaus Stratmann, 'Bundesregierung will Wasserstoff-Großprojekte vorantreiben', *handelsblatt.com*, 17 March 2021. https://www.handelsblatt.com/politik/deutschland/foerderkonzept-h2-global-bundesregierung-will-wasserstoff-grossprojekte-vorantreiben/27015140.html

101 Gabriela Cabaña & Mario Diaz, 'The Limits of Europe's Corporate-Led Hydrogen Project', *Green European Journal*, 29 November 2021. https://www.greeneuropeanjournal.eu/the-limits-of-europes-corporate-led-hydrogen-project/

102 Ursula von der Leyen, 'Strengthening the soul of our Union – 2021 State of the Union address', *ec.europa.eu*, 15 September 2021. https://ec.europa.eu/info/strategy/strategic-planning/state-union-addresses/state-union-2021_en

103 The Hague Centre for Strategic Studies, *Energy transition, Europe, and geopolitics*, 2021, p. 4. https://hcss.nl/report/energy-transition-europe-and-geopolitics/

104 Tobe Steel, 'Regering gaat voor grootschalige import van waterstof', *tijd.be*, 29 October 2021. https://www.tijd.be/politiek-economie/belgie/federaal/regering-gaat-voor-grootschalige-import-van-waterstof/10342883.html

have already signed a memorandum of understanding to promote the export of hydrogen from Portugal to the Netherlands.[105] In northern Europe, green hydrogen produced on and around the North Sea may not be sufficient to meet demand, but could be cost-competitive once renewables power the grid and electricity surpluses are more frequent. After all, intercontinental transportation adds considerably to the cost of imported green hydrogen.[106] The CO_2 footprint of maritime transport could also cast a dark shadow over imported green hydrogen – unless, for example, the tankers carrying the ammonia into which green hydrogen is converted to reduce transport volume are fuelled by their own cargo.

For these reasons, "made in the EU" green hydrogen will not necessarily be driven off the market by hydrogen imported from sunnier and windier places. By 2050, domestic production may well meet half of the EU's demand for green hydrogen, with imports covering the other half.[107] This compares favourably with the EU's current import dependency on oil (97 per cent) and natural gas (90 per cent).[108] The green hydrogen transition could therefore increase the strategic autonomy of the EU, even if it were to become part of a global green hydrogen market.

Here looms a completely different geopolitical challenge. How are we to deal with the fossil fuel exporters that are in danger of becoming the losers in the energy transition? The switch to renewables will redraw the world geopolitical map. A country like Russia, with its denial of the inevitable end of the fossil fuels bonanza, could sink into economic insignificance. But with its nuclear weapons, veto right on the UN Security Council, and talent for hybrid warfare and cybercrime, it would retain plenty of nuisance power. Can the EU stand up for the values openly flouted by the Putin regime – democracy, human rights, the rule of law, the territorial integrity of neighbouring countries – and still help Russia find its way into the Green Age, for the sake of climate protection and European security? One possible route is to support Russia in producing green hydrogen for the European market. Whereas relatively low solar radiation and wind speeds put Russia at a disadvantage, the country's vast surface area and EU-connected natural gas pipelines speak in its favour. Some of the latter could be retrofitted for hydrogen once the EU has kicked its gas habit.

Saudi Arabia, that other fossil fuel giant, is more aware of the need to reinvent itself in the face of the Green Age. The desert kingdom plans to capitalise on its excellent climatic conditions and large surface area in order to become the world's largest supplier of green hydrogen. Construction has already begun on a huge electrolysis plant which will run on renewable electricity and desalinated sea water, and exports may begin as early as 2025.[109]

However, both Saudi Arabia[110] and Russia[111] also have big plans for blue hydrogen. Neither country wants to keep its natural gas reserves in the ground. As discussed,[112] the lifespan of new blue hydrogen facilities makes it difficult to achieve climate neutrality in time. Avoiding setting a bad example should be one more reason for the EU to shun the construction of new blue hydrogen plants.

Standards, certificates, and labels

The emergence of a global market for hydrogen of different colours creates the need for standards and certification. Many buyers will prefer green over grey or blue hydrogen because of its higher purity, or for reasons of sustainability, and want guarantees that the hydrogen they receive was produced with renewable electricity. The EU, for its part, must facilitate the importation of green hydrogen over grey and blue, for instance through carbon border pricing, if only to reach the 2030 target

105 Minister of Environment and Climate Action of the Portuguese Republic & Minister of Economic Affairs and Climate Policy of the Netherlands, *Memorandum of understanding – Hydrogen*, 17 August 2020. https://www.government.nl/documents/publications/2020/09/23/memorandum-of-understanding-between-the-netherlands-and-portugal-concerning-green-hydrogen

106 See chapter 1.

107 See for instance Belfer Center for Science and International Affairs, *Geopolitical and market implications of renewable hydrogen. New dependencies in a low-carbon energy world*, 2020, p. 31 https://www.belfercenter.org/publication/geopolitical-and-market-implications-renewable-hydrogen-new-dependencies-low-carbon and Word Energy Council Europe, *Decarbonised hydrogen imports into the European Union: challenges and opportunities*, 2021, p. 5. https://www.weltenergierat.de/publikationen/studien/hydrogen-imports-into-the-eu/

108 Eurostat, 'Energy production and imports', *ec.europa.eu/eurostat,* 2021. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_production_and_imports

109 Verity Ratcliffe, 'Saudi Arabia's bold plan to rule the $700 billion hydrogen market', *economictimes.indiatimes.com*, 7 March 2021. https://economictimes.indiatimes.com/news/international/saudi-arabia/saudi-arabias-bold-plan-to-rule-the-700-billion-hydrogen-market/articleshow/81374199.cms

110 Matthew Martin & Salma El Wardany, 'Saudi Arabia to use $110 billion gas field for blue hydrogen', *bloomberg.com*, 24 October 2021. https://www.bloomberg.com/news/articles/2021-10-24/saudi-arabia-to-use-110-billion-gas-project-for-blue-hydrogen

111 Angelina Davydova, 'Will Russia ever leave fossil fuels behind?', *bbc.com*, 24th November 2021. https://www.bbc.com/future/article/20211115-climate-change-can-russia-leave-fossil-fuels-behind

112 See chapter 3.

for green hydrogen.[113] This requires a methodology to calculate the carbon emissions within the production chain of hydrogen and its derivatives.

As a potential large importer of hydrogen, not at the mercy of a single supplier, the EU has leverage to set standards not just for itself, but for the world market.[114] These should include the certification and labelling of all hydrogen on its market, documenting the origin, method of production, purity, and carbon footprint of each unit of hydrogen and derived products.[115] Footprinting must cover the whole lifecycle, including transportation. For hydrogen from electrolysis to qualify as green, the additionality of the renewable electricity used in the process is key.[116] In many countries with great hydrogen ambitions but few renewables as yet – from the Netherlands to Saudi Arabia – there is a considerable risk that green hydrogen production will slow down the greening of the electricity mix. Ultimately, hydrogen should only be certified as green if its production is time-aligned with the generation of renewable electricity in the same market zone.

Sustainability beyond carbon footprinting

The standards set out above primarily address the climate impacts of hydrogen in its various colours. If we want green hydrogen to work to the advantage of the people in both exporting and importing countries, as well as the planet, these will not be sufficient. We need a broader range of sustainability standards. Green hydrogen requires not only solar or wind energy but also land, water, and metals.[117] Its production can have significant impacts on environments and economies, and may give rise to conflicts with local communities. This is especially the case in countries in which democracy, accountability, and the rule of law are not firmly anchored.

As discussed, green hydrogen production requires sizeable amounts of land for huge solar or wind farms in order to generate the renewable energy needed for electrolysis. In Namibia, this is supposedly not a problem. According to Germany's then-federal research minister Anja Karliczek, who clinched the August 2021 hydrogen deal with the Namibian government, the country has "large, so far unused areas".[118] We should be careful when using words such as "unused" and "empty". An unused area might more aptly be called nature. Even deserts are home to a great variety of plants and animals. Renewable energy developers should assess and minimise their impact on biodiversity.

Moreover, an apparent wasteland can still be actively used by local and nomadic communities for gathering food, grazing herds, hunting, fishing, transit, or performing rituals or ceremonies. Even if these groups lack formal property rights, they are stakeholders who cannot be ignored. The renewables sector should take to heart the lessons learned (by some) in the mining sector. Today's most progressive standards, those of the Initiative for Responsible Mining Assurance (IRMA), prescribe that mining companies gain and maintain broad support from impacted communities.[119] Particular attention is paid to indigenous peoples; their free, prior, and informed consent is required for projects that affect their rights.[120] One possible way to obtain consent is to ensure that solar and wind farms provide local benefits, including decent jobs, affordable electricity, and profit-sharing.[121]

On a broader scale, investments in renewables, power lines, and electrolysers should not focus exclusively on hydrogen exportation; they should also reduce energy poverty and speed up the decarbonisation of the domestic power grid, transport, and industry. Furthermore, foreign investors and hydrogen-importing countries must enable exporting countries to add value to their hydrogen. For example, green hydrogen can be used as a feedstock for the domestic production of nitrogen fertiliser, which may help farmers struggling with poor soils to

113 Ibid.

114 Mark Leonard et al., 'The geopolitics of the European Green Deal', *Policy Contribution* 04, 2021, p. 19. https://www.bruegel.org/2021/02/the-geopolitics-of-the-european-green-deal/

115 See the CertifHy® project, financed by the European Commission: https://www.certifhy.eu/

116 See chapter 2.

117 Ibid.

118 Nadia Weekes, 'Germany seals Namibia green hydrogen partnership', *windpowermonthly.com*, 25 August 2021. https://www.windpowermonthly.com/article/1725661/germany-seals-namibia-green-hydrogen-partnership Quoted in Gabriela Cabaña & Mario Diaz, 'The Limits of Europe's Corporate-Led Hydrogen Project', *Green European Journal*, 29 November 2021. https://www.greeneuropeanjournal.eu/the-limits-of-europes-corporate-led-hydrogen-project/

119 Initiative for Responsible Mining Assurance, *Standard for Responsible Mining*. https://responsiblemining.net/resources

120 ILO, *Indigenous and Tribal Peoples Convention* (no. 169), 1989 www.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:12100:0::NO::P12100_ILO_CODE:C169 and United Nations, *Declaration on the Rights of Indigenous Peoples*, 2007. www.un.org/development/desa/indigenouspeoples/declaration-on-the-rights-of-indigenous-peoples.html

121 As promoted by the Sustainable Hydrogen Club and its SDGproof® quality mark: https://sustainablehydrogenclub.com/ and https://sdgproof.org/

increase their yields.[122] Value addition requires technology transfer, skill-building, private investments, public grants, and loans – from the European Investment Bank, among others.

The same principle of benefit-sharing should apply to the desalination of sea water, essential for the production of green hydrogen in areas without an abundance of fresh water. It is important that desalination plants do not simply feed the production process, but also provide clean water to residents without an existing supply. Desalination waste, brine mixed with chemicals such as copper and chlorine, should not be pumped back out to sea, where it can damage ecosystems. Instead, it should be safely treated and stored until methods have been developed to recycle it into useful materials, such as lithium for portable batteries.[123]

Safe recycling is also crucial for the wind turbines, solar installations, and electrolysers involved in green hydrogen production. Scarce metals should not end up as waste. Closing material loops starts with circular design. Additionally, the responsible sourcing of metals, in keeping with IRMA standards, is no less important for renewable energy generation abroad than it is within the EU.[124]

These are just some of the challenges facing green hydrogen producers and the governments supporting them, especially in the Global South. There are also other risks to be addressed, such as poor working conditions, safety incidents, gender injustices, corruption, and tax evasion. If developing countries rely too heavily on green hydrogen exports, they may expose themselves to economic shocks due to price volatility, or lose competitiveness because of currency appreciation ("Dutch disease").

In Germany, the multi-stakeholder National Hydrogen Council has recognised many of these challenges. Its sustainability criteria for green hydrogen import projects provide a good basis for cross-border standards that can help trade in green hydrogen contribute to the United Nations Sustainable Development Goals instead of casting yet another resource curse over the Global South.[125] The European Commission should pick up on these proposals and carry them forward, in dialogue with governments and civil society in potential hydrogen-exporting countries.

European hydrogen sustainability standards would allow for a more comprehensive certification of green hydrogen projects and flows, going beyond carbon footprinting. Once these have been established, they should become part of hydrogen partnerships with third countries. The transferral of these partnerships to the EU level, as suggested by the new German governing coalition, would result in a stronger impact and more uniform implementation.[126] The offer of contracts for difference[127] to companies that want to switch to green hydrogen should be made conditional upon compliance with the sustainability standards. As a next step, the standards should be made binding for all companies operating in the EU market. One way to do this would be to explicitly include them in the planned legislation on mandatory value chain due diligence, accompanied by the IRMA standards for industrial mining.[128] The EU should continuously promote its standards and certificates in international fora, from the G20 and G7 to the International Renewable Energy Agency (IRENA) and the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE).

Redistribution of industry

In accordance with the Sustainable Development Goal of "industrial diversification and value addition to commodities",[129] green hydrogen production should allow countries of the Global South to move up the value chain. Opportunities for value addition include the domestic processing of hydrogen into fertilisers and synthetic fuels and its use in the production of green steel. If developing countries succeed in achieving this, industrial activities that rely on hydrogen may shift out of the EU. Relocating a fertiliser plant to Namibia makes a lot of sense when the primary feedstock is produced there, the end product is easier to transport and/or destined for the African market. Ditto for the relocation of a steel

122 Pablo Tittonell et al., 'Combining organic and mineral fertilizers for integrated soil fertility management in smallholder farming systems of Kenya: explorations using the crop-soil model FIELD', *Agronomy Journal* 100/5, 2008. http://dx.doi.org/10.2134/agronj2007.0355

123 Hwajoo Joo et al., 'Pilot-scale demonstration of an electrochemical system for lithium recovery from the desalination concentrate', *Environmental Science: Water Research & Technology* 2, 2020. http://dx.doi.org/10.1039/c9ew00756c

124 See chapter 2.

125 Nationaler Wasserstoffrat, *Nachhaltigkeitskriterien für Importprojekte von erneuerbarem Wasserstoff und PtX-Produkten*, 29 October 2021. https://www.wasserstoffrat.de/aktuelles/pressemitteilung-vom-05112021

126 SPD, Bündnis 90/Die Grünen & FDP, *Mehr Fortschritt wagen. Bündnis für Freiheit, Gerechtigkeit und Nachhaltigkeit*, 24 November 2021, p. 60. https://www.gruene.de/artikel/koalitionsvertrag-mehr-fortschritt-wagen

127 See chapter 2.

128 Unfortunately, the announced draft directive was postponed by the European Commission at the end of 2021. The European Parliament set out its demands in a *Resolution on corporate due diligence and corporate accountability*, 10 March 2021. https://www.europarl.europa.eu/doceo/document/TA-9-2021-0073_EN.html

129 United Nations, *Goal 9: Build resilient infrastructure, promote sustainable industrialization and foster innovation*. https://www.un.org/sustainabledevelopment/infrastructure-industrialization/

factory to Chile when the iron ore comes from nearby mines. Supply chains would be shortened, and transport emissions reduced. While such relocations would be blow to the EU and oblige it to help dismissed workers find reemployment, they contain a large measure of economic and environmental justice.

At the same time, geopolitical wisdom dictates that the EU must not become too dependent on third countries for so-called "strategic products". Steel is an important ingredient for the energy transition, and nitrogen fertiliser will underpin food security until our agricultural systems are fully circular. The desire to avoid strategic dependencies is one more reason for producing a substantial share of green hydrogen within the EU's borders, as well as for ensuring that the EU has the world's most eco-efficient industry.

Especially in the Global South, synthetic fuels come with the risk of entrenching fossil fuel use. These fuels are inefficient propellants for cars, but probably the least bad option for long-haul aircraft. They require not only hydrogen, but also carbon. For the moment, the most obvious supply comes from industrial processes with CO_2 streams that would otherwise have ended up in the atmosphere. That could create a fossil lock-in, however, in countries that have no effective mechanism (like the EU ETS) to reduce CO_2 emissions.[130] Although the EU is in no place to lecture developing countries on greenhouse gases, it can take a step towards making synthetic fuels truly fossil-free. E-kerosene made from green hydrogen and CO_2 extracted from the air via direct air capture (DAC) should be gradually blended into the standard kerosene used by aircraft travelling to and from European airports. Such a blending obligation would begin at around a hundredth of a per cent, increasing over time. Its introduction requires just a minor tweak of the aviation fuel regulation proposed by the European Commission as part of its Fit for 55 package.[131]

However, DAC is expensive. An obligation to cycle ambient CO_2 into jet fuel would therefore drive up the price of air tickets. A corresponding drop in air travel would be good news for the climate, given that the aviation sector is still a long way from achieving climate neutrality.[132] At the same time, a blending obligation would boost the further development of DAC, one of the methods for removing CO_2 from the atmosphere that may one day be needed for negative emissions.[133]

The countries that are the best fit for green hydrogen production also have potential for DAC, given that both require large amounts of renewable energy. When choosing a specific DAC technology, careful consideration must be given to heat, land, and water requirements.[134] In water-scarce areas, DAC should preferably produce more water than it uses. With strict sustainability standards, the production of fossil-free synthetic fuels could be a smart way for hydrogen-exporting countries to capture a larger share of the value chain.

Sufficiency over self-sufficiency

In making the case for renewable energy, many Green parties and movements have not only pointed to its environmental benefits, but also offered the prospect of a self-sufficient Europe no longer dependent on oil sheikhs and other autocrats for its energy supply. The need for imported green hydrogen on top of intra-EU production, hydrogen prioritisation measures, and the (limited) use of blue hydrogen may therefore come as a disappointment to many.

The reason energy self-sufficiency eludes us is because another fundamental green message has fallen by the wayside. In order to preserve the natural resources on which we depend, we need to radically change our ways of producing and consuming. This message is more urgent than ever. The Earth's depletion and the disruption of its natural processes can no longer be ignored. Several planetary boundaries have been crossed due to excessive resource use by rich countries and people. Not only climate change, but also biodiversity loss, land use change, and nitrogen and phosphorus pollution have reached the point at which "human activities could inadvertently drive the Earth System into a much less hospitable state", according to the Stockholm Resilience Centre.[135]

Even green hydrogen comes with an ecological footprint. This is one more reason to rethink the metabolism of our economy. To temper the demand for hydrogen, we must go beyond the hydrogen ladder and critically appraise our

130 Nationaler Wasserstoffrat, *Nachhaltigkeitskriterien für Importprojekte von erneuerbarem Wasserstoff und PtX-Produkten*, 29 October 2021, p. 6. https://www.wasserstoffrat.de/aktuelles/pressemitteilung-vom-05112021

131 Transport & Environment, *ReFuelEU Aviation: T&E's recommendations*, 2021, p. 3. https://www.transportenvironment.org/discover/the-eus-sustainable-aviation-fuels-initiative-tes-recommendations/

132 It is doubtful whether enough fossil-free e-kerosene can be produced to replace the current fossil fuel consumption of long-haul aviation. Moreover, the non-CO_2 climate effects of e-kerosene, although smaller than those of conventional kerosene, are not zero. This means that even the use of fossil-free e-kerosene is not climate-neutral.

133 See chapter 3.

134 World Resources Institute, 'Direct air capture: resource considerations and costs for carbon removal', *wri.org*, 6 January 2021. https://www.wri.org/insights/direct-air-capture-resource-considerations-and-costs-carbon-removal

135 Stockholm Resilience Centre, 'Planetary Boundaries – an update', *stockholmresilience.org*, 15 January 2015. https://www.stockholmresilience.org/research/research-news/2015-01-15-planetary-boundaries---an-update.html

use of fertiliser, plastics, steel, and fuels. Regenerative agriculture that protects soils and biodiversity would need fewer chemical inputs. The safe recycling of sewage sludge would lead to the further closure of the nutrient cycle. More selective packaging, reusable and with a deposit, would require lower quantities of plastics. An architecture that aims to reverse the growth in average living space per person and promotes more communal forms of living would reduce the need for building materials, including steel. The use of timber for construction would further reduce steel demand and permit carbon storage within buildings. In mobility, a shift from private cars to walking, cycling, public transport, and shared electric cars would save a substantial amount of materials, not least steel, and energy at that. The enormous challenge of greening aviation would become more manageable if business and holiday flights were once again exceptional, as they were not so long ago.

To return to the green vision, the case of hydrogen could teach us that sufficiency – implying a decent quality of life for all within planetary boundaries – is more important than self-sufficiency, which would deny poorer countries the opportunity to include fair trade with the EU in their development strategies. Europe should lead the way into the Green Age, but must take care that no one is left behind.

6. Recommendations

Demand for green hydrogen as a zero-emissions energy carrier, industrial feedstock, and energy buffer will grow rapidly in the coming years. Even if the European Union were to go beyond its goals of climate neutrality, circularity, and zero pollution and aim for all-out sufficiency, it would still need an increasing amount of green hydrogen over the next two decades to wean itself off fossil-based fuels and feedstocks. However, there are limits to the pace at which Europe can scale up production. Aside from costs and lead times, the main limitation is the huge quantity of renewable electricity consumed during the green hydrogen production process. This would add several gigawatts to the renewables capacity that the EU must install year-on-year to decarbonise its energy sector and accommodate the electrification of vehicles and heating. Since a delay in the greening of the electricity mix is to be avoided, green hydrogen will be in short supply for a long time to come. Green industrial policies must take this into account.

In this report, we have examined three possible responses to the shortage of green hydrogen: blue hydrogen, the hydrogen ladder, and the importation of hydrogen. Each of these can help accelerate the green hydrogen transition; however, important caveats apply. In particular, an overreliance on blue hydrogen should be avoided, in order to prevent a fossil lock-in. The political recommendations set out below, developed out of this investigation, are primarily addressed to European and national policy-makers, from Green parties and beyond. In many cases, they will have to work together – around the negotiating table in Brussels, for instance, and within the European political families – in order to get the most out of green hydrogen on the road towards the Green Age.

Green hydrogen

1. Apply an additionality requirement for the renewable electricity used for green hydrogen production. The European Commission should only allow subsidies for electrolysers if it can be demonstrated that the renewable electricity they require would be generated by installations that would not otherwise have been built.
2. Develop a public infrastructure for green hydrogen, starting with likely no-regret options including the retrofitting of existing natural gas pipelines.
3. Support the European Commission proposal that would oblige EU member states to ensure that, by 2030, at least 50 per cent of the hydrogen used by industry is green hydrogen. By 2040, all hydrogen, both domestically produced and imported, should be green.
4. In the context of the ongoing revision of the emissions trading system (EU ETS), and through national policies if necessary, aim for a CO_2 (floor) price that swiftly puts an end to the cost disadvantage of green hydrogen over grey and blue hydrogen.
5. Continue to invest research and development funds in increasing the energy and material efficiency of electrolysis, including the substitution of scarce metals by other more abundant materials. Make the responsible sourcing and safe recycling of metals and minerals mandatory.[136]

Blue hydrogen

6. Promote blue hydrogen as a transitional fuel and feedstock only:
   a. where it replaces grey hydrogen, in electricity market zones where renewables cannot be scaled up fast enough to produce sufficient quantities of green hydrogen, or if industrial waste gases are used as a feedstock instead of natural gas;
   b. when national authorities and citizens are convinced of the safety and feasibility of carbon capture and storage (CCS) and a capture rate of no less than 90 per cent can be achieved.
7. In the context of the ongoing revision of the EU ETS, and through national policies if necessary, aim for a CO_2 (floor) price that is high enough to make CCS financially feasible without subsidies.
8. Develop a public CCS infrastructure (conditional upon safety and feasibility). Charge user fees. Block access to CCS for industries that already have a fossil-free alternative. Keep CCS reservoirs under the seabed available for negative emissions.
9. Tackle methane leaks in the natural gas supply chain, including end users. Introduce a performance standard and a pricing system for methane emissions from both domestic and imported gas.

Hydrogen ladder

10. Develop a hydrogen ladder: a ranking of applications of (green) hydrogen that indicates which uses should be prioritised.
11. Refer to the following criteria when defining priority applications of green hydrogen:

136 See recommendation 15.

a. Is there, or will there be in time, a sustainable alternative available? If not, this application deserves a high position on the hydrogen ladder.
b. Is the alternative more energy efficient? Alternatives with higher energy efficiency, notably direct electrification, are preferable to hydrogen.
c. Would the alternative lead to lower costs to society? Broader societal considerations, such as the preservation of historical architecture in the built environment, may prevail over energy efficiency, justifying the use of hydrogen.

12. Use the hydrogen ladder as a dynamic instrument which takes account of technological innovations and differing national or regional contexts.

13. Consider using the following green industrial policy instruments to implement the hydrogen ladder:
    a. Subsidies. The hydrogen ladder should be the guiding principle when awarding subsidies, for instance for compensating early adopters for the extra costs of green hydrogen over fossil fuel and feedstock through carbon contracts for difference (CCfDs).
    b. Infrastructure. The development of green hydrogen infrastructure should be a public task; this allows priorities to be set according to the hydrogen ladder.
    c. Regulation. Governments, ideally at the EU level, should set product requirements that promote the use of green hydrogen. These requirements should apply to products that are high on the hydrogen ladder (such as steel), as opposed to those that are low on the ladder (such as synthetic fuels for cars). For maritime transport, the EU should set rules to increase the share of green hydrogen and green hydrogen-based ammonia in the fuel mix. For jet fuel, it should introduce an obligation to blend in e-kerosene made from green hydrogen and CO_2, including through direct air capture (DAC).
    d. Public procurement. When buying products or putting construction projects out to tender, governments could attach conditions that promote the use of green hydrogen, provided this is in line with the hydrogen ladder.

Importation of hydrogen

14. Develop a methodology to calculate carbon emissions within the production chain of hydrogen and its derivatives. Require the certification and labelling of all hydrogen on the EU market, documenting the origin, production method, purity, and carbon footprint of each unit of hydrogen and derived products. Footprinting must cover the whole lifecycle, including the additionality of the renewable electricity consumed, as well as transportation.

15. In parallel, set broader sustainability standards for imported (green) hydrogen that:
    a. counter the risks of biodiversity loss, land grabbing, water and renewable electricity diversion, worker exploitation, safety incidents, gender injustices, tax evasion, corruption, and (other) human rights violations;
    b. prescribe the responsible sourcing and safe recycling of the materials used in renewable electricity and green hydrogen production;
    c. include local benefits for impacted communities and value addition in exporting countries.

    The EU should make these standards binding and promote them in international fora.

16. Ensure that green hydrogen comes from a variety of supplier countries, with a substantial share produced within the EU.

17. Support countries that are heavily dependent on fossil fuel exports in making the switch to green hydrogen production and exportation, if the political situation allows it and sustainability standards can be met.

18. Favour the importation of green over grey and blue hydrogen, including through carbon border pricing.

19. Transfer green hydrogen partnerships with potential supplier states to the EU level in order to prevent member states from being played off against each other, and to promote the uniform implementation of sustainability standards.

20. Reduce demand for both imported and domestic green hydrogen by directing production and consumption towards sufficiency, thus reducing the need for fertilisers, plastics, steel, and fuels.

STUDY & DEBATE

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