HYDROGEN

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Council
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The Dutch version of the advisory report contains an additional analytical section.

SUMMARY

Interest in the use of hydrogen as a source of sustainable energy is increasing, both in the Netherlands and internationally. There are many places where this is being discussed and publicised. Opinions differ as to the deployability of hydrogen and the conditions under which this should take place. This raises a number of key questions:

- *What is the significance of climate-neutral hydrogen as a feedstock, fuel and energy carrier in a sustainable Dutch economy?*
- *How realistic are the forecasts with regard to hydrogen and are the blueprints for the future consistent with them?*
- *What is the strategic importance of hydrogen for the Netherlands?*
- *What does the strategic importance of hydrogen mean for the efforts of the Dutch government and others?*

The Council for the Environment and Infrastructure ("the Council") addresses these questions in this advisory report.

Hydrogen already plays a substantial role as a feedstock in the chemical industry. The Council's conclusion in this advisory report is that hydrogen is a vital link in the future climate-neutral supply of energy and feedstocks. However, the hydrogen market that is needed for this purpose will not materialise automatically; it will require the active commitment of government to creating demand for hydrogen. The government's role is to invest in the infrastructure, but also, for example, to garner public support. Its active commitment is needed not only to make the Dutch economy more sustainable, but also because it contributes to the Netherlands' earning potential. In this advisory report, the main message is further elaborated on the basis of the questions posed in the report. The Council's ambition in this advisory report is to adopt a holistic approach to the subject, to provide an overview and to sketch out a realistic picture.

What is the significance of climate-neutral hydrogen as a feedstock, fuel and energy carrier in a sustainable Dutch economy?
Future scenarios and potential studies show that hydrogen will be an essential part of the future climate-neutral energy system of the Netherlands. The contribution of oil, natural gas and coal will be greatly reduced over the long term. Many more processes will be electrically powered. Wind and solar power in particular will be used as sustainable energy sources. But electricity alone cannot meet all energy needs. Transport costs are higher for electricity than for gaseous energy carriers while its transport capacities are lower. Moreover, there are periods when the wind and the sun simply do not deliver enough energy in Northwest Europe. Clean ("climate-neutral") hydrogen – that is, hydrogen produced without carbon emissions – offers a solution to these problems as electricity can be converted into hydrogen, stored in that form and later converted back into electricity. This makes it possible to capture and trade periodic surpluses and shortfalls of electricity generated by the sun and wind in a cost-effective manner.

Hydrogen will also become an important part of the Dutch feedstock system. This is because, in addition, hydrogen's molecular structure makes it very useful as a feedstock for manufacturing fuels, materials and products that are currently still made from oil, natural gas and coal and in chemical processes such as plastics recycling.

It is not yet possible to say exactly how big a part hydrogen will play in our energy and feedstock system. Hydrogen will play a vital part in a number of applications (see Section 2.3), as a result of which at least 15-25% of the energy carriers in the final demand for energy and non-energy applications will come from hydrogen. For other applications, hydrogen is one of the possible routes. With lower costs and greater availability, hydrogen could therefore have an even more important role than it does today.

Since hydrogen will be needed simultaneously in various branches of industry as a climate-neutral feedstock for the production of basic materials (such as plastics, fertilisers and steel), it will be an integrating element in a new energy and feedstock system, enabling exchanges between parts of this system. This guarantees flexibility and security of supply.

There are several potential applications for hydrogen. At present, hydrogen is the only climate-neutral alternative for generating high-temperature heat in industry and for producing clean fuel for aircraft and sea-going vessels. Furthermore, hydrogen can be used to heat buildings and as a clean alternative to natural gas. This can be particularly useful in situations where other forms of renewable energy are difficult or expensive to deploy.

How realistic are the forecasts with regard to hydrogen and are the blueprints for the future consistent with them?
Climate-neutral hydrogen will not automatically find its place in the Dutch energy and feedstock system. At present, there is still insufficient demand for and supply of climate-neutral hydrogen and the infrastructure needed for its transport, distribution and storage is not yet ready. For all this to happen, government incentives will be required. A hydrogen exchange, along the lines of the electricity and gas exchanges, could then act as an economic coordination mechanism and catalyst for a market for climate-neutral hydrogen.

Hydrogen will have a vital part to play in the final system, as mentioned above. The Council expects that "green" hydrogen produced from renewable sources will primarily be used in this "blueprint for the future". However, if the desired final situation is to be achieved, it will be impossible to avoid an interim period in which "blue" hydrogen – produced from fossil fuels – is used and the carbon emissions from this process are stored.

What is the strategic importance of hydrogen for the Netherlands?
The hydrogen market is now developing internationally. The question is therefore whether the Netherlands should take the lead. Would it not be better to wait for action from the European Union (EU) and other countries? Both the European Commission and the countries neighbouring the Netherlands, especially Germany, have presented concrete plans for developing a hydrogen market and have made funds available for this purpose. Globally, too, several regions (including the Middle East, North Africa, Japan, China and South Korea along with Australia and New Zealand) are exploring the possibilities of producing and exporting hydrogen. The developments in Germany and Belgium are particularly important for the Netherlands and may have a positive effect on the development of the Dutch market.

Nevertheless, the Council believes it advisable for the Netherlands to make an active effort in the short term to kick-start a hydrogen market in the Netherlands, not only because this is necessary to make the Dutch economy more sustainable, but also because it is important not to lag behind our neighbours. The Dutch government will have to invest in infrastructure, and transport and storage capacity. By simultaneously stimulating the production of hydrogen in the Netherlands, the government can increase security of supply in the long term. This will make the Netherlands less dependent on other countries, which is sensible in today's turbulent geopolitical situation. Added to this is the fact that the Netherlands has a comparatively favourable starting position from which to build up a hydrogen market. Various forms of hydrogen production are feasible in the Netherlands, the Netherlands has good carbon capture and storage facilities and there is an existing gas transport and distribution network that can be used for hydrogen. Moreover, the Netherlands has relevant knowledge and experience. It is conceivable that the Netherlands being in a leading position in the international hydrogen market will in time lead to economic benefits.

What does the strategic importance of hydrogen mean for the efforts of the Dutch government and others?
A market for climate-neutral hydrogen in the Netherlands will not materialise without active government involvement. The main barriers that the government can help reduce are:

1. the high start-up costs for infrastructure, technology, etc.;
2. the lack of demand for climate-neutral hydrogen due to the price advantage fossil energy sources currently still enjoy over climate-neutral alternatives;
3. the unwillingness on the part of market players to invest in the production of climate-neutral hydrogen when there is no guarantee that it will be purchased;
4. no sense of urgency among the general public as regards the importance of climate-neutral hydrogen;
5. the risk that public resistance might emerge due to a perception that hydrogen is unsafe and very expensive.

The Council believes that the government should facilitate the creation of a transport and distribution network for hydrogen. The Netherlands has an extensive (and, given the reduction in the use of natural gas, significantly oversized) natural gas transport network. This network can be made suitable for hydrogen. An infrastructure consisting of a mains network that enables the transport of hydrogen between industrial clusters, to storage facilities and to import and export locations is a prerequisite for the development of the hydrogen market.

The Dutch government also has a vital role to play in stimulating demand for climate-neutral hydrogen. The best way to do this is to price the carbon emissions from non-climate-neutral alternatives. This will create a consistently fair competitive position for climate-neutral hydrogen (and other climate-neutral alternatives). Besides, granting temporary subsidies is a good way of developing production of climate-neutral hydrogen in the Netherlands.

The competitive position of climate-neutral hydrogen in relation to the alternatives differs from sector to sector. A sector-specific approach will therefore be needed. The Council makes the following distinction in this regard:

- Sectors not covered by the EU emissions trading system, such as the transport sector and the built environment sector, will require national measures to increase demand for climate-neutral hydrogen.
- In the case of large industrial enterprises and electricity producers, the EU emissions trading system will in time provide an effective instrument for stimulating demand for hydrogen, particularly when combined with a more stringent EU climate policy. As more comprehensive EU policy is still being developed, the Council believes that, in the short term, demand for hydrogen in these sectors should also be stimulated by means of specific national measures.

As climate-neutral hydrogen gains a more prominent place in the Dutch energy and feedstock system, it will become more important than ever to win the necessary public support. It is therefore essential that the government should communicate clearly the reason why hydrogen is needed and how the various consequences of its use will be dealt with.

One of these consequences relates to safety. The use of hydrogen is currently still very much concentrated in industrial applications. However, the introduction of new hydrogen applications and technologies into the public domain, including large-scale transport and storage, will inevitably involve risks. The government should make a budget available for a careful and comprehensive study to gain a better understanding of the risks involved and the measures needed to manage these risks. We must prevent large-scale applications from coming onto the market that are not safe enough. Even small-scale applications involving hydrogen may not be safe enough. At the stage we are at now, in particular, minor incidents will come under the microscope, potentially undermining support for hydrogen.

Another concern is transparency about the cost of hydrogen. The introduction of any form of renewable energy, particularly in the initial phase, has the effect of increasing prices for the consumer or user. For example, households and businesses will see their energy costs rise when hydrogen is used to heat buildings. This can be compensated by fiscal measures, but this compensation can only be temporary. The government will have to provide clear communication on the costs associated with the energy transition and on forms of compensation.

The Council has drawn up six recommendations detailing measures that the national government must take in the near future. The recommendations are summarised below.

1. Invest in the establishment of a hydrogen backbone with import and export facilities in the short term

An essential precondition for the creation of a hydrogen market is the presence of storage facilities, import and export facilities and a backbone linking these facilities to the industrial clusters. This kind of nationwide hydrogen backbone with import and export facilities will not come about without government commitment. Given the presence of a natural gas network that can be exploited for hydrogen transport, the cost of establishing a hydrogen backbone is relatively low and therefore the public investment required will be limited.

2. Emphasise safety and public support more explicitly in policy

The safety of new hydrogen technologies must be carefully and comprehensively investigated in advance. The government must make a budget available for this. Safety can then be taken into account for applications of hydrogen technology before they reach the market on a large scale. This is an essential precondition for the deployment of hydrogen in various applications in the public domain.

In addition, the government should actively focus on garnering public support for hydrogen. This primarily involves clear communication about the need to use hydrogen and dialogue concerning the safety risks associated with its use. Local initiatives to promote hydrogen can make a valuable contribution. In addition, the affordability of hydrogen must be taken into account in policy. Compensation can be considered for individuals or companies who will have to pay more for their energy supply after the transition.

3. Stimulate demand for climate-neutral hydrogen

The government must ensure that climate-neutral hydrogen can compete with non-sustainable alternatives. Only then will there be a demand for hydrogen that is consistent with the blueprint for the future of various sectors of the Dutch economy. In theory, the best way to create demand is to price carbon emissions. The price level will rise as a consequence, making climate-neutral alternatives more competitive. In its advisory report "Towards a Sustainable Economy", the Council also advocates reversing the burden of proof with regard to the competitive disadvantage and carbon leakage effects resulting from levies of this kind if they were only to apply in the Netherlands.

In the case of climate-neutral hydrogen, a carbon price of well over a hundred euros per tonne would currently be needed for it to be able to compete. The level playing field test indicates that industry's margins are tight, the options for sustainability are still limited and the risk of carbon leakage is considerable.[1] It is therefore important that carbon emissions pricing is effected at EU level.[2] This is provided for in the EU plan for an import tax on products from outside the EU based on their carbon footprint. The Netherlands must make a case for this *carbon border adjustment mechanism* in Brussels. The Netherlands should also push for a further tightening of the European carbon emissions trading system, ensuring that the price industry has to pay for its carbon emissions will continue to rise.

The international competitive position of energy-intensive industry in the Netherlands does not currently allow for the national increase in the carbon price that would be required to make climate-neutral hydrogen competitive. Decision-making at EU level is slow and uncertain. Other instruments will therefore have to be used in the short term to create a demand for hydrogen and a hydrogen market.
At national level, government can make hydrogen competitive through specific measures in each sector. In aviation, shipping and the built environment, a physical or administrative blending obligation for suppliers of fossil fuels will be the most effective way of achieving this. Tax incentives or a requirement to use climate-neutral hydrogen will work better in other sectors.

In the longer term, it is expected that the rising ETS price combined with the falling cost of climate-neutral hydrogen will provide sufficient momentum to make climate-neutral hydrogen competitive. These instruments are

1 The "level playing field test" is a study into the impact of the announced climate policy on the competitive position of Dutch industry, conducted by PwC (2020).

2 It must be ensured that products such as steel, aluminium and cement cannot be imported free of tax from countries where industrial companies are not subject to strict climate regulations. This is provided for in the EU plan for an import tax on products from outside the EU based on their carbon footprint.

therefore of a temporary nature, involving options chosen up to 2030. After 2030, the use of instruments will have to be reassessed.

4. Do not exclude any forms of hydrogen production when developing a hydrogen market

The production of “blue” hydrogen, made from natural gas and industrial waste gases with carbon capture and storage, will be an important transition technology for the next fifteen to twenty years. Blue hydrogen capacity also contributes to the security of supply, even in the longer term when more and cheaper green hydrogen (produced by means of electrolysis) becomes available. Imports of hydrogen will also play a role, but complete dependence on hydrogen produced outside the EU is undesirable because of the importance of maintaining security of supply.

5. Provide financial support for production and other technologies that promote the creation of a Dutch market for climate-neutral hydrogen technology

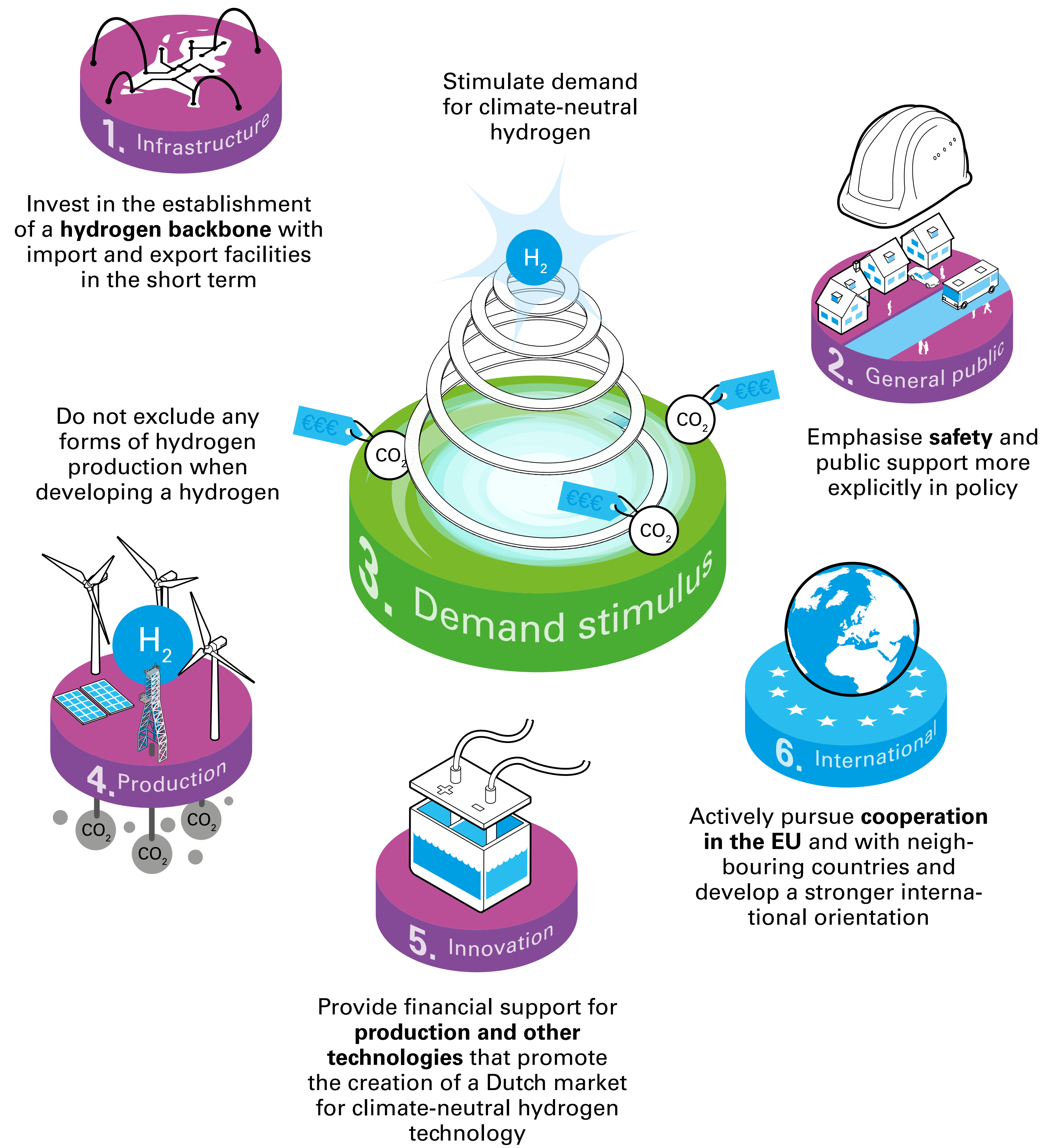
Various hydrogen technologies could contribute to the creation of a Dutch climate-neutral hydrogen market: combined carbon capture and storage, combined power generation and hydrogen production from offshore wind, hydrogen storage in salt caverns and the production of hydrogen-based fuels. The government should provide financial support to ensure the ongoing development of this type of technology.[3] This could be done by, for example, drawing up “contracts for difference”, under which manufacturers of products made using these relatively expensive technologies are refunded the price difference by the government.

6. Actively pursue cooperation in the EU and with neighbouring countries and develop a stronger international orientation

When it comes to securing a meaningful position in the hydrogen market, the Netherlands has the advantage over other countries that it is already an international energy hub. To exploit this advantage to the full and help make Europe more sustainable, active efforts must be made to promote European cooperation. In particular, cooperation with Germany and Belgium, North Sea countries or in the Pentalateral region[4] should be further intensified to ensure a coordinated roll-out of the hydrogen market and a high degree of security of supply.

3 The report “*Waterstof: kansen voor de Nederlandse industrie*” (Reijerkerk & Van Rhee, 2019) provides an overview of opportunities for Dutch industry.

4 The Pentalateral Forum is an energy forum involving the Benelux countries, Germany, France, Austria and Switzerland.


1. Infrastructure
Invest in the establishment of a **hydrogen backbone** with import and export facilities in the short term
Stimulate demand for climate-neutral hydrogen
H_2
€€€
CO_2
3. Demand stimulus
2. General public
Emphasise **safety** and public support more explicitly in policy
Do not exclude any forms of hydrogen production when developing a hydrogen
H_2
4. Production
CO_2
6. International
Actively pursue **cooperation in the EU** and with neighbouring countries and develop a stronger international orientation
5. Innovation
Provide financial support for **production and other technologies** that promote the creation of a Dutch market for climate-neutral hydrogen technology

1 INTRODUCTION

1.1 Hydrogen and the climate challenge

In the Paris climate agreement, 197 countries agreed to reduce carbon emissions by 95% by 2050 compared to 1990, with an intermediate step of a 49% reduction by 2030. The European Commission further tightened the 2030 carbon reduction target to 55% in September 2020. In order to achieve these climate targets, a transition is needed to a “climate-neutral” energy and feedstock system, which is organised completely differently from what we are used to.

Current Dutch energy consumption, including losses occurring during production, transport and distribution,[5] amounts to more than 3,000 petajoules (PJ) per year. Most of this energy (over 90%) is obtained from fossil sources (oil, natural gas and coal). Much of this is used to generate heat and electricity and to produce fuels for vehicles and aircraft. In addition, an equivalent of some 380 PJ of fossil energy is used in the chemical industry as a feedstock for the manufacture of materials. By way of comparison: all 7.9 million Dutch households together consume about 455 PJ of energy annually, of which about 20% is in the form of electricity and 80% in the form of gas.

5 Energy losses occur, for example, during the conversion of gas into electricity in gas-fired power stations and during the transportation of energy.

In the climate-neutral energy system of the future, electricity will have a greater share than it does today. Moreover, this electricity will be generated much more sustainably than now, by means of solar panels and wind turbines, among other things. At present, approximately 20% of the energy consumed in the Netherlands (both households and industry) consists of electricity, with electrons as the energy carrier. These electrons are currently still mainly produced from natural gas and coal.[6] The other 80% of energy consumed comes entirely from the direct use of natural gas, oil or coal, where the molecules are the energy carriers.

Energy carriers in the form of molecules will continue to be needed even in a climate-neutral system. This is because molecules, unlike electrons, are cheaper to store and transport in larger quantities. Molecular energy carriers are also more efficient when compared to alternative forms of energy such as residual heat and geothermal heat. Molecules will also continue to be needed as a feedstock for the production of all kinds of base materials, such as plastics and steel. The quantity of molecules required will be smaller than at present, but still considerable.

The challenge facing the countries that have signed up to the climate agreement therefore largely consists of a search for *climate-neutral molecules*. These include biomass,[7] green gases, biogases[8] and fossil gases whose CO_2 has been captured. Hydrogen is also part of this spectrum of potential solutions.

6 In 2019, almost 90% of all electricity consumed in the Netherlands was generated by burning natural gas and coal.
7 Biomass consists of all kinds of organic materials, including wood, organic waste, vegetable oil, manure and specially grown crops.
8 Biogas is produced from sources including sewage sludge, garden waste, fruit and vegetable residues and cattle manure. If it is then treated to the same quality as natural gas, it can be called "green gas".

What is hydrogen, how can we make it and what can we use it for?

Hydrogen is a colourless, odourless, tasteless and highly flammable (but non-toxic) gas, which is lighter than air. At a temperature of -253 degrees Celsius, hydrogen becomes liquid.
In chemistry, hydrogen – denoted by the symbol H – has atomic number 1.
If hydrogen existed on earth in pure form, the transition to a clean energy system would be easy to achieve. However, chemical element H is not present in nature in pure form; it only occurs bonded to oxygen in the form of water (H_2O) and/or carbon in the form of a hydrocarbon (CxHy).

Hydrogen cannot therefore be extracted; it has to be manufactured. This can be done in various ways:

- Hydrogen is easily produced from fossil fuels (hydrocarbons) such as natural gas or coal. These substances are then chemically decomposed into carbon and hydrogen but this conversion process is not sustainable, because it emits CO_2. This production method is therefore referred to as "grey" hydrogen.
- It is more sustainable to produce hydrogen from natural gas, industrial waste gases or coal and to capture the carbon emissions and reuse them or store them underground, for example in empty natural gas fields under the North Sea. This is known as "blue" hydrogen.

- A third method is to extract hydrogen from water by means of “electrolysis”. In this case, an electric current splits pure water into hydrogen and oxygen. This process does not produce carbon emissions. If this electricity is generated entirely from sustainable sources (e.g. from wind or solar energy), the result is “green” hydrogen.
- Other methods of producing hydrogen are currently less of an issue in the Netherlands, but could be relevant in view of possible imports. For example, nuclear reactors can also efficiently split water into hydrogen and oxygen using the power generated, possibly combined with the heat generated. This is known as “purple” hydrogen. In addition, methane pyrolysis is a relatively new technique for producing hydrogen. This involves making hydrogen from natural gas, with carbon – not CO_2 – as a valuable by-product. This variant is known as “turquoise” hydrogen.
  Finally, “yellow” hydrogen is “green” hydrogen imported from Middle Eastern and Saharan countries, based on electrolysis and electricity generated from solar energy.[9]

Once produced, hydrogen can be used in various ways. Firstly, as a clean fuel. Unlike burning fossil fuels, the combustion of hydrogen only produces water vapour and therefore not CO_2. Cars can run on hydrogen when fitted with a hydrogen fuel cell. Hydrogen can also serve as a feedstock for chemical processes such as recycling plastics or making synthetic kerosene.

To use hydrogen for these purposes, it must be stored and transported, either as a gas or a liquid. As a liquid, hydrogen has a relatively high energy density: four times that of natural gas. On the other hand, very high pressure is needed to liquefy hydrogen. This problem does not arise in the storage and transport of hydrogen as a gas. But the energy density of hydrogen in the form of gas is three times less than that of natural gas.[10]

1.2 Awareness of hydrogen among policymakers, the energy sector and industry

Policymakers and the energy and industrial sectors at home and abroad are becoming increasingly aware of hydrogen as an alternative to fossil fuels. This can be seen from the various agreements, plans, recommendations and strategies that have been drawn up in recent years with regard to energy and climate.

For example, hydrogen is attributed an important role in the 2019 Dutch Climate Agreement co-signed by the industry sector, the energy sector and environmental organisations, in the government’s climate plan for

9 For a broader overview of hydrogen production methods, see https://www.wattisduurzaam.nl/17586/featured/duurzame-en-fossiele-waterstof-in-alle-kleuren-van-de-regenboog

10 See also the appendix containing key figures at the end of this report.

the period 2021-2030 published last spring, and in various regional energy strategies and municipal heating strategies. Energy providers TenneT and Gasunie have also recently jointly declared their support for an energy infrastructure in which hydrogen plays a key role (TenneT & Gasunie, 2020). And, in a recent advisory report on an industrial frontrunner programme for the Netherlands' five industrial regions, the Social and Economic Council (SER) has also explicitly highlighted the potential role of hydrogen and the importance of building hydrogen infrastructure (SER, 2019).

In addition to the climate plan mentioned above, the government presented a vision on hydrogen in April 2020, followed by a vision for making Dutch basic industries more sustainable. Both documents highlight the future role of hydrogen. The government refers in this connection to the work of the Infrastructure Taskforce for the Climate Agreement on Industry (TIKI). This task force published its report in May 2020, recommending investment in hydrogen infrastructure based on the existing mains gas network.

By combining forces and improving their coordination, the government intends to speed up decision-making on investment in the energy infrastructure. A Sustainable Industry Infrastructure Programme (PIDI) is to be set up to support this process. The government also wants to ensure that an integrated assessment of interests is carried out. An assessment framework will be drawn up for this purpose. In addition, the Main Energy Structure Assessment Programme looks at spatial integration. Specifically, the Ministry of Economic Affairs and Climate Policy is working with Gasunie and TenneT on the Hyway 27 study to investigate the steps needed to create a hydrogen infrastructure (House of Representatives, 2020).

Hydrogen is also the subject of a great deal of attention internationally. For example, the European Commission presented an ambitious hydrogen strategy in the summer of 2020, in which hydrogen is described as a vital component in a climate-neutral energy system. Germany, too, has clear ambitions in the area of hydrogen; it has set aside €9 billion in its national recovery fund to develop a hydrogen market. Almost all other European countries have also expressed ambitions in the area of hydrogen, with Japan, South Korea and Australia being the frontrunners worldwide. But countries in the Middle East and North Africa are also showing an interest as they see opportunities to use their potential surplus of sustainable solar energy to become exporters of hydrogen. Furthermore, global and European industry is showing great interest in hydrogen and a wide range of activities are being undertaken.

1.3 The question considered in this report

Against the background of the developments outlined above, the Council for the Environment and Infrastructure ("the Council") has drawn up an advisory report based on the following questions:

- What is the significance of hydrogen as a feedstock, fuel and energy carrier in a sustainable Dutch economy?
- How realistic are the forecasts with regard to hydrogen and are the blueprints for the future consistent with them?

- What is the strategic importance of hydrogen for the Netherlands?
- What does the strategic importance of hydrogen mean for the efforts of the Dutch government and others?

1.4 The structure of this report

The remainder of this report is structured as follows:

- In Section 2, the Council outlines the role and potential applications of hydrogen in a sustainable economy.
- In Section 3, the Council sets out what is needed to develop a fully-fledged hydrogen market and the problems involved.
- In Section 4, the Council describes the international playing field in relation to hydrogen, the starting position of the Netherlands and its strategic interest in investing in hydrogen production.
- In Section 5, the Council discusses a number of essential preconditions, including a legal framework for hydrogen and the importance of public awareness of the need for hydrogen.
- Finally, in Section 6, the Council sets out six specific recommendations for the Dutch government.

2 THE ROLE AND POTENTIAL APPLICATIONS OF HYDROGEN

Part of the transition to a climate-neutral economy can be achieved by increasing the proportion of electricity generated by wind turbines and solar farms. But an additional alternative is needed because the use of wind and solar energy will not be sufficient to make our energy and feedstock system completely climate-neutral. Hydrogen is one of the options available (Section 2.1). Another part of the transition to a climate-neutral economy can be achieved by replacing molecular feedstocks such as coal, oil and natural gas with climate-neutral molecules. Hydrogen is a good option from this point of view as well, as it can also be used as a feedstock for the manufacture of basic products (Section 2.2). Hydrogen has the potential to be used in many parts of the economy and will eventually become a competitive alternative in various sectors (Section 2.3).

2.1 Hydrogen as an energy alternative

Electricity will have a bigger share of the climate-neutral energy system of the future than it does today. However, there are limits to the potential for electrification of the energy system. The Council notes that there are at least three factors that stand in the way of extensive electrification.

1. Electrification not technically feasible for all processes

Not all processes currently using fossil fuels as energy sources can technically be switched to electrification. This applies, for example, to industrial processes that require a higher temperature than can be achieved with electric boilers. The production of basic products and materials also requires feedstocks other than electricity. The propulsion of shipping and air transport is also not feasible with electrical energy at the present state of the art.

2. Electricity storage is insufficient for cold, dark and windless periods of longer duration

Because the sun does not always shine, because the wind sometimes blows and sometimes does not, but also because the supply and demand for electricity varies by season and does not always match, there will be times when there is too little or too much electricity. This means not only that demand management is required (e.g. by adjusting production units), but also that buffers are needed in the energy system. These buffers require flexible transport capacity and large-scale energy storage.

The required flexibility in the network and storage can be decentralised using short-term buffers, batteries and flexibility mechanisms. However, seasonal energy storage is necessary in order to cope with prolonged cold, dark and windless periods, known as *dunkelflautes*. Estimates by Gasunie and TenneT (2019) indicate that there will be a need for large-scale storage of 100 PJ to 150 PJ to ensure security of supply.[11] For the time being, such large amounts of energy cannot be stored in the form of electricity or batteries. Hydrogen is currently the most promising, if not the only, technical option.

3. Bottlenecks in electricity generation, transport and distribution

According to current estimates, the Netherlands will have a maximum of 60 GW in offshore wind farms and 80 GW in solar panels by 2050.[12] Together, this would produce an average of 1350 PJ (375 TWh) of energy annually.[13] This amount of energy could meet about half to three-quarters of the country's entire annual energy demand.[14] Electricity imports could further increase this share and the security of supply. However, it is

11 By way of comparison, in the current energy system natural gas fulfils the role of seasonal storage with a storage capacity of over 500 PJ. However, this much centrally stored energy will not be needed in a new climate-neutral energy system.

12 The Dutch Climate Agreement assumes that offshore wind power will continue to grow up to a maximum of 60 GW by 2050 (Climate Agreement, p. 158). The Climate Agreement does not specify a maximum capacity for solar energy; the 80 GW mentioned here is an assumption that is used as a practical maximum in various scenarios.

13 For the calculation of this estimated return, see Section 1 of Part 2 of this report. (*Not included in this translation. It is available in the complete Dutch version.*)

14 These estimates are based on the four climate-neutral energy scenarios for 2050 recently drawn up for Gasunie, TenneT and the regional network operators (Den Ouden *et al.* , 2020). According to these scenarios, the Netherlands will have a primary energy demand (excluding synthetic fuels for shipping and aviation) of between 1,775 PJ and 2,964 PJ by 2050.

uncertain how large electricity's share of the future energy supply can really be. This depends in part on how much energy is saved and how much money is invested in the construction of wind farms, solar parks and other facilities for generating sustainable electricity.[15]

The transmission and distribution capacity of the electricity network poses an additional problem. The entire Dutch electricity network currently transports approximately 130 terawatt hours (TWh) of electricity per year. In 2019, the industry organisation for Dutch network operators, Netbeheer Nederland, indicated that the network reinforcement required to transport the additional 35 TWh of sustainably generated onshore electricity from 2030 onwards, as agreed in the Climate Agreement, will not be readily achievable without changes to rules and requirements (Netbeheer Nederland, 2019). The current demand-driven and centrally supplied electricity grid will have to be converted into a supply-driven and decentralised, weather-dependent electricity grid. The above-mentioned Infrastructure Taskforce for the Climate Agreement on Industry has calculated that in the period up to 2030 alone, this will cost approximately €40 billion (TIKI, 2020).[16] An additional problem is that peak demand for electricity is now increasing faster than the rate at which the system can be adapted to meet the new requirements.[17] The biggest expansion of the electricity network to a capacity of about 220 TWh per year will still have to take place after that, during the period 2030-2050.[18]

Overall picture

Although it is technically possible to create an energy supply in the Netherlands that is entirely based on electricity, the Council believes that such a system is vulnerable and therefore poses too many risks for the Dutch economy. Moreover, the costs involved are too high (this is discussed in detail in Section 1 of Part 2[19]).

In the Council's opinion, it would therefore be wise to develop a system based on molecular energy carriers in tandem with electrification and to ensure it is possible to swap between these systems. As part of such a solution, hydrogen is an obvious molecular energy carrier because hydrogen can be produced in a climate-neutral way and is interchangeable with electricity. An additional advantage of the latter is that a high degree of system integration and flexibility can be achieved, with electricity and hydrogen together at the heart of an energy supply system and able to keep it in balance. Figure 1 shows what this system of the future might look like.

15 There are major physical, planning and financial challenges involved in the development of renewable energy production capacity, including the installation of thousands of wind turbines offshore and solar farms on land. A major concern is that an oversupply of electricity (on windy and sunny days) and the resulting low and sometimes even negative electricity prices will deter investors from initiating new projects.

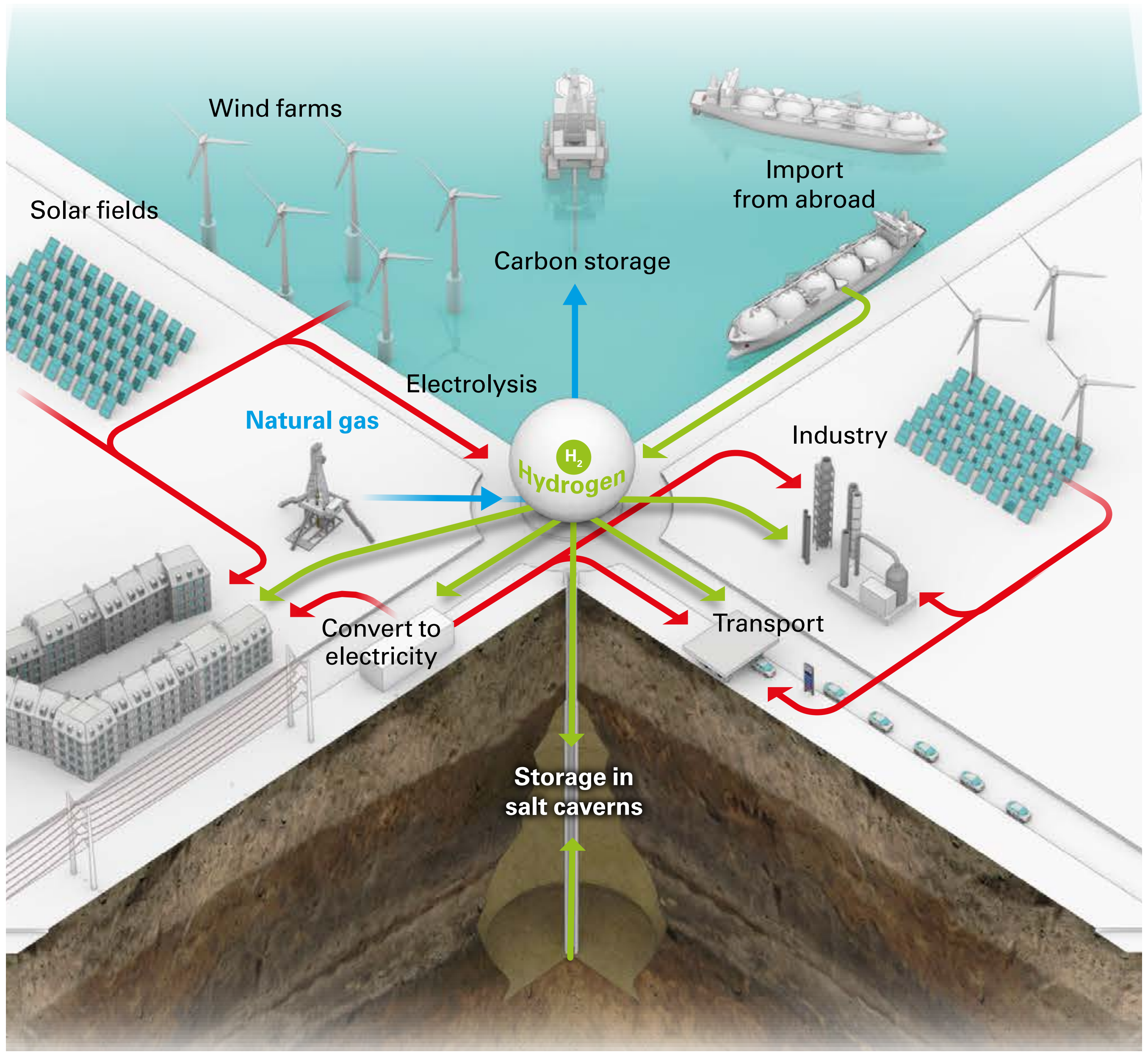
16 By way of comparison, the task force indicates in the same report that the cost of creating a hydrogen backbone, based on freeing up pipelines in the existing gas transmission network, would amount to around €2 billion during the first phase (TIKI, 2020). This network is expected to be have been completed in its basic form by around 2027.

17 Currently, peak demand is about 16,000 MW in winter, while maximum supply is about 30,000 MW in spring. However, scenarios indicate that this peak demand will increase to between 40,000 and 50,000 MW in the winter months, while the capacity of the high-voltage grid is only 20,000 MW.

18 The details and required steps are the subject of the Hyway 27 project which the Ministry of Economic Affairs and Climate Policy is carrying out in cooperation with Gasunie and TenneT.

19 Not included in this translation. It is available in the complete Dutch version.

Figure 1: Simplified impression of energy and feedstock system based on electricity and hydrogen



2.2 Hydrogen as a feedstock alternative

Fossil sources such as coal, oil and natural gas are not only used as energy sources in today's economy, but also as feedstocks. Natural gas is used, for example, to make ammonia (which in turn is a feedstock for artificial fertiliser), oil is used as a feedstock for plastics and many other synthetic materials, while the uses of coal include the production of iron.
Only molecular substances lend themselves to this kind of chemical conversion process. This means that in a climate-neutral economy, where coal, oil and natural gas no longer play a major role, "climate-neutral molecules" will be needed to make the basic materials mentioned above.

Because hydrogen consists of molecules, it is a reliable, climate-neutral alternative not only as an energy source but also as a feedstock, provided that it is "clean" (produced with no carbon emissions). But there are more climate-neutral feedstock alternatives. For example, it is possible to use natural gas from which the CO_2 is captured and stored. The same process can be applied to gas produced through the gasification or fermentation of biomass. Gas produced from natural waste products such as manure, sewage sludge and organic waste ("biogas") can also be used as a feedstock in a climate-neutral economy. In addition, recycled molecules from waste streams can be used as feedstocks.

There are therefore numerous options for creating industrial production processes based on clean feedstocks. The use of hydrogen is one of these options. Den Ouden *et al.* (2020) predict that the use of hydrogen as a feedstock in the industrial sector will increase from 12% to 37% over the next three decades. According to the above-mentioned study, this increase corresponds to the orientation of European and international policy, which is expected to promote the use of hydrogen both as a source of energy and as a feedstock. This will increase the size of the hydrogen markets and give Dutch industry more opportunities to integrate hydrogen into production processes.

2.3 Potential applications in the Dutch economy at sector level

Various scenarios have been developed to explore what a future carbon-neutral energy and feedstock system might look like in practice and what possibilities there are for creating such a system.[20] The Council studied several scenarios for this advisory report and then organised sessions with experts to set out the potential applications of hydrogen in the various scenarios and their scale.

The Council notes that there is a broad consensus that hydrogen will be part of the energy and feedstock system of the future, both in the final situation in 2050 and on the way there. All the scenarios also assume that hydrogen will have a significant part to play. On average, hydrogen's share of the energy demand[21] would be at least between 15% and 25%, although the range is considerable (Section 2 of Part 2 discusses absolute quantities per sector).

The Council sees a role for industry in the transition to a sustainable economy, both in the final situation when hydrogen has an important function in the circular economy and in the transition towards it. Large quantities of hydrogen are currently produced from natural gas for the chemical and petrochemical industries.[22] The production of "grey" hydrogen, often made from natural gas and industrial waste gases, results in carbon emissions. Due to the industrial scale of production and the fact that cooperation can take place in clusters, an acceleration in the development of climate-neutral hydrogen can be achieved efficiently and in the shorter term by using both CCS (blue hydrogen) and green hydrogen. These hydrogen developments can act as a catalyst for the other sectors.

In the transition to a more climate-neutral economy, each sector can choose from a number of options for replacing current fossil solutions. Hydrogen is one of these options. The greatest demand for hydrogen can be expected in the following sectors and applications:

20 See, for example, Hydrogen Council (2020); Netbeheer Nederland (2017); Berenschot & Kalavasta (Den Ouden *et al.*, 2020).

21 This refers to the "final" energy demand, i.e. the amount of energy actually consumed by customers. Because hydrogen always has to be produced from another energy source (e.g. electricity, gas, waste gases, coal) and there are always conversion losses in the production of hydrogen, the "primary energy demand" (the amount of energy that must be generated to meet demand) is even greater. Incidentally, the phenomenon of conversion loss is normal in the energy world and does not just apply to hydrogen. Of course, it is important to keep any losses to a minimum.

22 This is about 175 PJ annually. By way of comparison: the entire Dutch energy demand is 3,000 PJ. It is a modest amount, but big enough to get off to a good start. Ultimately, the total demand for climate-neutral hydrogen will be two to three times this amount.

Economic sectors	Options for hydrogen use
Industrial sector	High-temperature heat Feedstock for materials
Energy sector	Flexible storage and transport of energy
Transport and mobility sector	Fuel for transport
Built environment sector	Domestic heating, domestic hot water

A brief explanation for each option:

- *High-temperature heat*. Hydrogen can be used in the chemical, petrochemical and steel industries for the carbon-neutral generation of high-temperature heat required in numerous manufacturing processes.
- *Feedstock for materials*. Hydrogen is a flexible chemical building block and can therefore be used as a feedstock, combined with other feedstocks, in the production of various materials. For example, hydrogen can be used in the production of plastics, steel and fertilisers, as well as in the production of synthetic fuels for the shipping or aviation industries.[23] The large-scale use of climate-neutral hydrogen is expected not only to make existing industry more sustainable, but when used as a raw material, also to lead to the creation of new sustainable industries.
- F*lexible storage and transport of energy*. Hydrogen can be used in the electricity system to store large surpluses of electricity, to accommodate peak demand and long-term shortages, to balance supply and demand and to transport energy efficiently.
- *Fuel for transport*. In the transport and mobility sector, hydrogen is a possible alternative to carbon-emitting fuels such as petrol, diesel and kerosene. For example, hydrogen can be used in combination with fuel cells in trucks and also to produce synthetic fuels. The latter appears to be a particularly promising option for powering heavier means of transport over longer distances (heavy trucks, ships, aircraft).
- *Heating of houses and buildings*. In the built environment, hydrogen can be used to heat houses and provide domestic hot water. At present, natural gas is still largely used for this purpose. There are several alternatives, but each has its own advantages and disadvantages. For example, switching to fully electric heating or to a district heating system is expensive or complicated in some residential areas. Moreover, these solutions sometimes meet with resistance. Green gas may be a solution in these cases, but it is not yet available on a large scale. The cost of hydrogen, delivered via existing natural gas pipelines, will be lower than the cost of all-electric or district heating options by 2030 (PBL 2020a and PBL 2020b). Hydrogen could also play a role in hybrid solutions, such as hybrid heat pumps or in "topping up" district heating systems in situations where geothermal heat or waste heat does not provide sufficient capacity on a permanent basis or at peak load.

This means that sufficient cheap climate-neutral hydrogen must be available. As hydrogen is used in more ways, system efficiency may emerge. Both economies of scale and availability will then increase.

23 Hydrogen is already used on a large scale as a feedstock in ammonia production and in petrochemicals. According to estimates by TNO and CBS (2020), this involves about 175 PJ of hydrogen annually. This is hydrogen that is not produced in a climate-neutral way.

The extent to which hydrogen will actually be included in the applications outlined above differs from sector to sector and depends in part on the alternatives available. The balance between the advantages and disadvantages is not static, as both hydrogen and its alternatives are still being developed. This means that demand for hydrogen must be stimulated in a targeted and tailored way in order to ensure a greater role for hydrogen in certain sectors of the Dutch economy, if this is considered desirable.

2.4 Conclusion

The Council's conclusion is that energy carriers in the form of both molecules and electrons (i.e. electricity) will remain important for the Netherlands' energy supply. The molecules used will have to be climate-neutral. Climate-neutral molecules will also be indispensable for the supply of feedstocks in industry as an alternative to natural gas, oil and coal.

Among the various options, hydrogen emerges in many scenarios – sometimes as the only option available. The versatility of hydrogen is a factor here. Hydrogen can be used in various economic sectors as a clean, climate-neutral energy carrier, fuel and feedstock. Because, in this case, the supply of energy and feedstock is based on both electrons and molecules and because the two are interchangeable, system integration is possible. Interchangeability also increases the security of supply in the energy system.

But these expectations still have to be met, and that won't happen by itself. The use of hydrogen in the economy outlined above requires a fully-fledged hydrogen market, with associated production and transport chains. This market will not materialise without active government involvement. This aspect of the hydrogen issue is discussed in detail in the next section.

3 TOWARDS A FULLY-FLEDGED HYDROGEN MARKET

In this section, the Council sets out what is needed to develop a fully-fledged hydrogen market. Such a market is an essential condition for ensuring that hydrogen is involved in the economy as outlined in the previous section. In this section, the Council discusses a number of problems that arise in the construction of a hydrogen market (Section 3.1). Next, the preconditions for the creation of a hydrogen market are discussed. The first vital step is to reduce the price of hydrogen, which does of course depend on production costs (Section 3.2). Climate-neutral hydrogen will also need to be competitive. To this end, the government will have to put a price on the environmental impact of the currently cheaper fossil alternatives (Section 3.3). Finally, a nationwide infrastructure for the transport and distribution of hydrogen will have to be set up (Section 3.4).

3.1 Problems in building a hydrogen market

The Netherlands would benefit from a fully-fledged market for climate-neutral hydrogen with a combination of import, export and local production, adequate transport and storage facilities, plus a stable demand of sufficient volume from the various economic sectors. The Council predicts that a market for climate-neutral hydrogen in the Netherlands will not materialise without active government involvement. The main obstacles identified by the Council are:

1. the high start-up costs for infrastructure and technology that are associated with a market at the beginning of its development;
2. the lack of demand for climate-neutral hydrogen, due to the price advantage fossil energy sources currently enjoy over climate-neutral alternatives (as the social costs of external effects are not included in the price);
3. the unwillingness of market players to invest in infrastructure and in the production of climate-neutral hydrogen as long as the uptake is not guaranteed;
4. no sense of urgency among the general public as regards the importance of climate-neutral hydrogen for achieving the climate and sustainability objectives;
5. the risk of public resistance due to a perception that hydrogen is unsafe and unaffordable.

Without a targeted government policy, climate-neutral hydrogen cannot compete with the fossil-based, non-climate-neutral alternatives that are currently cheaper. It is therefore important to create conditions in which a stable demand for hydrogen can arise.

3.2 Cost of hydrogen production

The production costs of hydrogen are a key factor in the development of the hydrogen market. However, the exact production costs are not yet clear. The technologies for producing green hydrogen, and to a lesser extent blue hydrogen, are in fact still being developed. This means that costs are constantly being reduced and that cost estimates by independent parties are soon out of date. Cost reductions are the result of innovations, but in particular also of learning effects and economies of scale, for example in electrolysis technology and in the rest of the chain. In addition, the cost of hydrogen depends on many variables: the production technique (including the price of green electricity in the case of hydrogen production by electrolysis), the number of hours per year that the electrolysis plant is productive, the production location, and the method of transport. It is therefore unsurprising that published cost estimates for hydrogen differ greatly.

Since the cost of green hydrogen is based on the cost of electricity and the number of operating hours of the electrolysis plant, a breakthrough in price can be expected in the Sahara (with a current price of less than 2ct/kWh). However, large-scale imports can only be part of the hydrogen portfolio for reasons that will be discussed in detail in Section 4.3.

The overall picture of the costs for different production techniques is currently as follows:[24]

- Grey hydrogen is currently the cheapest option. The cost is estimated to be around €1.50 per kilogram. This cost is expected to rise as a result of rising CO_2 prices (and possibly also the price of natural gas, but that is far from certain).
- Blue hydrogen is slightly more expensive and costs between €1.50 and €2.50 per kilogram. The additional price compared to grey hydrogen is mainly determined by the cost of carbon capture, transport and storage. When these costs become lower than the price of carbon emissions, blue hydrogen will be cheaper than grey hydrogen. It is also important to note that the carbon capture rate during the production of blue hydrogen varies, depending on the technique, from 50% to over 90%. Recent projects have only involved techniques with high rates.
- Green hydrogen is currently the most expensive option, but it also has the greatest potential for cost reduction. Cost estimates range from €2.50 to €5.00 per kilogram in 2020 and from €1.50 to well over €3.00 per kilogram by 2030. In the period up to 2050, the price will fall even further, possibly to around €1.00 per kilogram. So it seems likely that green hydrogen will eventually become the cheapest option, but when this will happen is still very uncertain.

For reference, a quantity of natural gas with the same energy content as 1 kilogram of hydrogen was *traded* in the Netherlands in 2019 at a price of around €0.70 per kilogram. Since the outbreak of the coronavirus pandemic, however, the price has dropped to around €0.50 per kilogram.[25] If the cost of carbon emissions is also included in this price, it is about €0.15 per kilogram higher.[26]

The cost of hydrogen production and the volume at which hydrogen can be produced are two separate aspects. Thus, in addition to the cost of a particular production method, the volumes to be achieved are an essential factor in the development of a hydrogen market. It is uncertain whether, in a developing market, the *trading price* of climate-neutral hydrogen will be in line with the *cost price*.

3.3 Pricing the environmental impact of non-climate-neutral fuels and feedstocks

In the previously published advisory report *Towards a sustainable economy* (Rli, 2019), the Council outlined the broad raft of policy instruments the government can use to support a transition process. In that report, the Council advocated the use of pricing and regulation as instruments for promoting a more sustainable economy. This report follows that line.

Demand for hydrogen will have to be stimulated if a fully-fledged hydrogen market is to be achieved. This demand will not come about automatically; the government has a role to play here. However, the Council believes that

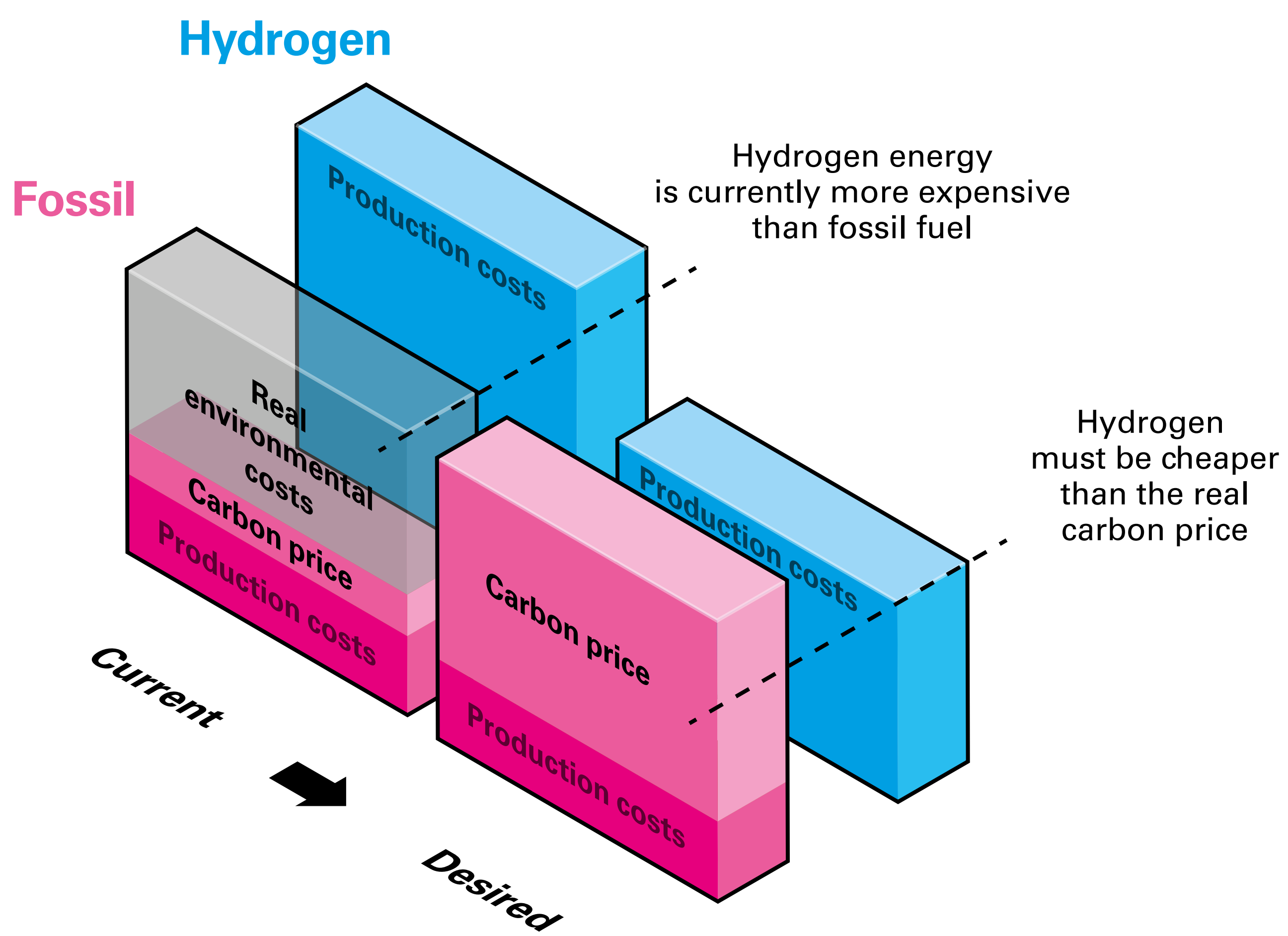
24 The Council has based the picture presented here on a large number of sources consulted and on various interviews with experts. See appendix containing key figures.

25 Source: www.theice.com

26 Based on a carbon price of €25/t and carbon emissions of 1.78 kg per m^3 of natural gas.

government subsidies should be used as little as possible to stimulate the demand for hydrogen. It is more effective for the government to raise the price level of non-climate-neutral alternatives. Only then will there be a consistent competitive position for climate-neutral hydrogen (and other climate-neutral alternatives). Figure 2 shows how pricing, when combined with cost reductions due to upscaling, can lead to a more favourable competitive position for climate-neutral hydrogen.

Figure 2: Pricing of environmental costs improves competitive position of climate-neutral energy carriers



Currently, the use of fossil fuels and feedstocks that produce carbon emissions is cheaper than the climate-neutral alternatives. This is mainly because the carbon impact of fossil production chains is only marginally discounted in the price of fossil fuels and feedstocks. This is a form of market failure: an external effect (in this case carbon emissions) is not included in the price of a product. As a result, the cost of the emissions is not borne by the customer but by society as a whole, which has to deal with the climate effects. Non-climate-neutral production methods and products are therefore considered “too cheap” and have a competitive advantage over sustainable products such as climate-neutral hydrogen.

The competitive position of climate-neutral hydrogen in relation to the alternatives differs from sector to sector. A sector-specific approach will therefore be needed. The Council makes the following distinction in this regard:

- Sectors not covered by the European Union’s Emissions Trading System (EU ETS)[27], such as the transport sector and the built environment sector, will require national measures to increase demand for climate-neutral hydrogen.
- For large industrial concerns and electricity producers that do fall under the ETS, this EU trading system is an effective instrument for stimulating the demand for hydrogen, especially when combined with the more stringent European climate targets and the EU plan that is being prepared

27 The Emissions Trading System (ETS), which came into force in the EU in 2005, is a system for trading emission allowances. If a company emits more than it has allowances, it must buy additional allowances. Conversely, a company can sell its allowances when it emits less. Together with the ever-decreasing emissions cap, this ensures that total carbon emissions are reduced cost-effectively.

for an import tax on products from outside the EU with a large carbon footprint.[28] However, the Council thinks that until this plan – known as the carbon border adjustment mechanism (CBAM) – becomes operational, the best way to stimulate the demand for hydrogen in these sectors is also to introduce specific national measures, provided that there is no unacceptable damage to their competitive position.[29]

Another instrument that the government could use to prevent products with negative external effects from being put on the market "too cheaply" is regulation: making the use of sustainable alternatives mandatory. The government can, for example, set a legal requirement for a certain percentage of blending. The advantage of this method is that the use of climate-neutral hydrogen can grow steadily and in a controlled way by gradually increasing the blending percentage. Which government instrument is preferable will differ from sector to sector. Table 1 in Section 6 containing recommendations discusses this in greater detail.

3.4 Creating a transport and distribution network

Increasing the price level of non-climate-neutral fuels and feedstocks, as discussed in the previous section, will only be effective if certain preconditions are met. The availability of infrastructure for the transport and storage of hydrogen is one such precondition. After all, if this is not the case, a levy on carbon emissions is primarily a tax rather than an incentive to invest.

Therefore, in order to create a fully-fledged hydrogen market, the government will have to ensure that a basic infrastructure is available to provide access to the market. This involves the construction of a hydrogen backbone covering the whole country, with connections for distribution, import and export. In addition, hydrogen storage facilities will have to be provided. The recently published TIKI report provides a useful overview of the infrastructure needed and the steps required to meet industry's needs.

A hydrogen exchange, along the lines of the electricity and gas exchanges, could then act as an economic coordination mechanism and catalyst for a market for climate-neutral hydrogen.

3.5 Conclusion

A fully-fledged hydrogen market will not materialise automatically. The government will have to implement targeted policies to make climate-neutral hydrogen competitive with fossil fuels and feedstocks that harm the environment. The Council believes that *pricing* (particularly at European level) and *regulation* (e.g. making the use of sustainable alternatives mandatory) should be used as instruments to promote demand for climate-neutral hydrogen. Finally, an infrastructure for the transport and distribution of hydrogen will have to be set up across the Netherlands.

28 EU Green Deal and carbon border adjustment mechanism.
29 See also PwC's recent "level playing field test" (2020).

4 STRATEGIC IMPORTANCE OF HYDROGEN FOR THE NETHERLANDS AND THE EU

This section looks at the international context of public investment in hydrogen and the strategic interests that may be served by it. First of all, we outline how government policy on hydrogen is developing in various countries inside and outside Europe (Section 4.1) and how the Dutch starting position for the development of a hydrogen market relates to the international playing field (Section 4.2). Next, the geopolitical importance of hydrogen is discussed (Section 4.3). We then consider the potential opportunities that hydrogen offers for making industry more sustainable (Section 4.4). Finally, the Council highlights the need to promote innovation processes involving hydrogen (Section 4.5).

4.1 International context

There is currently increasing awareness of hydrogen worldwide. Countries around the North Sea are investigating its possible uses. Germany's ambition is to become the world leader in the use of hydrogen as an energy carrier. To this end, the Federal Government has recently adopted a national

hydrogen strategy, including a funding package of €9 billion. The strategy is to build an industry around hydrogen. Denmark, Norway, Spain, France and the United Kingdom have also launched similar plans, at varying stages of development.
Hydrogen also plays an important role in the policy initiatives forming part of the European Commission's "Green Deal"[30].
Globally, several regions with surplus sources of green power generation (including the Middle East and North Africa) are turning their attention to the possibility of producing hydrogen. Australia is the most advanced country in this respect; it is working on a hydrogen transport chain to Japan, which has chosen to focus its energy and feedstock system mainly on hydrogen.

There is clearly a growing global momentum; the whole world is considering taking action. However, nothing is happening yet, with the world waiting for certainty about the development of demand and a sales market. Geopolitical considerations are another factor at play (see also Section 4 in Part 2[31]). Countries that are first to move and are able to develop a stable market demand for climate-neutral hydrogen will reap the benefits of building a competitive trading position and creating a location for new industry.

30 The Green Deal presented by the European Commission on 11 December 2019 is a set of policy initiatives with the overarching aim of making Europe climate neutral by 2050.
31 Not included in this translation. It is available in the complete Dutch version.

4.2 Starting position of the Netherlands

Compared to other countries, the Netherlands has a favourable starting position for using climate-neutral hydrogen as an alternative to oil, natural gas and coal. Below is a list of the favourable characteristics of the Dutch economy that are decisive in this respect (see also Section 3 in Part 2).

Dutch chemical industry already works with hydrogen

In the Netherlands, hydrogen is already being used on a large scale as a feedstock and auxiliary agent in the chemical industry (particularly in the production of artificial fertiliser) and in refineries. According to recent estimates (TNO & CBS, 2020), this amounts to about 175 PJ of (currently "grey") hydrogen.[32] In the chemical industry hydrogen is of particular interest because some production processes require high temperatures that cannot be achieved with electric boilers. Where temperatures above a few hundred degrees Celsius are required, hydrogen is a good alternative to electricity. In addition, hydrogen is a chemically versatile molecule that can be used as a building block for many products.

The hydrogen economy is not just about gas. There are various other carriers that can provide significant cost benefits, especially during the transition phase, because they can use existing assets and supply chains. Examples include ammonia and LOHC. A carrier such as ammonia can also continue to play an important role for specific markets in an end game.

32 Until recently it was assumed that 8 billion m^3, or about 100 to 110 PJ, of hydrogen was used annually in the chemical industry. However, TNO & CBS (2020) have found that hydrogen consumption, which is not a separate category in energy statistics, is actually much higher.

The North Sea offers potential for generating sustainable electricity

The Netherlands has space in its sector of the North Sea for the development of large wind farms. This green electricity will be needed to phase out grey electricity. Using some of this potential in wind energy, the Netherlands can play a leading role in developing “green” hydrogen production by means of electrolysis.

Various ways of producing climate-neutral hydrogen are feasible in the Netherlands

The Netherlands has the potential to produce climate-neutral hydrogen in various ways. First, there are the industrial complexes where CO_2 can be captured from hydrogen-containing intermediates such as refinery gas (see below). Second, CO_2 can be extracted from natural gas, after which the remaining hydrogen can be used to produce fertiliser, for example. Third, hydrogen can be produced using electrolysers close to renewable energy generation sites, for example where the electricity from offshore wind farms makes landfall, or located at the offshore wind farm itself. In the current economic situation, the industry generates high added value. Building a hydrogen economy in the right way can ensure that this added value is maintained.

The Netherlands has excellent facilities for carbon capture and storage

Dutch industry already has a great deal of experience with techniques for capturing the carbon emissions released during the production of hydrogen from natural gas or coal. To this end, for example, “gas scrubbers” are used to clean the flue gases post-combustion. There are also techniques that capture CO_2 pre-combustion.

The Netherlands also has options for storing captured CO_2 underground, for example in the empty natural gas fields under the Dutch sector of the North Sea. However, this capture and storage is not without disadvantages as it involves additional costs and energy consumption and the long-term management of the storage represents an additional challenge.

Existing Dutch network for gas transport and distribution can be used for hydrogen

Since the 1960s the Netherlands has had a high-quality, widespread network for transporting natural gas. This involves not only a backbone but also a widespread distribution network. Both types of network are technically suitable and already prepared for the transport of hydrogen. With the role of natural gas in our energy supply being phased out, there is an opportunity to use the gas pipeline network in a different way. The capacity released in the gas network forms a cost-efficient opportunity to create a hydrogen backbone. The main adaptation needed is the construction of compressor stations.

The Netherlands also has salt caverns in which hydrogen can be stored. Whether hydrogen can also be stored in empty natural gas fields is not yet entirely certain. What is clear, however, is that the Netherlands has plenty of scope for storing hydrogen at peak times. On average, this is the case (not only in the Netherlands but across Europe) for 200 to 600 hours a year.

All in all, the large-scale transport and storage of hydrogen will become an important part of the hydrogen market of the future.

Dutch ports also allow hydrogen imports

The geographical location of the Netherlands is also favourable when it comes to our starting position in developing a hydrogen market. Dutch seaports, including Rotterdam, IJmuiden, Delfzijl/Eemshaven and Vlissingen/Terneuzen offer the possibility of large-scale landfall and transit of imported hydrogen generated internationally using solar energy.

The Netherlands has relevant knowledge and experience

Dutch research institutes and numerous industrial concerns have extensive knowledge and experience with hydrogen-related technologies. TNO and Gasterra, for example, are conducting research into the production and transport of hydrogen. And in the industrial sector, potential applications are being developed by both the regional industrial clusters and individual companies.

The Netherlands has a strong position in trade, industry and the international energy field

Finally, the Netherlands benefits from favourable additional "soft factors" in the form of existing trade relations, large companies with knowledge of hydrogen and goodwill in the international energy field and energy diplomacy. These are factors that will help to build a competitive international position in the area of hydrogen and create a location for new hydrogen-related industry.

4.3 Choosing hydrogen in geopolitically turbulent times

The geopolitical setting is currently undergoing rapid change around the world, both within the EU and between the other world power blocs: China, the United States and the Middle East. There is less EU-wide coherence and less worldwide coherence, which makes the long international production and trade chains vulnerable. Moreover, the global coronavirus pandemic exposes the intrinsic vulnerabilities of the current system and geopolitical balance. Governments are supporting their own economies on a large scale in order to alleviate the economic crisis in their own countries. This distorts free competition and makes economic policy more nationalistic. At the same time, the European Commission has formulated additional ambitions to combat climate change, the EU wants to invest in the Green Deal and in the hydrogen economy, and countries are being urged to cooperate in this.

In these geopolitically and economically volatile times, what does a possible choice by the Netherlands for hydrogen during the energy transition mean? Is it wise to invest in hydrogen and if so, what is the best route to take?

The Council believes that the Netherlands could strengthen its role in the international hydrogen arena by choosing the right balance between (a) domestic production of hydrogen, (b) EU production of hydrogen and (c) importing hydrogen from non-EU countries. The Netherlands will have to align the role that hydrogen is to play explicitly and deliberately with the desired degree of dependence on other countries and with the desired contribution to European and international developments in the area of energy and feedstocks. Which types of supplies from which countries do we want to be dependent on and what level of dependence gives rise to a sufficient “level of comfort”?

In 2019, the Clingendael International Energy Programme (CIEP) outlined two scenarios showing how the world might develop geopolitically between now and 2032 and what this would mean for the role of hydrogen in Dutch long-term energy and climate policy (CIEP, 2019):

- Scenario 1: A decrease in international trade and cooperation makes national security of supply and protection of the domestic economy more important. Climate policy is kicked into the long grass.
- Scenario 2: Increased international cooperation makes it possible to reach binding agreements on limiting carbon emissions, creating the necessary preconditions for developing sustainable energy production on Dutch soil and a more sustainable industry.

The Council believes that in the event of both favourable and less favourable geopolitical trends, using hydrogen to facilitate the energy and feedstocks transition is a solid and safe choice that can help to establish a sufficient “level of comfort” for the Netherlands. The Council also notes that there is a trade-off to be made by the government: opting for the cheapest hydrogen (e.g. imported from outside Europe) may entail greater dependence, while opting for in-house production and generation of hydrogen may mean a higher price level.

4.4 Opportunities for making Dutch industry more sustainable

Given the global economic, energy and climate challenges, it is important for the national government to consider its own earning and production capacity in order to (a) kick-start and maintain the economy, (b) meet the national demand for energy and feedstocks, and (c) achieve the climate targets and meet the commitments in the climate agreement.

The Netherlands currently occupies a powerful position in global energy and feedstock flows. However, there is no guarantee that the Netherlands will retain this position once the energy transition has made further progress. The Netherlands will have to make efforts to achieve this through targeted government policy. It needs to direct its attention to facilitating innovation in and the sustainability of strong domestic industries, especially in the vital and strategic sectors. Encouraging the use of hydrogen provides opportunities to do so. Many industrial processes that are currently responsible for considerable carbon emissions can be made climate-neutral if the industry concerned switches to hydrogen.

Strategic sectors include chemicals (including the production of new fuels and new plastics and the recycling of existing plastic products), fertiliser production (which will remain necessary even with sustainable forms of agriculture) and the steel industry. The process of increasing sustainability is relevant to both new (i.e. circular) and existing industry: they need not be mutually exclusive.

4.5 The importance of promoting innovation in hydrogen technology

The large-scale use of hydrogen outside the chemical and petrochemical industries and plans to make all hydrogen production climate-neutral are still in the early stages of development, while the fossil routes and chains have long been developed and optimised. It will be possible to reduce the cost of hydrogen substantially once the necessary learning curve in the field of hydrogen has been completed and production can take place on a much larger scale. But there are significant barriers, as innovation is expensive, results are uncertain and successes can be quickly copied by competitors. That is why the Dutch government has a task here too: to promote and accelerate the innovation process for hydrogen technology.

The government can promote innovation in climate-neutral hydrogen technology in various ways. According to the Council, it is important that the Dutch government chooses a targeted strategy that plays to the strengths of the Netherlands and the opportunities that exist for our country in the various uses of hydrogen.[33] It is also important to monitor the development of innovations and to adjust the incentive strategy accordingly, focusing on the most promising alternatives. Examples include:

- making a budget available for research and development and
- providing finance to facilitate pilot projects.

33 The report "*Waterstof: kansen voor de Nederlandse industrie*" provides an overview of opportunities and possibilities for Dutch industry (Reijerkerk & Van Rhee, 2019).

How much money the Dutch government should make available for such measures depends on the importance it attaches to industrial policy and geopolitics. It is likely that innovations in the hydrogen chain will take place somewhere in the world, anyway; the question is what part does the Netherlands want to play in this, possibly in collaboration with other northwestern European countries? If the Netherlands wishes to play a leading role, as the Council advocates in this advisory report, it must invest substantial sums in the short term. In the longer term, this could lead to a strong Dutch hydrogen industry.

4.6 Conclusion

Given the international momentum, the Council believes it is important for the Dutch government to take steps in the short term to exploit the favourable starting position our country has in terms of developing a hydrogen market. The Council believes that using hydrogen to facilitate the energy and feedstock transition is a sound and safe choice, in the event of both favourable and less favourable trends in the global geopolitical situation. By investing in innovation in hydrogen technology now, the Netherlands will be able to create a strong hydrogen industry in future. In the current economic situation, the industry generates high added value. Building a hydrogen economy in the right way can ensure that this added value is maintained. The Council believes that this will not only benefit the economy and the future supply of energy and feedstocks, but will also help to achieve national climate targets.

5 ESSENTIAL PRECONDITIONS

Before a hydrogen market can develop, the government must ensure that a number of essential preconditions are met. These preconditions include a legal framework covering the production, transport, storage and use of hydrogen. In addition, society will have to be prepared to accept the increased role of hydrogen in various applications in our homes and on our streets, the fact that it is needed and the costs that it will incur. It is also vital to focus explicitly on and invest in safety.

5.1 Legal framework for production and handling of hydrogen

As yet there are no regulations governing the required quality and purity of manufactured hydrogen or the mandatory addition of odorant (“odorisation”). Neither is there any legal basis as yet for the transport of hydrogen by the operators of regional natural gas networks. In addition, a licensing system will have to be put in place for issues such as the safe supply of hydrogen to households, the certification of metering installations and the qualifications of maintenance engineers.

5.2 Public acceptance of hydrogen

The fact that hydrogen will play an increasing role in the public domain, because it is necessary to ensure an affordable, reliable and climate-neutral supply of energy and feedstocks, will have to become part of the collective Dutch consciousness. The government will have to prepare the general public for the fact that hydrogen will become an integral part of our society, whether in our homes or more remotely in the production, storage and transport of hydrogen. It will have to explain in an accessible way that the transition from fossil energy sources to climate-neutral energy and feedstock sources will take place via temporary transition measures, such as the use of blue hydrogen until such time as there is sufficient green electricity available for the production of green hydrogen.

There will inevitably be additional costs during the transition phase, which will also have to be clearly communicated. To ensure public acceptance, it is vital to set out clearly how the additional costs are to be shared between the public and industry and between population groups.

The Council warns against painting too rosy a picture as regards the cost of the transition to hydrogen. Every form of renewable energy will have the effect of increasing prices, especially during the transition. This applies to both industrial customers and consumers. As the computer models used to draw up the regional energy strategies become more detailed, the cost of using hydrogen in the built environment, for example, is becoming clearer.[34] This information can be used by the government to provide transparent communication with the public about the cost aspect of using hydrogen for heating homes.

5.3 Safety of hydrogen use in public spaces

A third precondition that will have to be met by government before a hydrogen market can develop is the establishment of safety standards for the use of hydrogen in public spaces. These standards must be based on sound real-world research. Hydrogen is no less safe than other energy carriers but it is important that there is more knowledge about the risks of hydrogen. We must prevent large-scale applications coming onto the market that are not safe enough because the government has not set any standards for them. After all, this could lead to incidents that cause damage, potentially reducing public support for hydrogen.

However, simply setting safety standards is not enough. Attention must also be given to preparing society for the introduction of new hydrogen-related technologies. More than other technologies, hydrogen sometimes gives rise to unjustified negative associations among the general public, such as the hydrogen bomb and the Hindenburg airship disaster. Regardless of whether these associations are justified or not, what matters is that the risk assessment involved in the introduction of hydrogen is accepted, including

34 See, for example, Startanalyse aardgasvrije buurten; Achtergrondstudie [Start Analysis for Natural Gas-Free Districts; Background Study] (PBL, 2020a) and Waterstof voor de gebouwde omgeving; Operationalisering in de startanalyse 2020 [Hydrogen for the Built Environment; Operationalisation in the Start Analysis] (PBL, 2020b).

the risks posed by current and alternative energy carriers.[35] Clear rules for the safe handling of hydrogen must be established in order to minimise the risks.[36]

The public debate should distinguish between the types of risk that may be involved in the use of hydrogen and its alternatives: risks to people and safety, risks to the environment, risks to the economy and risks to society. At each stage in the decision-making process, from hydrogen visions to the elaboration of regional energy strategies, the public must be involved and engaged in terms of dealing with these risks.

5.4 Conclusion

It is essential for the government to create a legal framework for the production, transport, storage and use of hydrogen. At the same time, the public will need to be prepared for hydrogen becoming an integral part of society. The government will have to provide clear communication about the additional costs to be incurred during the transitional phase. Another matter for the government to attend to is to ensure that safety standards and regulations are drawn up to cover the safe handling of hydrogen in public spaces, so that the risks are kept to a minimum.

35 Current energy carriers also carry risks, such as gas explosions and cases of carbon monoxide poisoning.
36 See also the advisory report Risks assessed (Rli, 2014), in which the Council discusses these points in more detail.

6 RECOMMENDATIONS

In the final section of Part 1 of this advisory report, the Council discusses the concrete measures that the national government can and should take in the near future to promote to the best of its ability the strategic importance of hydrogen to the Netherlands. The Council has set this out in six recommendations to the government.

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1. Invest in the establishment of a hydrogen backbone with import and export facilities in the short term

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A precondition for the creation of a hydrogen market is the presence of a basic infrastructure for hydrogen, consisting of storage facilities, import and export facilities and a backbone linking these facilities to the industrial clusters where supply and demand are located. A nationwide hydrogen backbone with import and export facilities is an essential part of this basic infrastructure. This network will not come into being without government involvement. However, given the presence of a natural gas network that can be exploited for hydrogen transport, the cost of establishing a hydrogen backbone is relatively low and the public investment required will therefore be limited. In time, this network will play an essential part in society by helping to ensure the security of supply of energy and feedstocks.

2. Emphasise safety and public support more explicitly in policy

It is important that the safety of new technology is carefully and comprehensively examined in advance, ensuring that safety standards are incorporated into the design of products before they are widely marketed. The government must make a budget available for this. This is an essential precondition for the deployment of hydrogen in various applications in the public domain and should therefore be given top priority.

In addition, the government should actively focus on gaining public support for the development of a Dutch hydrogen market. In the first place, this involves clear communication about the need for hydrogen and a dialogue about the safety risks associated with the use of both hydrogen and its alternatives. Local initiatives to promote hydrogen can make a valuable contribution. In addition, the affordability of hydrogen must be taken into account in policy. Instruments to intervene in the distribution of costs among the public or businesses could be considered.

3. Stimulate demand for climate-neutral hydrogen

The government must ensure that climate-neutral hydrogen can compete with non-sustainable alternatives. Only then will there be a demand for hydrogen that is consistent with the blueprint for the future of various sectors of the Dutch economy. In theory, the best way to create demand is to price carbon emissions. The price level will rise as a consequence, making climate-neutral alternatives more competitive. In its advisory report "Towards a Sustainable Economy", the Council also advocates reversing the burden of proof with regard to the competitive disadvantage and carbon leakage effects resulting from levies of this kind if they were only to apply in the Netherlands.

In the case of climate-neutral hydrogen, a carbon price of well over a hundred euros per tonne would currently be needed for it to be able to compete. The level playing field test indicates that industry's margins are tight, the options for sustainability are still limited and the risk of carbon leakage is considerable.[37] It is therefore important that carbon emissions pricing is effected at EU level.[38] This is provided for in the EU plan for an import tax on products from outside the EU based on their carbon footprint. The Netherlands must make a case for this carbon border adjustment mechanism (CBAM) in Brussels. The Netherlands should also push for a further tightening of the European carbon emissions trading system, ensuring that the price industry has to pay for its carbon emissions will continue to rise.

37 The "level playing field test" is a study into the impact of the announced climate policy on the competitive position of Dutch industry, conducted by PwC (2020).
38 It must be ensured that products such as steel, aluminium and cement cannot be imported free of tax from countries where industrial companies are not subject to strict climate regulations. This is provided for in the EU plan for an import tax on products from outside the EU based on their carbon footprint.

The international competitive position of energy-intensive industry in the Netherlands does not currently allow for the national increase in the carbon price that would be required to make climate-neutral hydrogen competitive. Decision-making at EU level is slow and uncertain. Other instruments will therefore now have to be used to create a demand for hydrogen and a hydrogen market.

At national level, government can make hydrogen competitive through specific measures in each sector. In aviation, shipping and the built environment, a physical or administrative blending obligation for suppliers of fossil fuels will be the most effective way of achieving this. Tax incentives or a requirement to use climate-neutral hydrogen will work better in other sectors. Table 1 and Figure 3 provide an overview of measures that could be considered.

In the longer term, it is expected that the rising ETS price combined with the falling cost of climate-neutral hydrogen will provide sufficient momentum to make climate-neutral hydrogen competitive. These instruments are therefore of a temporary nature. These are choices to be made until 2030 to create a Northwest European playing field; after 2030 the use of instruments will have to be reassessed.

4. Do not exclude any forms of hydrogen production when developing a hydrogen market

The production of blue hydrogen, based on natural gas and industrial waste gases with carbon capture and storage, will be an important transition technology for the next fifteen to twenty years. Although the blue hydrogen variant is not 100% climate-neutral, it can assist in the creation of a hydrogen market. In the current economic situation, the industry generates high added value. Building a hydrogen economy in the right way can ensure that this added value is maintained. Blue hydrogen capacity also contributes to the security of supply, even in the longer term when more and cheaper green hydrogen (produced by means of electrolysis) becomes available. Imports of hydrogen are another possibility, but *complete* dependence on hydrogen produced outside the EU is undesirable because of the importance of maintaining security of supply. The Netherlands will probably have to accept a higher price for hydrogen, as it does now for oil and natural gas.

Figure 3: Measures to be taken in each sector to stimulate demand for climate-neutral hydrogen

Aviation

- Introduce a physical requirement to blend with carbon-free kerosene for use in aviation, if possible throughout the EU.

Built environment

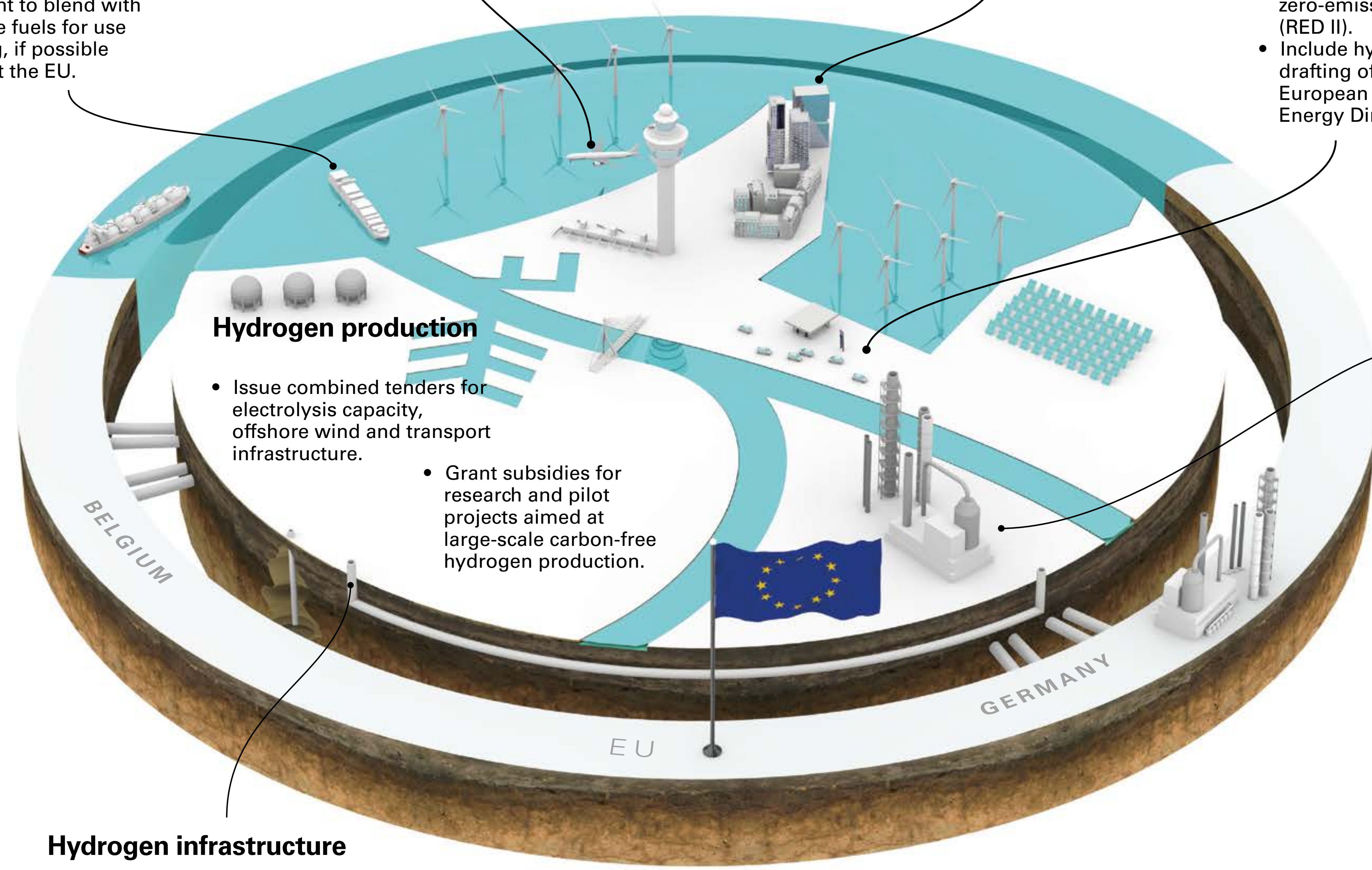
- Administrative requirement to blend with carbon-free gas for use by natural gas suppliers.
- Introduce an energy tax exemption for carbon-free gas.

Shipping

- Introduce a physical requirement to blend with carbon-free fuels for use in shipping, if possible throughout the EU.

Road transport

- Tax incentives for zero-emission vehicles (RED II).
- Include hydrogen in the drafting of the revised European Renewable Energy Directive.



Hydrogen production

- Issue combined tenders for electrolysis capacity, offshore wind and transport infrastructure.
- Grant subsidies for research and pilot projects aimed at large-scale carbon-free hydrogen production.

Industry

- Introduce a requirement combined with subsidies for
  - replacing grey hydrogen with blue hydrogen;
  - users switching from low-calorific gas to hydrogen.
- Grant subsidies for research and development of new applications for hydrogen.

Hydrogen infrastructure

- Instruct Gasunie to install, manage and assume system responsibility for a nationwide hydrogen transport network.

EU policy

- Emission Trading System
- EU carbon border adjustment mechanism.

5. Provide financial support for production and other technologies that promote the creation of a Dutch market for climate-neutral hydrogen technology

Various hydrogen technologies could contribute to the creation of a Dutch climate-neutral hydrogen market: combined carbon capture and storage, combined power generation and hydrogen production from offshore wind, hydrogen storage in salt caverns and the production of hydrogen-based fuels.
The government should provide financial support to ensure the ongoing development of this type of technology.[39] This could be done by, for example, drawing up “contracts for difference”, under which manufacturers of products made using these relatively expensive technologies are refunded the price difference by the government. These arrangements would make it possible to establish major parts of the hydrogen value chain within the Netherlands, which has strategic advantages. In time, it could also contribute to the earning power of the Dutch economy.

39 The report “Waterstof: kansen voor de Nederlandse industrie” provides an overview of opportunities and possibilities for Dutch industry (Reijerkerk & Van Rhee, 2019).

6. Actively pursue cooperation in the EU and with neighbouring countries and develop a stronger international orientation

When it comes to securing a meaningful position in the hydrogen market, the Netherlands has the advantage over other countries that it is already an international energy hub. To exploit this advantage to the full and help make Europe more sustainable, active efforts must be made to promote European cooperation. In particular, cooperation with Germany and Belgium or at any rate in the Pentalateral region[40] should be further intensified to ensure a coordinated roll-out of the hydrogen market and a high degree of security of supply.

40 Benelux, Germany, France, Austria and Switzerland.

Table 1: Instruments for increasing demand for hydrogen, broken down by sector

Sector	Instruments	Flanking policy
Built environment sector	• Introduce an administrative requirement for suppliers of natural gas to households to blend in carbon-free gas. • Introduce an energy tax exemption for carbon-free gas.	• Establish rules and safety requirements for the use of hydrogen in the built environment.
Mobility sector – road transport	• Provide tax incentives for zero-emission vehicles. • Include hydrogen in the drafting of the revised European Renewable Energy Directive (RED II).	• Establish nationwide refuelling infrastructure for hydrogen vehicles by including requirements in the concessions and subsidies. • Establish rules and safety requirements for the use of hydrogen in public spaces. • Encourage sustainable mobility by establishing environmental zones. • Use zero-emission vehicles in public services (refuse vehicles, buses, etc.).
Mobility sector – aviation	• Introduce an increasing physical requirement to blend in carbon-free kerosene for use in aviation, if possible throughout the EU.	
Mobility sector – shipping	• Introduce an increasing physical requirement to blend in carbon-free fuels for use in shipping, if possible throughout the EU.	
Industrial sector	• Introduce mandatory substitution of grey hydrogen with climate-neutral hydrogen, combined with subsidies. • Introduce a mandatory switch from low-calorific gas to hydrogen, combined with subsidies. • Establish subsidies for research into and the development and roll-out of new hydrogen applications (steel production, green chemicals, synthetic fuels).	
Energiesector – waterstofinfrastructuur	• Instruct Gasunie to develop a hydrogen backbone, including storage in salt caverns and connections to Belgium, Germany and the North Sea.	• Provide legal and financial support for initiatives to build a carbon infrastructure. • Consider ways of organising the market and integrating private infrastructure. • Establish subsidies for research into the possibilities of storing hydrogen in empty gas fields and other suitable locations.
Energiesector – waterstofproductie	• Issue combined tenders for building electrolysis capacity, offshore wind farms and transport infrastructure. • Establish subsidies for research and pilot projects aimed at large-scale carbon-free hydrogen production.	

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APPENDICES

KEY FIGURES

Introduction

There are many figures in circulation about hydrogen. To be able to interpret them and estimate their value, some basic knowledge of the units used and the underlying assumptions is required.

Prices

The price of hydrogen is often expressed as €/kg. In this report, the quantity is therefore expressed as a measure of weight, unlike the prices for electricity and natural gas, which are usually expressed as a measure of energy (€/MWh or €ct/kWh) or as a measure of volume (€ct/m^3). This unit is practical to use, as cost estimates are typically in the range of 0.5 to 5 €/kg. To express the price of hydrogen as a measure of energy, the following conversion factors can be used:

1 €/kg = 8.33 €/GJ = 30 €/MWh = 3 €ct/kWh.

A conversion factor is also needed to compare the price of hydrogen with the price of natural gas in m^3. 1 kg of hydrogen has the same energy content as 3.4 m^3 of natural gas (both 120 MJ), therefore:

1 €/kg of hydrogen = 0.29 €/m^3 of natural gas.

One option for producing hydrogen is to use an electrolyser. The capacity of an electrolyser is expressed as electrical power: kW, MW or GW, depending on the size. The cost of an electrolyser is generally expressed as €/kW. Estimates of the current and expected future costs of an electrolyser are in the range of 100-1,000 €/kW.

When hydrogen is produced from electricity, the purchase price of electricity is a major component of the cost price of hydrogen. As a rule of thumb, one can say that 10 €/MWh of electricity corresponds to 0.5 €/kg of hydrogen (excluding other costs such as CAPEX), 20 €/MWh of electricity corresponds to 1.0 €/kg of hydrogen and so on. This assumes a conversion efficiency of 80% (Hydrogen Europe, 2020).

Something similar applies to the relationship between the price of grey hydrogen and the price of CO_2. Each 10 €/tonne of CO_2 contributes 0.1 €/kg to the price of grey hydrogen (Hydrogen Europe, 2020).

Quantities

When writing about the quantities produced in major hydrogen projects or the hydrogen consumption of whole countries, the kg is not a very practical unit. In this case, these quantities are expressed as Mton (=10^9 kg) or as PJ (=10^{15} Joule, a unit of energy). Based on the lower heating value (LHV), the ratio is 1 Mton = 120 PJ (or 1 kg = 120 MJ) (Institute for Sustainable Process Technology, 2019).

Estimates of the current annual hydrogen consumption in the Netherlands vary widely. The most recent estimate comes from TNO and CBS (TNO & CBS, 2020), who estimated consumption at 1.48 Mton or 178 PJ. Precise estimates of consumption in the Netherlands are difficult to obtain because a large part of the production is for internal use and is therefore not recorded. The TNO and CBS estimate is based on the assumption that hydrogen production is running at 90% capacity.

Almost 60% of the total amount of hydrogen is obtained from natural gas. The rest comes from oil (37%), coal (3%) and electricity (1%). The main applications of hydrogen are its use in refineries (37%), the production of ammonia (33%) and methanol (7%) and its use as a fuel (13%). In addition, hydrogen is used on a smaller scale in a wide range of industrial applications. The consumption of hydrogen is entirely concentrated in the five large industrial clusters. The largest consumer is Rotterdam Moerdijk (44%), followed by Zeeland (32%), South Limburg (14%), Delfzijl (7%) and IJmond (3%) (TNO & CBS, 2020).

To estimate the amount of hydrogen produced by an electrolyser of a given power, two assumptions have to be made:

1. The amount of electricity required to produce 1 kg of hydrogen. This is currently between 40 and 60 kWh/kg, depending on the technology used (Kearney Energy Transition Institute, 2020). This amount is expected to decline steadily over the coming years.
2. The load factor: the number of hours per year that an electrolyser is actually “on”. This varies depending on the business model and the

sources to which an electrolyser is connected. For example, at near-maximum utilisation, 8,000 hours/year can be assumed. However, if the only source is an offshore wind farm, this is not feasible and an estimate of 4,000-5,000 hours is more realistic. For example, the plans for a 10 GW wind farm on the North Sea recently presented by the NortH2 consortium, consisting of Shell, Gasunie and Groningen Seaports,[1] refer to a production rate of 800,000 tons of hydrogen per year, which is equivalent to: 10 GW (= 10,000,000 kW) times 4,000 hours/year, divided by 50 kWh/kg = 800,000 tons of hydrogen.

Cost estimates (now, 2030, 2050)

Several recent cost estimates for hydrogen production are available, according to the production method used. Various forms of blue hydrogen (mainly produced using steam methane reforming (SMR) and autothermal reforming (ATR)) and green hydrogen (mainly produced using solar and wind energy) are discussed. The production location (the Netherlands, Morocco, onshore/offshore, etc.) is also important. Because of the rapid decline in prices, the year (2020, 2030, 2050 and beyond) to which the estimate relates is another important factor. The estimates vary, even when these differences are taken into account. This indicates that there is still a considerable lack of clarity about current production costs and much uncertainty about the future trend of these costs.

1 See https://nos.nl/artikel/2324772-plannen-voor-het-grootste-europese-waterstofproject-in-groningen.html

In a 2018 study, CE Delft compared the costs of three hydrogen chains: blue and green from North Sea wind and green from Moroccan sun.[2] This leads to the following cost estimates:

	Integral costs	vs	marginal costs
€/kg:	*2017 => 2030*		*2017 => 2030*
• Blue:	1.6 => 2.2	vs	1.0 => 1.7
• Green-wind (North Sea):	5.2 => 2.9	vs	2.5 => 1.7
• Green-sun (Morocco):	4.1 => 2.2	vs	1.8 => 1.2

Mulder & Perey (2019) estimate the current production cost of hydrogen as follows:

- Blue – SMR: 1.5 – 2 €/kg (depending on carbon capture rates and transport costs).
- Green – electricity from the wholesale market: 3.6 €/kg.
- Green – offshore electrolysis: 2.8 €/kg excluding transport to land, 4.0 €/kg including transport to land.

M. Visser (2020) estimates the cost trend for green hydrogen from the Sahara, based on projections by Bloomberg New Energy Finance, as follows:

- Current production costs: 2.7 €/kg
- By 2030: 1.4 €/kg
- By 2050: 0.8 €/kg

2 Afman, M. & Rooijers, F. (2017). Net voor de Toekomst: achtergrondrapport. Delft.

Plus an additional 0.3 €/kg for transport by pipeline from the Sahara to the Netherlands.

In a recent scenario study, Berenschot & Kalavasta (Den Ouden *et al.*, 2020) arrive at the following figures[3]:

Type of hydrogen and production method	2025	2030	2035
Grey SMR	By 2025: 1.8 €/kg	By 2030: 1.9 €/kg	By 2035: 2.0 €/kg
Blue SMR	By 2025: 2.3 €/kg	By 2030: 2.3 €/kg	By 2035: 2.4 v/kg
Blue ATR	By 2025: 2.3 €/kg	By 2030: 2.3 €/kg	By 2035: 2.3 €/kg
Green NL PEM	By 2025: 2.4 €/kg	By 2030: 2.2 €/kg	By 2035: 2.1 €/kg
Green NL Alkaline	By 2025: 2.2 €/kg	By 2030: 2.1 €/kg	By 2035: 1.9 €/kg
Green Portugal PEM	By 2025: 3.2 €/kg	By 2030: 2.9 €/kg	By 2035: 1.8 €/kg
Green Portugal Alkaline	By 2025: 3.0 €/kg	By 2030: 2.8 €/kg	By 2035: 1.7 €/kg

It should be noted that Berenschot & Kalavasta (2020) assume that by 2035 it will be possible to transport hydrogen from Portugal to the Netherlands by pipeline. Whether this will be achieved is very much open to question.

3 Ouden, B. den, Kerkhoven, J., Warnaars, J., Terwel, R., Coenen, M., Verboon, T., Tiihonen, T. & Koot, A. (2020). Klimaatneutrale energiescenario's 2050: scenariostudie ten behoeve van de integrale infrastructuurverkenning 2030-2050. Utrecht: Berenschot.

RESPONSIBILITY AND ACKNOWLEDGEMENTS

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Expert meeting on the Built Environment, 22 January 2020

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Expert meeting on Hydrogen in Mobility, 22 January 2020
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Chris van Dijk, RAI Vereniging
Jeroen Erens, Leaseplan
Carlijne Mouthaan, Shell
Jean-Paul de Poorter, H2-platform
Marc van der Steen, Rebel
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Expert meeting on Industry, 15 January 2020
Kees Biesheuvel, Dow Benelux B.V.
Katharina Gruenberg, Shell
Jaap Oldenziel, Air Liquide
Harro van de Rhee, ExxonMobil
Joost Sandberg, Nouryon

Expert meeting on the Energy System, 15 January 2020
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Pallas Agterberg, Alliander
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OVERVIEW OF PUBLICATIONS

2020

Access to the city: How public amenities, housing and transport are the key for citizens. [Toegang tot de stad: Hoe publieke voorzieningen, wonen en vervoer de sleutel voor burgers vormen]. September 2020 (Rli 2020/06)

Stop Land Subsidence in Peat Meadow Areas: The ‘Green Heart’ Area as an Example. [Stop bodemdaling in veenweidegebieden: het groene hart als voorbeeld]. September 2020 (Rli 2020/05)

Green Recovery. [‘Groen uit de crisis’]. July 2020 (Rli 2020/04)

Changing Tracks: Towards Better International Passenger Transport by Train. [‘Verzet de wissel: naar beter internationaal reizigersvervoer per trein’]. July 2020 (Rli 2020/03)

Soils for Sustainability. [‘De Bodem bereikt?!’]. June 2020 (Rli 2020/02)

A Grip on Hazardous Substances. [‘Greep op gevaarlijke stoffen’]. February 2020 (Rli 2020/01)

2019

Towards a Sustainable Economy: The Governance of Transitions. [‘Naar een duurzame economie: overheidssturing op transities’]. November 2019 (Rli 2019/05).

Desirable Tourism: Capitalising on Opportunities in the Living Environment. [‘Waardevol toerisme: onze leefomgeving verdient het’]. September 2019 (Rli 2019/04).

European Agricultural Policy: Working Towards Circular Agriculture. [‘Europees Landbouwbeleid: inzetten op kringlooplandbouw’]. May 2019 (Rli 2019/03).

Aviation Policy: A New Approach Path. [‘Luchtvaartbeleid: een nieuwe aanvliegroute’]. April 2019 (Rli 2019/02).

The Sum of the Parts: Converging National and Regional Challenges. [‘De som der delen: verkenning samenvallende opgaven in de regio’]. March 2019 (Rli 2019/01).

2018

Warmly Recommended: Towards a Low-CO_2 Heat Supply in the Built Environment [‘Warm aanbevolen: CO_2-arme verwarming van de gebouwde omgeving’]. December 2018 (Rli 2018/07)

National Environment and Planning Strategy: Litmus Test for the New Environmental and Planning Policy ['Nationale omgevingsvisie: lakmoesproef voor de Omgevingswet']. November 2018 (Rli 2018/06)

Accelerating Housing Production, While Maintaining Quality ['Versnellen woningbouwproductie, met behoud van kwaliteit']. June 2018 (Rli 2018/05)

Better and Different Mobility: Investing in Mobility for the Future '[Van B naar Anders: investeren in mobiliteit voor de toekomst']. May 2018 (Rli 2018/04)

The Healthy City: Delivering Health Through Environmental and Planning Policy ['De stad als gezonde habitat: gezondheidswinst door omgevingsbeleid']. April 2018 (Rli 2018/03)

Sustainable and Healthy: Working Together Towards a Sustainable Food System ['Duurzaam en gezond: samen naar een houdbaar voedselsysteem']. March 2018 (Rli 2018/02)

Electricity Provision in the Face of Ongoing Digitalisation ['Stroomvoorziening onder digitale spanning']. February 2018 (Rli 2018/01)

2017

A Broad View of Heritage: The Interactions Between Heritage and Transitions in the Physical Environment ['Brede blik op erfgoed: over de wisselwerking tussen erfgoed en transities in de leefomgeving']. December 2017 (Rli 2017/03)

Energietransitie en leefomgeving: kennisnotitie. December 2017 (Rli 2017) [only available in Dutch]

Land for Development: Land Policy Instruments for an Enterprising Society ['Grond voor gebiedsontwikkeling: instrumenten voor grondbeleid in een energieke samenleving']. June 2017 (Rli 2017/02)

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