TKI NIEUW GAS
Topsector Energie

Outlines of a **Hydrogen Roadmap**

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5 Key Messages about Hydrogen

1 We can achieve our climate objectives for 2050 with hydrogen

Hydrogen is important for being able to achieve the social challenge of drastically reducing CO_2 emissions. It is a robust option that offers many possibilities for production and application, and fulfils a system role. Hydrogen can make a contribution to all transition pathways. It appears to have the greatest added value for industry (High-Temperature Heat and raw materials) and for transport (heavier segments). In addition to and in combination with other sustainable options, hydrogen is an essential element in the energy transition.

2 'Hydrogen' requires an integrated vision on the energy transition

Hydrogen has many interfaces with other major 'themes' in the climate debate: energy efficiency, the rollout of wind and solar-PV, the desirability and possibilities of CCS, the use of biomass, the use of existing infrastructure and the construction of new infrastructure, the need for system flexibility and storage, etc. The Dutch Climate and Energy Agreement, which is being prepared, is a good arena for holding such discussions and for presenting a vision with clear choices for the future.

3 Grey, blue and green hydrogen; as long as the final picture is sustainable

Hydrogen requires large-scale application to be successful. All three types, grey (fossil), blue (climate-neutral hydrogen via CCS) and green (sustainable) hydrogen, can help to accelerate the process and achieve the right scale. Each of these options has a different timescale, volume and cost. Grey hydrogen helps to get the market going, but the 'net development direction' is towards hydrogen with an ever decreasing CO_2 footprint, until it is fully sustainable. This objective should be secured in the approach, e.g. through clear CO_2 footprint targets for hydrogen.

4 Do not wait, but start with hydrogen today; we will then be ready later on

There is a lot of interest in initiating sustainable and climate-neutral hydrogen projects, as is shown by a wide range of over 100 initiatives in industry, transport, the built environment and power generation. Various regions and industrial clusters also seriously want to get started. The projects may help tear down barriers on an institutional and social level. Also, the Netherlands is not an island; international relations – especially with Germany and Belgium, but also further abroad – will have to be developed further. Both industry and the authorities will have to invest to make pilots and demos possible. Mutual coordination is required to guarantee maximum learning and sharing.

5 Keep innovating with hydrogen

One of the major challenges is to reduce the costs for the production and application of hydrogen. This can be done by scaling up (creating mass) and by innovating. A mission-driven innovation programme with ambitious objectives and a coordinated approach is required to achieve the desired progress. The Netherlands has an excellent knowledge infrastructure to be among the very best internationally in this field.

Summary

The focus on hydrogen as an energy carrier is greatly increasing on an international level and a lot is also being done on a national level. The Netherlands currently has over 100 hydrogen initiatives in various stages of development, and this number is growing. In the specification of the transition pathways of the Dutch Energy Agenda, hydrogen is emerging as one of the pillars of the energy transition, in addition to all kinds of other sustainable and climate-neutral options. To gain greater insight into the role hydrogen may play for the energy transition and the steps that will have to be taken towards achieving this, the Ministry of Economic Affairs and Climate Policy has asked TKI New Gas (Top Sector Energy) to manage the drafting of a Hydrogen Roadmap. This document, which was drafted in collaboration with TKI Energy & Industry, describes the outlines of such a roadmap. During its preparation, input from approximately 150 persons and organisations was gratefully used.

Hydrogen may play a major role in the huge social challenge of drastically reducing CO_2 emissions. It is a robust element for the energy transition, which may provide a sustainable solution to the constant need for fuels and raw materials – the 'molecules' of industry and transport in particular – apart from the greatly increasing role of sustainable power (the electrons) in this sector and others.

The production of hydrogen from water through electrolysis offers a flexible mechanism for the medium and long term to make good use of the huge potential for wind and solar energy. It fulfils a crucial system role. Buffering and storage will allow this mechanism to support the incorporation of these resources via the electricity route, but it should mainly be viewed as an option for using wind and solar energy to make fossil fuels and raw materials more sustainable and to replace them. Furthermore, the hydrogen route offers a solution to limitations faced when transporting electricity. In the future, the large-scale import of sustainable hydrogen from areas with great potential for sustainable energy, especially solar-PV and wind, will also be interesting and probably necessary, as shown by indicative calculations for the potential of hydrogen in various applications.

The concept of hydrogen as an energy carrier is relatively new, but it has been globally produced on a large scale for a long time as an industrial gas for many industrial applications. As such it is mainly produced on the basis of natural gas. Decarbonisation of natural gas through the application of CCS (Carbon Capture and Storage) and the use of hydrogen as an energy carrier may contribute significantly to the reduction of CO_2 emissions in the short and medium term; the conversion to hydrogen allows natural gas to be used for energy supply in a climate-neutral manner. The broad use of hydrogen as an energy carrier for mobility and transport, in the industry and the energy sector, and possibly also in the built environment, offers a realistic opportunity to achieve the required large-scale reduction of CO_2 emissions and at the same time facilitates the transition to sustainability by building a future-oriented infrastructure. It is expected that large sections of the current natural gas system can be used for this, which could contribute to a cost-effective energy transition.

Climate-neutral hydrogen is the bridge towards fully sustainable hydrogen; it can help initiate production and application, as long as sustainable electricity can still be easily absorbed in existing electricity markets. In terms of technology, CCS for the production of climate-neutral hydrogen is available, but no large-scale demonstrations have been developed yet under Dutch conditions, partly because of the ongoing public debate on this theme. Incidentally, this 'sustainability mechanism' should be monitored to prevent a fossil lock-in from occurring.

Apart from the various applications of hydrogen, the system role it may fulfil is also important. The conversion of electrical energy generated through sun and wind into chemical energy in the form of hydrogen ensures that large amounts of wind and solar energy can be stored relatively easily and can be transported over large distances. This makes the variable supply of sun and wind available and controllable in terms of time and location. The large-scale import of sustainable energy from wind and sun in the form of hydrogen or related compounds, such as ammonia, will therefore be one of the options in the future. Finally, the broad applicability of hydrogen adds even more flexibility to the energy system, as various markets are interconnected, such as industry, mobility and the built environment. This will also allow peak demand for energy to be covered fully sustainably in the future.

Apart from this potential and the many opportunities, there also remain, for the time being, many challenges. The technology to produce and apply hydrogen (electrolysis, fuel cells, burners) is already available, but the cost price will have to drop considerably in order to compete with current, often fossil-based alternatives. It is expected that, as a result of research and development into new materials, optimisation of components and systems, and upscaling of system sizes and production numbers, it will be possible to achieve serious cost price reductions. Similarly, the cost of sustainable electricity, which is a crucial ingredient for electrolysis, may reduce further. The question, however, is at what market price it can be purchased later on with large-scale production.

Apart from technology, other aspects that are highly important for the successful development of hydrogen are financing, regulations, codes and standards, market development, safety, the Human Capital Agenda (aimed at making the required workforce available) and public acceptance. That is why these themes should be integrated in the development of hydrogen.

We propose a three-pronged approach in order to develop hydrogen in the Netherlands:

1. **Integrated plan and vision building for hydrogen**
   This track focuses on the ‘meta-issues’ that play a role for hydrogen as an energy carrier. Part of this is the specification of the system role played by hydrogen, for example, in connection with the rollout of sustainable electricity production in the North Sea and elsewhere, the expected position of CCS, the timeframe within which the large-scale import of wind and solar energy in the form of hydrogen could be feasible, the future of the natural gas infrastructure and the role of biomass in the production of renewable gases. On the demand side, plans for increasing sustainability in industry are important, the degree of electrification in the transport sector, the role of controllable gas-fired power stations if the share of solar and wind is large, and the nature and scale of the need for renewable gas in the built environment. Good quantitative substantiations are required for this. Suitable reference points as a time horizon are 2030 and 2050. In view of the importance for the new Dutch Climate and Energy Agreement, the proposal is to incorporate the plan and vision building in it, e.g. in the coordination committee.

2. Putting hydrogen into practice over the next 3-5 years
In order to build up knowledge and experience, and to show hydrogen projects to stakeholders (including society), pilots are required with applications that are already available. Good starting points are industrial application on a larger scale for the production of hydrogen as a raw material and for High-Temperature Heat, and in the transport sector (such as logistics, buses, refuse collection vehicles). These projects provide the option to test the social, institutional and economic aspects in addition to the technical implementation. Industrial clusters, logistics centres and regions are suitable locations for such an approach.

3. Research, development and demonstration for hydrogen
The key R&D questions regarding hydrogen should be addressed and tackled to lower the costs of hydrogen production and application, to increase the efficiency of the technology, to develop new processes, to develop the application of more widely available materials and to show these in pilots with the ultimate goal of developing a sustainable, reliable and affordable supply of hydrogen. A mission-driven long-term innovation programme would be suitable for that purpose. The Top Sector Energy will take the initiative for such a programme in collaboration with other top sectors, such as Chemistry and Logistics.

Management is important within the proposed approach, to safeguard the interconnection between all the hydrogen activities and to monitor developments regarding hydrogen as part of a sustainable energy and raw materials system. This is the management function, which aims to achieve objectives efficiently and effectively, prioritise themes, coordinate matters between projects, programmes and regions, as well as providing open communication on these aspects, including accountability and monitoring. International issues, the Human Capital Agenda and the development of a transparent market are also part of this. Apart from safeguarding the 'meta-issues' as proposed under 1. (linking to the Climate and Energy Agreement coordination committee) the H_2-Platform could also be a suitable means for the mobility-related rollout. Within industry this could possibly be taken on by each of the five industry regions in the Netherlands separately, with information sharing between the industrial clusters being a key element.

In view of the robustness of hydrogen in our energy and raw materials system, it would be desirable to organise and initiate the aforementioned activities as soon as possible. Our advice for the coming period would therefore be to further specify this roadmap with stakeholders and enshrine it in the Climate and Energy Agreement, to determine what the most useful and effective organisation (type) is, what should be prioritised and how private and public funding can be secured. This will allow us to work on the successful introduction of sustainable hydrogen in our energy and raw materials system.

The outline document for the Hydrogen Roadmap outlines how hydrogen can contribute to the energy transition and includes an action plan that describes which steps can be taken to develop hydrogen into a serious option in the Netherlands.

0 | Background

Motivation

In July 2017, the Ministry of Economic Affairs and Climate Policy (EZK) asked TKI Gas to manage the process to define the outlines of a roadmap for hydrogen. This was because it had become apparent that the hydrogen theme was gradually gaining attention: the H_2 Platform (formerly the National Hydrogen Platform), the members of the NWBA (National Hydrogen and Fuel Cell Association) and WaterstofNet had already been developing hydrogen initiatives for quite a while and various coordinated activities were launched on a regional level, like in the north of the Netherlands, the Rotterdam region and on Goeree-Overflakkee. In the discussions about the transition pathways of the Energy Agenda, it also became apparent that sustainable and/or climate-neutral hydrogen could play a key role in fulfilling the need for 'molecules' in our energy and raw materials system. Additionally, ideas were gaining strength to partially convert the large wind potential into hydrogen and, as a result, to facilitate its incorporation into our energy system by providing storage and infrastructure alternatives. Increasing numbers of reports were received from abroad about large-scale hydrogen activities, such as the H_2 Mobility project in Germany, the development of hydrogen cars in Japan and South Korea, the launch of the 'Hydrogen Council' and the signing of a hydrogen manifesto by international companies in Switzerland in 2017. The hydrogen theme appeared to be more obviously present once again on national and international agendas.

Objectives

Because of these developments, the need for a roadmap arose, which provides better insight into the position that hydrogen could fulfil in the Dutch energy system and indicates the contribution that could be made to the energy transition. This roadmap could then initiate the further development of policies, especially for the ministries of Economic Affairs & Climate Policy and Infrastructure & Water Management. The Ministry of Economic Affairs & Climate Policy attached the following objectives to the roadmap:

1. Outlining the potential of sustainable hydrogen in the energy supply in 2050;
2. Mapping out the various actions and actors in the Netherlands regarding sustainable hydrogen;
3. Defining the initial steps and actions that would help to realise the potential of sustainable hydrogen and the role the central government and other parties are expected to play in this process.

The request was to involve the key players in the field of hydrogen as much as possible in the development of the roadmap, creating a vision that has wide support.

Process/approach

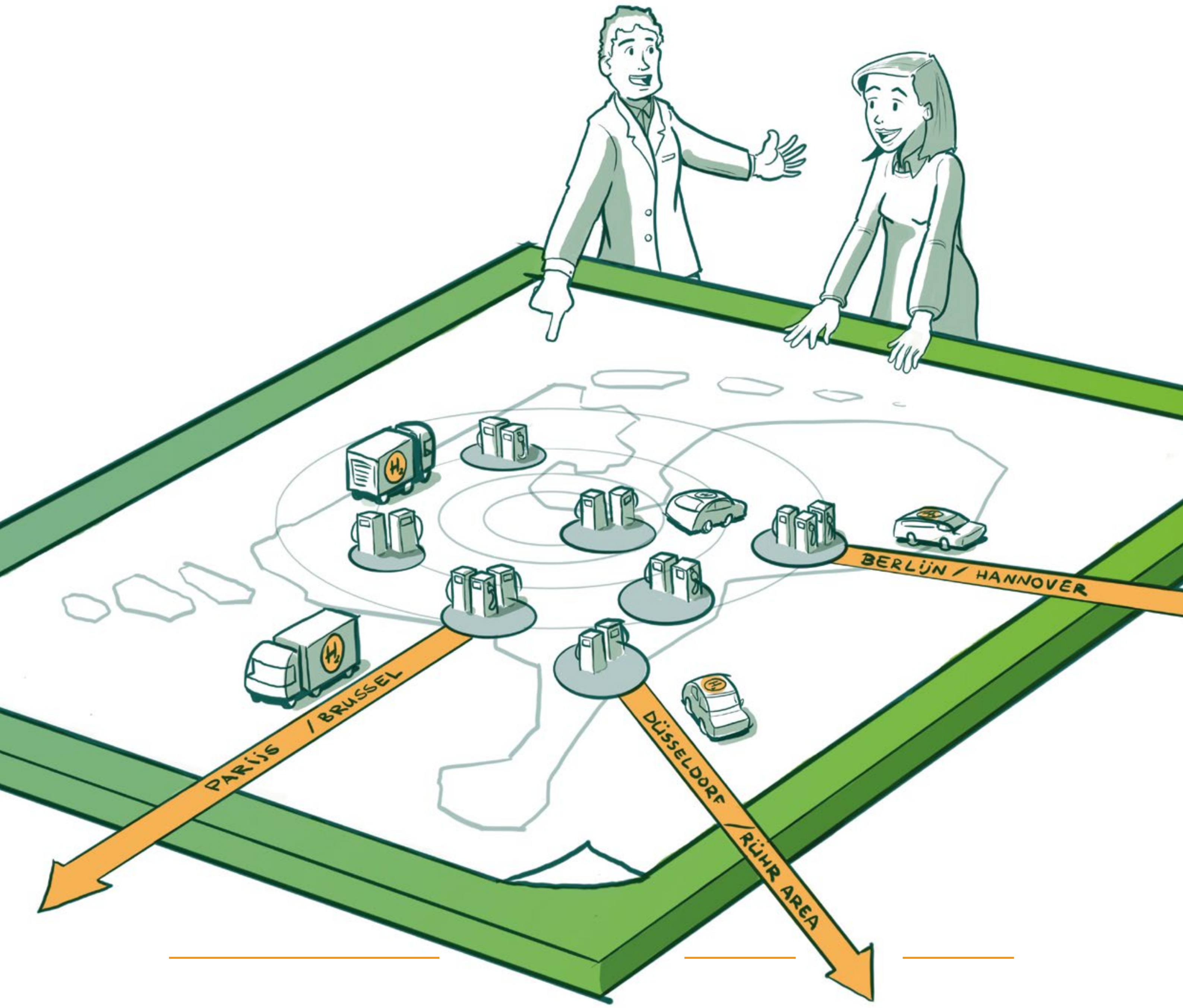
In order to prepare a roadmap within the available time, a three-pronged approach was chosen. First of all, two specific assignments were set out to gather information on the following subjects:

- Developments regarding hydrogen projects in the Netherlands and the lessons that can be learnt from them;
- The possibilities of the natural gas network to accommodate larger quantities of hydrogen, including potential locations and time-related availability.

Secondly, discussions were held with various parties involved in hydrogen, such as WaterstofNet, TU Delft, TKI New Gas (board) and TKI Energy & Industry, ECCM programme, Differ, VEMW, Akzo, Gasunie, VDL, Netbeheer Nederland and various other parties; Appendix 1 contains a full overview.

Thirdly, three workshops were organised in collaboration with the H_2 Platform involving its members. During these workshops, experiences and insights were shared and evaluated, and elements of the roadmap were further elaborated. Each meeting had 30 to 50 participants.

This input, combined with the experience and expertise of the persons who compiled this roadmap, has resulted in this outline document for the Hydrogen Roadmap. It outlines how hydrogen can contribute to the energy transition and includes an action plan that describes which steps can be taken to develop hydrogen into a serious option in the Netherlands. The roadmap is not yet complete; there are still various questions that have not been fully answered due to the limited time and resources. These questions will be addressed in the approach.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Ultimately, replacing fossil energy sources with renewables is the most important option to fully reduce greenhouse gas emissions and shape a sustainable energy supply.

1 | Introduction

General framework

A drastic reduction in greenhouse gas emissions is required in the short term to be able to mitigate global warming and climate change. The goal of international climate agreements, laid down in the Paris Agreement, is to limit global warming to well under 2°C and to aim for a maximum global warming of 1.5°C. The coalition agreement of the Rutte III government also focuses on this goal and states that it is our duty ‘to do everything we can to achieve this objective’. To this end the government wants to take measures ‘that prepare us for a reduction [in greenhouse gas emissions] of 49% in 2030’. At COP23 in Bonn, Minister Wiebes (EZK) indicated that he wanted to be one of the frontrunners in the EU and was jointly considering a reduction percentage of 55%.

In a European context we have set ourselves the aim of reducing greenhouse gas emissions by 80-95% in 2050 compared to the levels in 1990. These objectives require a rapid and fundamental change to the energy system. When taking into account greenhouse gas emissions that are difficult to reduce, such as those of livestock farming and ore processing[1], the objective basically means that the net greenhouse gas emissions related to the use of fossil energy sources[2] would have to be reduced to ‘zero’ in 2050.

Three major challenges for a sustainable energy supply

Ultimately, replacing fossil energy sources with renewables[3] is the most important option to fully reduce greenhouse gas emissions and shape a sustainable energy supply. Sun and wind undoubtedly play a major role here, in addition to biomass, which currently still provides the greatest share of sustainable energy. Solar energy is the most widely available source by far. In addition, there is a considerable potential for wind energy in the Netherlands, especially on the North Sea. The supply of these sources, however, fluctuates to a great extent and is inherently uncertain. Incorporation (system integration) and making maximum use of these sources is one of the biggest challenges for a sustainable energy supply.

As solar and wind energy are mainly produced with technology that generates electricity, the focus here is primarily on integration in the electricity system.

1 Examples are emissions of the powerful greenhouse gas methane in livestock farming and CO_2 emissions released during the processing of ores and rocks that contain carbonate.
2 Energy sources or primary energy carriers: coal, lignite, oil and natural gas.
3 Solar energy, wind energy, sustainable biomass, geothermal energy and hydropower

Solutions can be found in (1) reinforcing connections between various markets (interconnection), allowing supply peaks to be distributed over a greater area, (2) achieving an optimum balance between supply and demand through additional flexible production (e.g. rapidly controllable gas-fired power stations) and consumption (demand side management), and (3) storing electrical energy, for example, in battery systems and artificial lakes. Additionally, (4) increased electrification in various fields increases the demand outlets for electricity. Examples of these are transportation (battery-powered electric vehicles), heat supply in the built environment (hybrid and electric heat pumps) and industry (mechanical vapour recompression or industrial heat pumps, direct electric heating and electrochemistry).

The share of electricity in final energy consumption in the Netherlands is currently about 20%, and is estimated to double to 40% in 2050 as a result of electrification[4]. This means that, even if electrification were to accelerate and were to end up, for example, at 50% or even more, there would still be a great need for fuels ('molecules'). Full replacement by the middle of the century of our molecules, namely the current gaseous and liquid, carbon-containing fossil fuels[5], by climate-neutral variants therefore is the second major challenge in the transition towards a sustainable energy supply.

Making industry more sustainable is the third major challenge for achieving a sustainable energy supply. Fossil energy sources are also used there on a large scale as a raw material and reactant to produce a wide range of chemical products and materials (such as plastics), and steel. Alternatives will also have to be developed for this based on renewable energy sources and climate-neutral starting materials. So far, solutions have been mainly sought in options based on the use of sustainable biomass, just as for fuels (biofuels, green gas, etc.). However, the availability of sustainable biomass will probably not be sufficient to fully replace fossil energy sources for these applications. Other solutions based on climate-neutral sources of carbon (incl. circular carbon[6], and carbon from CO_2 in the air, an option also known as Direct Air Capture) combined with energy from other renewable sources are required here.

Hydrogen as a basis for climate-neutral molecules

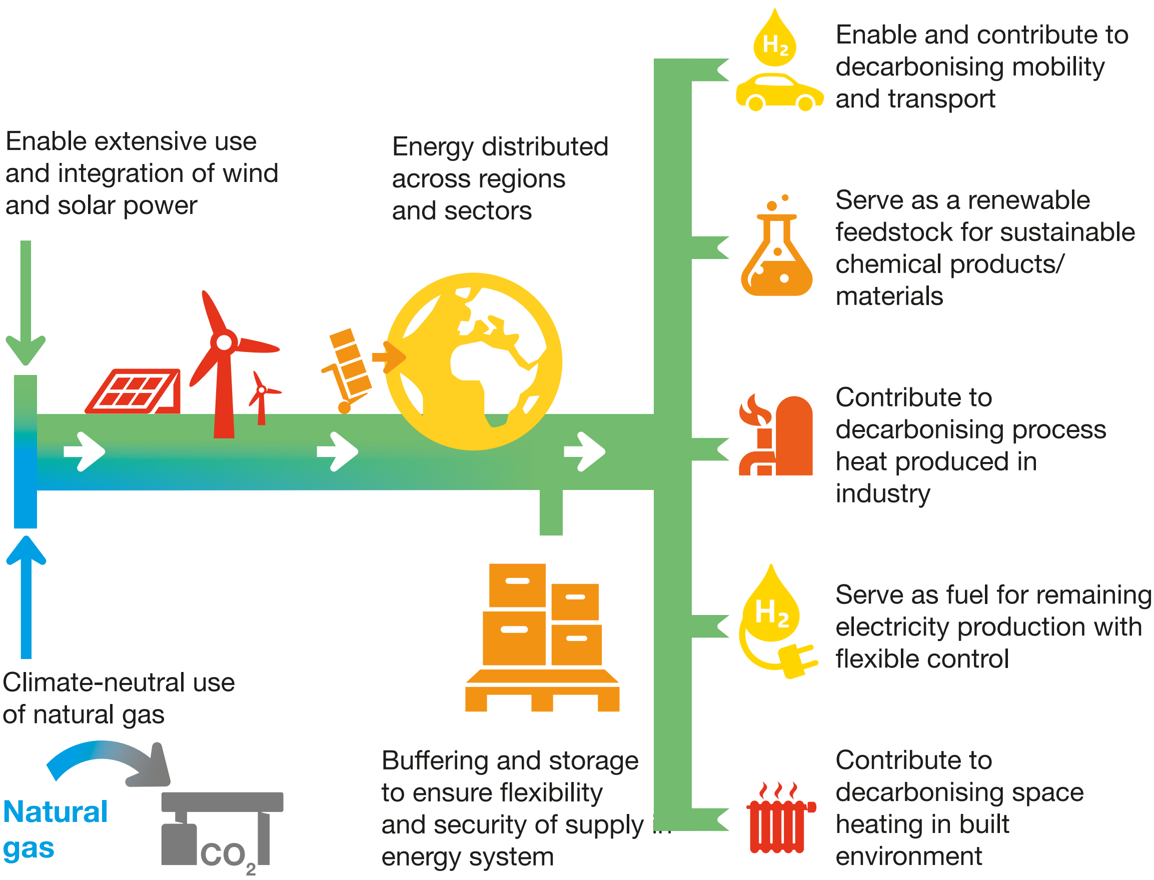
In the challenges outlined above – integration of variable sustainable energy, replacement of fossil fuels and raw materials with renewables, and making industry more sustainable – hydrogen could potentially play a key role in all the solution pathways. The reasons for this are the following:

4 Energy Roadmap 2050, EU, 2012. This roadmap is based on 21% electrification in 2030 and 36-39% in 2050 (2016 = approx. 19%)
5 Secondary energy carriers: petrol, diesel, LPG, natural gas (including CNG and LNG)
6 Circular carbon means carbon from CO_2 or CO that is formed during the incineration or gasification of waste, which is then used again as a raw material for new chemical products and materials.

- **Hydrogen is an important industrial gas; it is widely used in industry as a raw material, reducing agent or process gas in many processes and applications.** Bulk consumers are ammonia production and oil refining. Currently it is almost completely produced on the basis of natural gas. This type of fossil hydrogen can be replaced with hydrogen produced via the electrolysis route, making it fully sustainable. Hydrogen can also be produced from fossil resources in a largely climate-neutral manner if the CO_2 released at point sources is captured and stored. In future, the demand for hydrogen as a raw material for industry will increase further: this is because chemical products and materials, as well as synthetic fuels, will be increasingly based on biomass and circular carbon. These raw materials require addition of hydrogen in order to produce the hydrocarbon compounds that make up most chemical products and materials, and fuels.
- **Hydrogen can be widely used as fuel for boilers and furnaces. It can be used for the production of high-temperature process heat in industry,** especially for temperature levels exceeding 250°C, where only limited alternatives are available. If necessary it can also be used for Low-Temperature and where required also for Low-Temperature Heat for space heating in the existing built environment. The latter is indirectly possible by feeding heat networks, but possibly also directly through a central heating boiler or hybrid heat pump connected to houses, buildings and urban districts.
- **The production of hydrogen by splitting water by means of electricity (electrolysis) offers a flexible mechanism for integrating the variable supply of wind and solar energy.** Just like natural gas, hydrogen can be relatively easily transported and buffered in pipeline systems and stored in tanks and underground reserves. In this way, the electrolysis route allows large quantities of wind and solar energy to be stored to bridge periods in which the supply from these sources is limited. It adds a lot of flexibility to the electricity system. Conversion back to electricity is possible using power stations and combined heat and power plants based on gas turbines or fuel cells, although this option will be expensive due to the expected low number of operating hours.
- **Hydrogen is a suitable transport fuel.** Together with batteries, hydrogen in combination with fuel cells provides the option to fully electrify a wide range of vehicles, mobile equipment and possibly also ships, and to make them ‘zero emissions’. The advantage of hydrogen is that a relatively large amount of energy can be stored in tanks, with the weight and volume not scaling proportionally to the amount of energy, as is the case for batteries. In addition, the tanks can be filled up quickly, also in case of larger amounts. The option is therefore well suited to electrification of the more energy-intensive mobility and transport applications, especially if long-term and flexible use of vehicles is required. For applications that (for the time being) cannot be electrified, hydrogen is an essential component for the (sustainable) synthetic fuels that are required as replacement for the current fossil fuels. Examples are synthetic kerosene for aviation and liquid fuels for larger sea-going vessels.

In view of the limited surface area of the Netherlands and the intensive use of space, the question is whether we have enough options ourselves to produce all the sustainable energy required for the energy transition. Additionally, it may also be cheaper to import sustainable energy. Sustainable energy is currently mainly being imported in the form of biomass, which is basically a form of solar energy, and electricity produced using wind energy or hydropower in neighbouring countries. Hydrogen adds other possibilities to this. Elsewhere in the world there are vast areas with huge potential, in particular for solar and wind energy. With the rapidly reducing costs of solar panels and wind turbines, and the forecast cost reductions for electrolysis, it will in future be possible to produce sustainable hydrogen there on a large scale and at low cost. If required or cheaper, this form of sustainable energy import may in the future be a good supplement to our own production of sustainable energy and the import of biomass. Import from far-away regions may be performed with tankers, for example, in the form of liquefied hydrogen or as a compound with nitrogen in the form of ammonia. The roles and functions that hydrogen could fulfil are schematically presented in Figure 1.

Figure 1 | Schematic representation of various roles and functions of hydrogen
(source: the figure is a modified version, the original can be found in 'Hydrogen Council, Hydrogen scaling up, November 2017').



Hydrogen as an accelerator of the energy transition

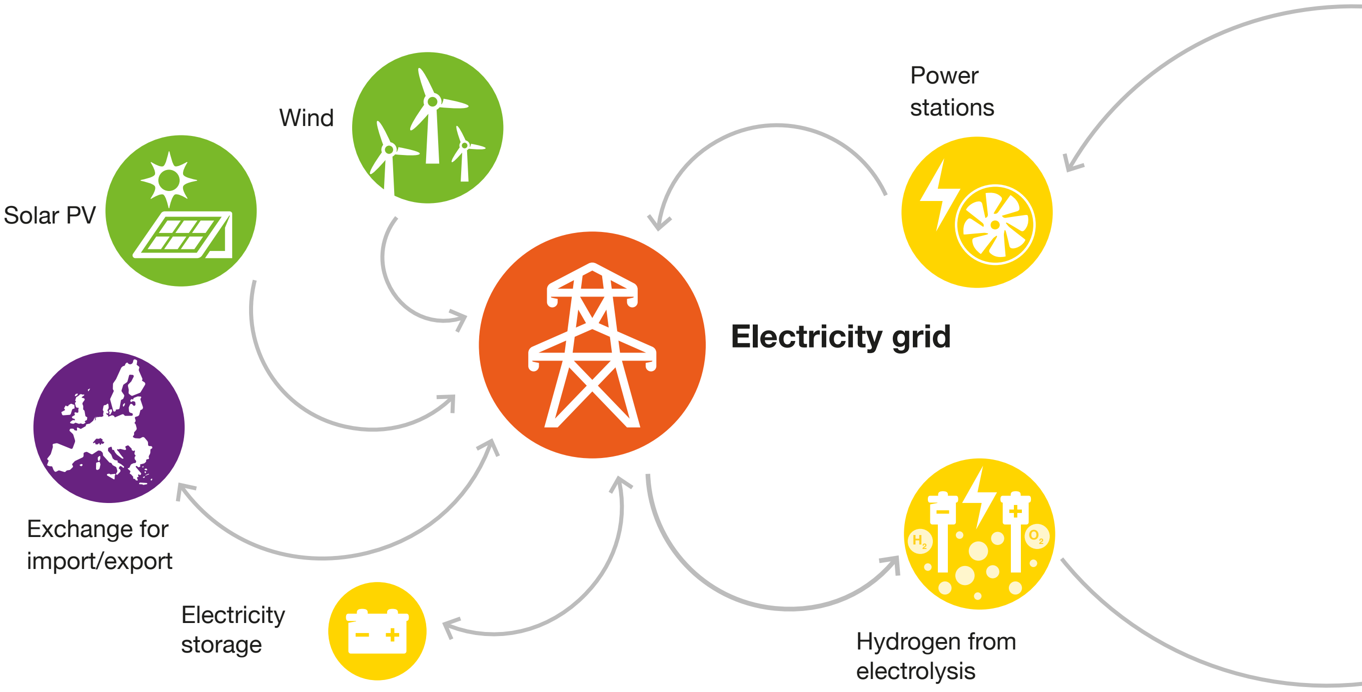
Apart from the perspectives offered by hydrogen for a sustainable energy and raw materials supply in the future, it may in the short term also play a key role in the transition towards it. Hydrogen is currently being produced highly efficiently on a large scale from natural gas for various industrial applications. A relatively concentrated stream of CO_2 is released during this production, which can be captured and stored underground (CCS), or utilised as feedstock in the chemical industry (CCU). When combined with a gas-fired power station for the production of electricity, this is known as the pre-combustion capture route.[7] However, central production with local use of hydrogen in industry, in transportation, in power stations and in the built environment is also possible. The current pipeline infrastructure for natural gas can be used here to transport and distribute the hydrogen. This allows natural gas to be used in a climate-neutral manner and a considerable acceleration of the decarbonisation of the energy supply to be achieved. As the transition progresses, with sustainable energy being further implemented and sustainable hydrogen production becoming cheaper due to development and upscaling, it will then be possible for sustainable hydrogen to cover a gradually increasing share of the energy mix.

Summarising it can be stated that, due to its diversity in terms of production and application options, hydrogen has a very big chance of fulfilling a key role in the sustainable energy system of the future and in the transition towards it.

It is an important basis for the molecular needs of our energy and raw materials system. The greatest advantage of hydrogen may be that it can fulfil a system role. After all, not only does hydrogen offer advantages in the various fields of application, like in industry, transport and electricity production, a key added value lies in the integrating role that hydrogen can play as a flexible intermediary between all the production methods, application options and as storage. As a result, a fully sustainable, efficient, flexible and integrated energy and raw materials system can be created, which is reliable and affordable, and can offer the right level of supply security. Figure 2 presents an illustration of the system function of hydrogen in a sustainable energy and raw materials system.

7 The 'Hydrogen in the energy transition' report by Berenschot and TNO (Nov 2017) contains a further explanation.

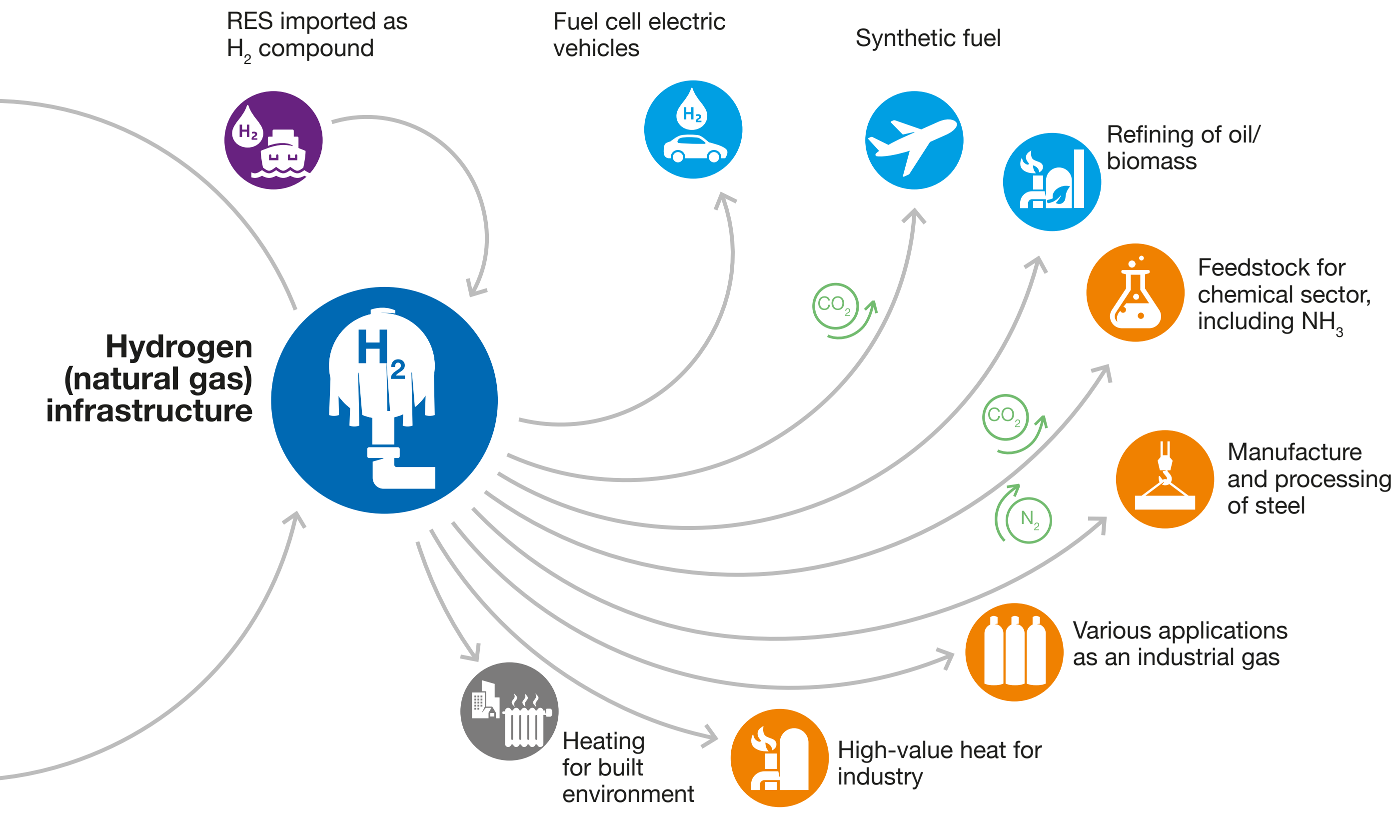
Figure 2 | System function of hydrogen in a sustainable energy and raw materials system
(source: the figure is a modified version, the original can be found in 'NREL, H2@Scale workshop report, March 2017').



Hydrogen in a force field of options

A future, in which hydrogen plays a major or even a dominant role is definitely not a 'fait accompli'! The actual application of hydrogen will partly depend on alternatives that are in development or will be developed and the actual success of these alternatives. Examples are replacement of fossil gaseous and liquid fuels with biomass-based variants and battery-powered electric transport. In the built environment, insulation in houses and buildings is constantly getting better, so more and more options are being created to use hybrid and fully electrical heat pumps to meet the remaining demand for heat. Other developments are heating and cooling of buildings using heat and cold storage systems and heating of horticultural greenhouses, for example, with geothermal heat. Industrial heat pumps and deep geothermal energy can possibly be used to meet part of the demand for process heat in industry, although there are also possibilities in the process industry for completely new processes that use efficient electrochemical synthesis routes and have much lower heat requirements as a result.

The mutual competition and relationship between alternatives is a dynamic and non-linear process. Just like many other options for a sustainable energy supply, the use of hydrogen is not yet a well-established option in many applications and a lot of experience still needs to be gained and developments need to occur to arrive at an optimised solution. Some options are somewhat more developed than others, but they are all still in full development.



It is important to explore and try out every serious option that presents itself in the best possible manner, and not to exclude any options right away. The uncertainties are too big for that right now. An assessment framework that contains a 'merit order' of options and applications would be desirable for this.

Due to the versatile production and application options of hydrogen, the extent to which it can be integrated into and is suitable for our changing energy and raw materials system, and the fact that it can be used in a fully climate-neutral manner, hydrogen could be highly important for the energy transition. Because of the diversity and promising prospects in various markets outlined above, it will be necessary to consider hydrogen in an integrated manner as well, to specify the system role, like the option to generate flexibility, to offer seasonal storage, to separate energy generation and application, as transport over large distances is possible and efficient, and to absorb highs and lows in supply and demand. This desired integration should not lead to delays in the production and application of hydrogen due to the associated complexity. It is important to start early, allowing the system role of hydrogen to be developed, explored and utilised in the best possible manner. Reducing the cost price of the technology and eliminating barriers are part of this. The more than 100 initiatives currently underway or in preparation in the Netherlands (see C8) and the many international initiatives in this field are good steps in that direction.

Only this time, the focus is not limited to mobility and transport applications, but is widely aimed at the entire supply of energy and raw materials. Among other things, this is because of the greatly increased feeling of urgency to reduce greenhouse gas emissions quickly and drastically.

2 | History and hydrogen initiatives from the recent past

In 1874, Jules Verne called hydrogen the energy carrier of the future in his novel The Mysterious Island. Verne wrote that electrolysis can be used to split water into hydrogen and oxygen, and the hydrogen could push coal – the most important fuel at the time – out of the market. Now, a century-and-a-half later, hydrogen as an energy carrier has become a reality to only a limited extent. It may be used on a large scale in industry, but that is mainly as a raw material in the petrochemical industry and as an industrial gas for the production of glass, metals, fats and, for example, microprocessors and computer chips.

About 60 million tonnes of hydrogen are produced worldwide, mostly from natural gas. The energy content of this is almost 3 times that of the total final energy consumption in the Netherlands. About 90% is used for the production of ammonia (largely for the production of fertiliser), methanol and for refining oil into fuels and basic commodities for the chemical industry. In Europe, the Netherlands is the second largest producer of hydrogen after Germany, with an estimated volume of around 10 billion cubic metres per year. About 10% of natural gas consumed in the Netherlands is used for the production of hydrogen.

Hydrogen as a fuel for clean and economic cars

It is not the first time that hydrogen is being considered as an energy carrier. Since the oil crisis in the early 1970s, the theme has regularly been the subject of research, both in the Netherlands and elsewhere. In the early 2000s it briefly looked like hydrogen was going to make good on its promise. At the time the emphasis was firmly on its application as a fuel for fuel-cell vehicles. This development was a continuation of attempts to produce clean and economic electric vehicles with batteries. As batteries were not yet sufficiently developed at the time, attention shifted to fuel cells, which were considered to have more potential. However, it also turned out to be too early for fuel cells to force a breakthrough, partly because combustion engines could still be improved.

During this wave of attention for fuel cells and hydrogen in the early 2000s, the Netherlands was one of the frontrunners in Europe for a while. The Netherlands was part of the first major demonstration project for electric buses powered by fuel cells (CUTE project in Amsterdam), the Netherlands had the first light duty truck that ran on hydrogen (HyTruck), the first fully hydrogen-based canal cruise boat was developed and built in the Netherlands (Fuel Cell Boat), and the first demonstration project in which up to 20% hydrogen was mixed in with the natural gas network for domestic use was carried out on the island of Ameland.

During that time the Netherlands also had a hydrogen and fuel-cell programme coordinated by a predecessor (Novem) of the current RVO (Netherlands Enterprise Agency). Despite the success of the aforementioned projects, they largely remained individual and one-off initiatives.

On a global level the focus was mainly on cars and due to the lack of a national car manufacturer in the Netherlands it was not important enough to continue these developments. Dutch companies in the field of hydrogen and fuel cells did not have enough mass to force a breakthrough. In addition, most of the focus regarding energy was on promoting other forms of renewable energy and on natural gas as a transition fuel. In short, there was no fertile ground at the time for the further development and application of hydrogen.

A new phase in thinking about hydrogen

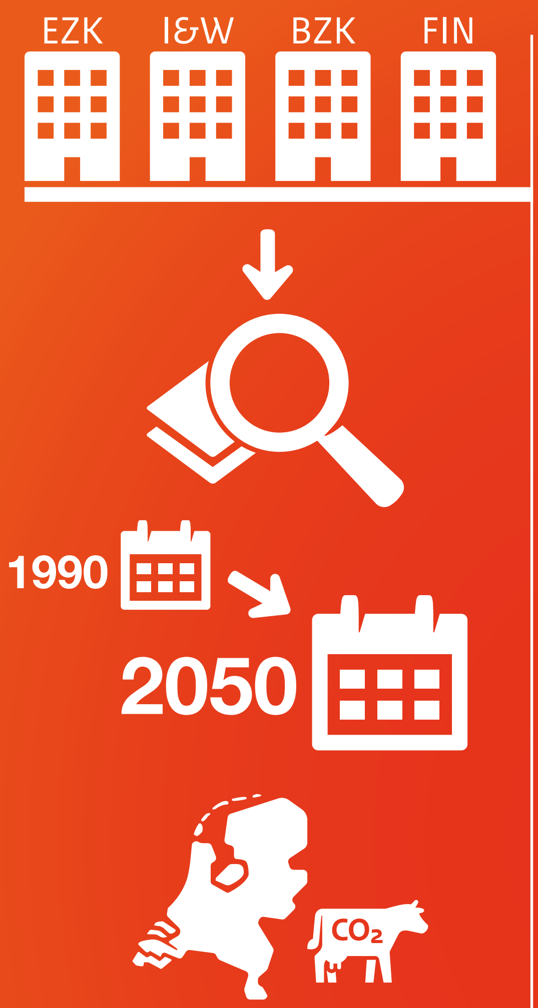
By now, hydrogen has rapidly started gaining popularity again. Only this time, the focus is not limited to mobility and transport applications, but is widely aimed at the entire supply of energy and raw materials. Among other things, this is because of the greatly increased feeling of urgency to reduce greenhouse gas emissions quickly and drastically. There has been a growing realisation that making our energy system more sustainable involves more than just the domain of electricity and that the domain of the ‘molecules’ is precisely what presents us with major challenges. Here the focus has gradually shifted more firmly to hydrogen. The expected very large scale and competing production of sustainable electricity from wind and sun, and the possible integration issues presented by this development, have led to a search for possibilities to accommodate that sustainable electricity in our energy system. Sustainable electricity combined with sustainable hydrogen offers a very good perspective on this.

The discussion on hydrogen has therefore broadened and has several dimensions that have some mutual overlap, but also many differences in terms of nature, scale, state of the art and parties involved. The following dimensions can be distinguished here:

- Temporarily making the current demand for industrial hydrogen more sustainable through decarbonisation of current production by utilising CCS/CCU and, in addition, replacing current production with sustainable hydrogen.
- The use of hydrogen as an energy carrier as a carbon-free alternative to natural gas for the production of High- and Low-Temperature Heat in industry and the built environment, and as transport fuel for electric mobility and transport applications powered by fuel cells.
- The use of hydrogen in new sustainable processes for the production of sustainable chemical products and materials, sustainable synthetic fuels and low-carbon production of iron and steel.

- The use of hydrogen as a medium for the storage or integration of electrical energy from solar-PV and wind farms in order to bridge periods with limited supply of solar and wind energy. Related to this – but certainly not the same – is the discussion about the use of electrolysis for the provision of services on the balancing market to keep the power grid stable. The use of hydrogen as a transport medium for sustainable electricity is also part of this and can be used to resolve challenges in the required reinforcement and expansion of the electricity infrastructure.

All of these subjects have their own dynamics and require a specific approach tailored to the subject. The roadmap addresses the outlines of this approach.



At the request from a few ministries there is carried out an exploration of the sets of measures available to shape an energy supply for 2050 with an 80 to 95 percent reduction in greenhouse gas emissions compared to 1990.

3 | Energy transition scenarios 2050

Following the Energy Agenda and the specification of the transition pathways, and upon request by the Ministry of Economic Affairs and Climate Policy (EZK), the Ministry of Infrastructure and Water Management (I&W), the Ministry of the Interior and Kingdom Relations (BZK) and the Ministry of Finance, ECN and PBL carried out an exploration of the sets of measures available to shape an energy supply for 2050 with an 80 to 95 percent reduction in greenhouse gas emissions compared to 1990[8].

The study was performed for five functionalities, including the four energy functionalities from the Energy Agenda, namely the transition pathways Power and Light, High-Temperature Heat, Low-Temperature Heat and Transport (consisting of mobility, and transport and logistics). The results should support the ministries in specifying the climate policy for these functionalities. The results of the study therefore are a good starting point for the hydrogen roadmap, as this relates to all four energy functionalities and provides the best picture of the specific Dutch situation.

In the study, twelve different variants were explored with preconditions mainly regarding the availability of wind energy, biomass and the capture and storage of CO_2 (CCS). These provide different detailed specifications of the energy supply and costing details. Hydrogen as an energy carrier is mentioned in various locations in the solution scope of the exploration, especially in variants with an emission reduction of 95 percent. This is understandable, as a 95% reduction requires 'all the stops to be pulled out' in order to reduce CO_2 emissions. This represents one of the major values of hydrogen.

For the position of hydrogen in these scenarios from PBL and ECN, two observations are important:

1. Hydrogen is partly 'indirectly' present in the scenarios, most prominently in the CCS options and the electrification options. CCS options are now mainly present in the model as *end-of-pipe* or *post-combustion* options. CCS for hydrogen production could be called *pre-combustion*, but this only relates to production for the conventional use of hydrogen in industrial applications. Advantages of central hydrogen production with CCS in combination with transport and distribution of hydrogen for both non-energy-related and energy-related applications still do not seem to be recognised enough. These options deserve more attention in view of the potential scale and speed at which climate-neutral energy carriers ('molecules') can be developed, including an analysis of the costs and benefits, and the

8 Exploration of climate objectives. From long-term visions to short-term action. Policy Brief. Jan Ros (PBL) and Bert Daniëls (ECN), October 2017

timeframe within which the options are relevant. As part of electrification in industry, the use of electricity for the production of hydrogen is also an important option. This is especially interesting for the production of hydrogen as feedstock for the chemical industry, and as a widely used industrial gas.

2. The model has a number of limitations that could impact the position of hydrogen. One of these is that the import of hydrogen has not been included. It is an interesting option to import large quantities of hydrogen (or energy carriers produced from it) from areas where large quantities of sustainable electricity can be produced cheaply, like the Middle East (solar-PV) or the Atlantic (floating wind), as a supplement to our own sustainable production. Based on this roadmap, the limitation that a maximum of 25% hydrogen can be mixed in with the natural gas network for use in central heating boilers and other equipment is also too restrictive an assumption, because one of the studies for this roadmap (see C. 6) shows that there are good opportunities to make the infrastructure suitable for 100% hydrogen.

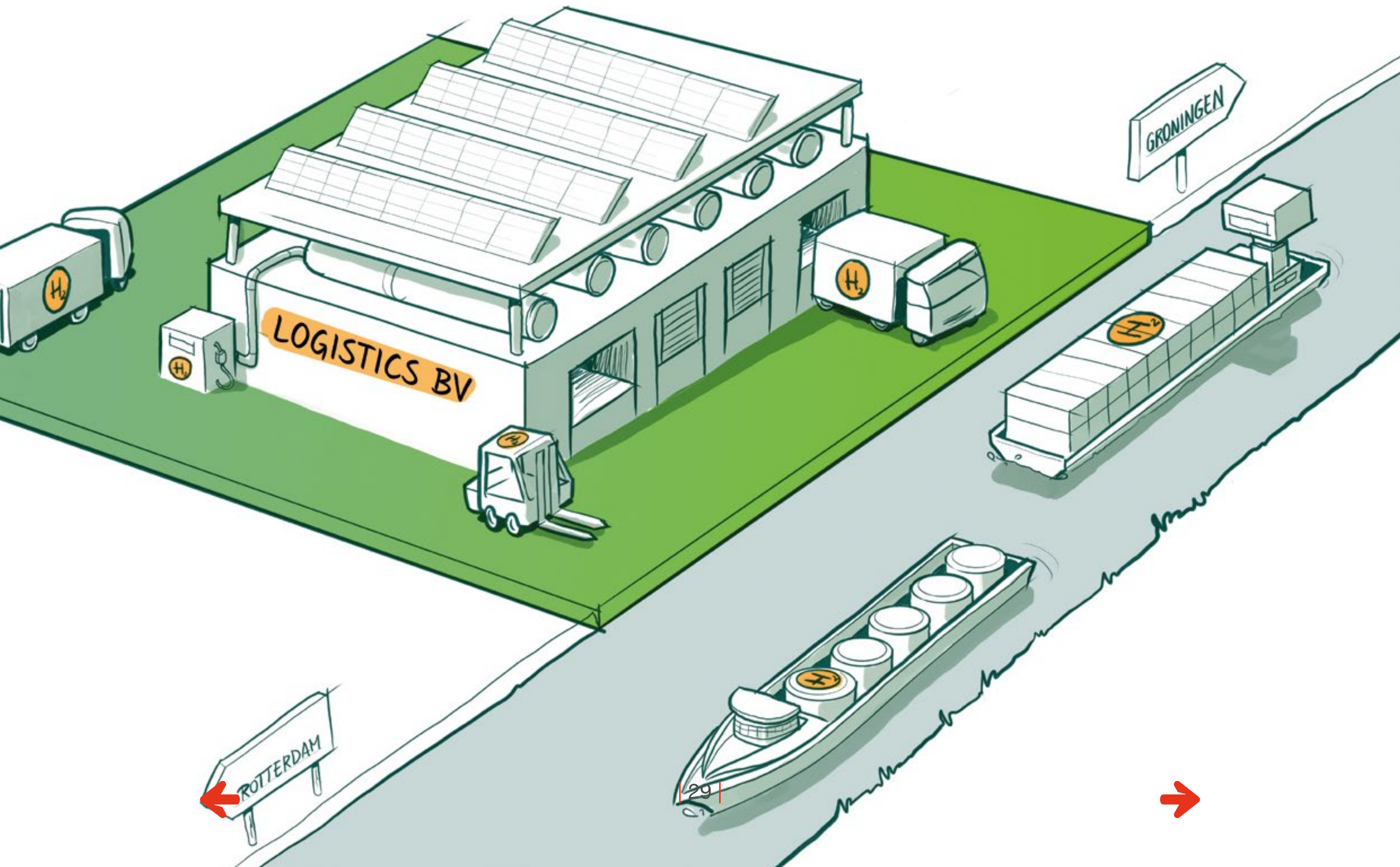
The illustrations indicate that the explorations still do not sufficiently consider the possible added value of the system role that hydrogen could play as a flexible intermediary between all the applications, production methods and storage options. Note that the goal of the explorations was not to consider hydrogen specifically, but to approach the issue from a broad perspective. The authors also indicate that there still are uncertainties regarding the application of hydrogen, and rightfully so. The report recognises the potential of hydrogen and the possibilities of contributing to several functionalities in the discussion of the results and the recommendations for actions and measures in the short term.

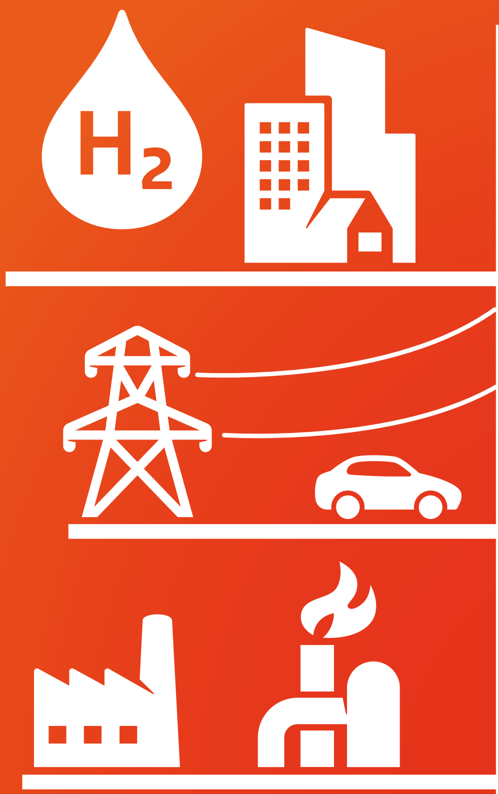
The recommendations in this exploration for the supply of hydrogen are as follows, grouped into three types of actions:

- Supporting actions to prepare for large-scale implementation: research, development and demonstration (RD&D), insight into possibilities for mixing hydrogen in with the gas network, and studies into process optimisation and integration of the power-to-gas (hydrogen) chain
- Implementation of measures with great potential: demonstration projects with hydrogen production from electricity
- Additional actions, which are less essential for 2050: CCS in hydrogen production from natural gas (with lock-in being a focal point due to the possible delaying effect on the electrification of hydrogen production).

Furthermore, the recommendation specifically for transport is to carry out RD&D and pilots with hydrogen.

Apart from this PBL/ECN exploration, various national and international reports have been published in which hydrogen plays a prominent role (sometimes summarised as an electrification option) or which have been drawn up specifically for hydrogen. Good examples are the McKinsey study for VEMW (Energy Transition: Mission (Im)possible for Industry), the Chemistry Roadmap 2050 from VNCI, recommendations from the Hydrogen Council (Hydrogen – Scaling Up), the Wuppertal study by the Rotterdam Port Authority, hydrogen studies for Shell, etc. It would go too far to cover these studies in detail in this roadmap. The message taken from these studies is that many stakeholders in different countries are exploring the significance of hydrogen for the energy transition and that hydrogen is considered to have great potential. All explorations also confirm that there still are many technological uncertainties and that more in-depth knowledge and application are required.





Hydrogen is an energy carrier that can be broadly applied in industry, in mobility, in the energy sector and in the built environment. A distinction can be made here between energy-related and non-energy-related applications.

4 | Applications for hydrogen

Hydrogen is an energy carrier that can be broadly applied in industry, in mobility, in the energy sector and in the built environment. A distinction can be made here between energy-related and non-energy-related applications.

Energy-related use involves the possible use of hydrogen as a fuel in the following applications:

- Production of High-Temperature Heat for processes in industry, such as the chemical industry, the steel industry and in oil refineries.
- Electrically driven zero-emission fuel-cell vehicles, such as cars, buses, HGVs, trains and ships.
- Production of electricity in flexible gas-fired power stations (combined cycle gas turbines), and in the future possibly also in fuel-cell units, e.g. combined with fuel-cell vehicles.
- Production of heat for space heating (Low-Temperature Heat) in the existing built environment and possibly also for hot tap water.

Note that in some applications, such as the chemical industry, hydrogen is also used for non-energy-related purposes. The following paragraphs will address the various applications for each energy functionality in more detail, bundled by theme and ordered by their level of market maturity. This is done to provide an indication of the development effort required to be able to apply a particular option on a large scale. The ordering by market maturity (or TRL level) is indicative; the boundaries will be less well-defined in practice than they appear to be based on the classification. Colour-coding has been used to indicate the level of priority for the development of activities in the Netherlands, mainly focusing on the importance of the application for the Netherlands regarding the potential for reduction of emissions and opportunities for businesses in the Netherlands. Green means very important (highest priority), orange means important (but not having the highest priority) and red means limited importance (currently not high priority).

4.1 Power and Light energy functionality

For the Power and Light (P&L) functionality a distinction is made here between the production of electricity from hydrogen (the route from hydrogen to electricity) and the conversion and end use of electricity for the production of hydrogen (the route from electricity to hydrogen). Both routes are rather difficult to fit into the P&L transition pathway in terms of their structure, as that is mainly about final consumption of electricity. Electricity production relates to the supply side, while the use of electricity for hydrogen basically does not involve final consumption.

The latter is about the conversion from electrical energy to energy in the form of hydrogen, which acts as an energy carrier (just like natural gas and petrol, for example) or as a raw material for industry. It is not an end product, but an intermediary product.

With respect to the production of electricity, Table 1 presents stationary fuel-cell applications.[9] Electricity production with fuel-cell power plants is currently still expensive due to the cost of fuel cells and hydrogen as a fuel. For the time being, this option mainly plays a role in electricity applications where security of supply is worth a great deal and the reliability of supply via the public network is not as good as it should be. This is not that relevant for the situation in the Netherlands, but there are activities in the Netherlands in that field: Nedstack and MTSA, for example, are companies that have already developed fuel-cell *power plants* abroad up to a capacity of 2 MW. This category is therefore still considered to be important. Additionally, the company Bredenoord has two mobile generators that make use of hydrogen-based fuel cells in its product range, which can be used at events and festivals. However, these are still *niche* products. Once fuel cells become more robust and affordable, it may become an interesting market in due course, because generators are quite often placed in locations in urban areas where air quality and noise pollution are key aspects.

The conversion and end-use theme in Table 1 includes various electrolysis options. These technologies convert electrical energy into chemical energy by splitting water into hydrogen and oxygen by means of electricity. In many ways, electrolysis of water is a key technology for the energy transition and a sustainable energy system. The two most developed electrolysis options currently have the highest priority. Out of the two technologies, alkaline electrolysis is the more mature technology, although the development of PEM (Proton Exchange Membrane) electrolysis is also quite advanced. Both are commercially available on a MW scale, but there is still considerable potential for improvement and optimisation.

Furthermore, scaling-up towards systems of tens and ultimately hundreds of MWs is required for it to play a significant role in industry and energy supply. Scaling-up and optimisation are performed successively and still require several intermediate steps before standardisation and scaling-up of production may contribute to reducing the costs to levels that can compete with conventional hydrogen production. This development requires projects in which the technology can be applied on a smaller scale to gain relevant practical experience for further scaling-up towards fully sustainable hydrogen. The following chapter will cover the costs and developments for the production of hydrogen by means of electrolysis in more detail.

9 It is uncertain whether mobile fuel-cell generators as an application should be included in this category. In energy statistics, these generators are usually included under mobile equipment as part of the Transport sector.

Table 1 also includes gas turbines, which can be used for the production of electricity directly from hydrogen. This usually requires modifications for them to be operated on pure hydrogen.

Table 1 | Overview of the status of hydrogen production and applications for the Power and Light energy functionality

Development stage of H_2 application / Energy-function	Exploration and study of feasibility TRL 1-3) | market-ready in 10+ yrs	Industrial research and experimental development TRL 4-7 | market-ready in 3-10 yrs	Demonstration, practical trials and market introduction TRL 8-9 | (almost) market-ready
Power and Light			
Electricity production		- Gas turbine (flexible gas turbine power stations) - Fuel cell power plants (1-10 MW) - Fuel cell gensets - Fuel cell micro CHP plant (kW scale)	Fuel cell systems for back-up and remote power
Conversion and end use	Hydrogen production using - AEM electrolysis - Solid Oxide Electrolysis		Hydrogen production using - Alkaline electrolysis - PEM electrolysis

Note: The ordering is indicative; the boundaries of TRL and market maturity will be less well-defined in practice. Colour coding: level of priority for the development of activities in the Netherlands regarding the potential for reduction of emissions and opportunities for businesses in the Netherlands; green = highest priority, orange = important, but not highest priority, red = limited importance, no priority now.

4.2 High-Temperature Heat energy functionality

Applications under the High-Temperature Heat (HTH) functionality are subdivided into three themes, namely non-energy-related, energy-related and a mixed form of these.

Non-energy-related application of hydrogen

Non-energy-related use of hydrogen includes its use as a raw material, as a reducing agent and as process gas for the surface treatment of materials in many industrial processes. A distinction can be made here between current applications and possible future applications. For many decades, hydrogen has been used on a large scale in industry for non-energy-related applications.

Most of it by far is used as a raw material for the production of ammonia, most of which is in turn used as a starting material for the production of fertiliser. Second place is taken up by its use in oil refineries for the desulphurisation of fuels and the reprocessing of heavy oil fractions. To an increasing degree, hydrogen is also required for the production of biofuels. Furthermore, it is used for the production of synthetic materials (plastics, polyester, nylon), for the hydrogenation of fats and vegetable oils in the food industry, and as a reducing agent and process gas for surface treatment in the glass industry, the metal industry and the semiconductor and electronics industry. This hydrogen is mainly produced by means of natural gas through SMR (Steam Methane Reforming). Decarbonisation of this is possible by replacing fossil hydrogen with sustainable hydrogen, but also through the application of CCS. Partial decarbonisation can also be achieved by replacing conventional production of hydrogen with hydrogen from hydrogen-rich residual gases formed elsewhere in industry. The ‘Hydrogen Symbiosis’ project with DOW, Yara and ICL in Zeelandic Flanders is an example of this.

In the future, a major increase in the demand for hydrogen is expected for the production of sustainable chemical products. Fossil resources currently still form the basis for these products, but here the fossil carbon will eventually also have to be replaced with the climate-neutral variant.[10] Options for this are carbon from sustainable biomass, circular carbon from recycling or waste processing of plastic products, and carbon from CO_2 collected from the air or water. All of these forms of carbon require the addition of varying quantities of hydrogen for the production of hydrocarbons.

Making the system fully sustainable requires production of hydrogen using energy from sustainable sources, such as electrolysis using electricity from the sun and wind. The technology for the production of sustainable hydrogen is currently still not advanced enough to replace conventional production. However, the scale of conventional production is suitable for facilitating projects that support the development and scaling-up of sustainable hydrogen, as the additional costs for partial replacement of fossil hydrogen with sustainable hydrogen only result in a limited cost increase on the overall production costs.

The possibility of industry to expand production in small units can also be interesting to respond to growth of the market in a flexible manner. It may help to limit the risks that a major expansion would involve, allowing a positive contribution to be made to the business case. In addition, these are major companies that have enough power to organise chains in which additional costs can be

10 The efforts made for the national emission-reduction task do not really focus on these applications at the moment. In the chemical industry, most of the fossil carbon used as a raw material is captured in products for a prolonged period of time. The carbon is not released until later in the waste phase. Furthermore, a large share of the products is exported, so the carbon is not released as CO_2 in the Netherlands. The same applies to fuels that are bunkered in the Netherlands or elsewhere for international aviation and shipping. The CO_2 released here does not fall under the national emission-reduction tasks. The quantities, however, are considerable. In the Netherlands, fuels bunkered over the past 5 years represent an average of about 700 PJ. That is well above the total final consumption of the transport sector in the Netherlands itself (approx. 500 PJ). Bunker fuel will eventually also have to become climate-neutral.

shared or converted into products with a more sustainable character that represent a higher market value. This certainly plays a role in industrial clusters where production and usage options can be close together.

Apart from the non-energy-related demand for hydrogen, increasing the sustainability of carbon chemistry could result in a significant additional demand for hydrogen from the chemical industry. In Table 2 this is called 'new chemistry'. This new chemistry is currently still at a low TRL level, but it may become highly important and has huge potential for the Netherlands, not only because of the major chemical industry, but also, for example, because of the leading knowledge position of the Netherlands in the field of catalysis. This field therefore also deserves a high priority, which is recognised in the Electrochemical Conversion and Materials (ECCM) programme.

Non-energy-related/energy-related application of hydrogen

The application of hydrogen for the production of sustainable synthetic fuels, e.g. for aviation and sea shipping, is classified in a separate category, but this application has many similarities with 'new chemistry'. In the production of the fuels, hydrogen acts as a raw material, whilst the use of the fuel produced in this way involves an energy-related application. Just as for 'new chemistry', the preference is to use sustainable hydrogen for the production of synthetic fuels. Converting natural gas into CO_2 and hydrogen, with storage of CO_2, and then recombining the hydrogen with sustainable carbon may be technically possible, but is not such an obvious option.

The production of liquid fuels based on natural gas (gas-to-liquids) is currently being performed on a large scale. Here natural gas is first reformed into syngas, a mixture of carbon monoxide (CO) and hydrogen, which is used to synthesise new hydrocarbons. This is currently also being done using biomass as a starting material in combination with fossil hydrogen. The challenges faced here are mainly in the field of sustainable hydrogen production and future use of CO_2 as a source of carbon, which requires efficient methods for reducing CO_2 to CO.

Energy-related use of hydrogen for HTH

Hydrogen is one of the options for producing High-Temperature Heat. Many hydrogen-rich residual gases are present in industry, formed while refining oil and cracking naphtha and LPG to produce base chemicals for the chemical industry. Coking gas formed during the production of coke from coal also largely consists of hydrogen. The chloralkali process for the production of chlorine and caustic soda (electrolysis of salt dissolved in water) even involves the formation of pure hydrogen as a by-product. These gases are mostly used directly or in a mixture with natural gas in boilers and furnaces for the production of steam and high-temperature process heat, or for the production of electricity in combined heat and power or regular power plants.

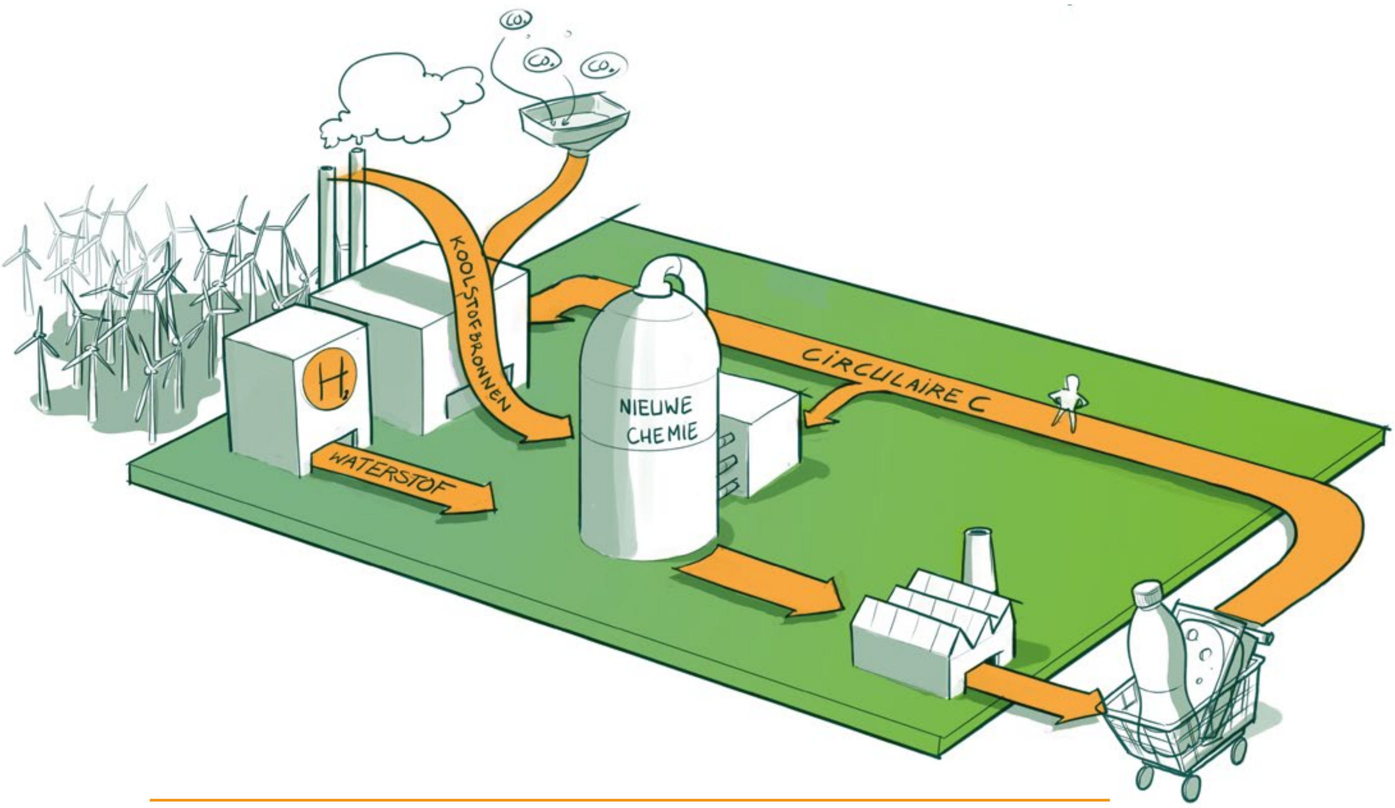
This application mainly has a high priority because it can be used to learn which modifications are required for a possible switch to pure hydrogen. This may be important for the use of pure hydrogen in gas turbines, but also for the development of products using burners for pure hydrogen elsewhere in industry or in the built environment.

Table 2 | Overview and status of hydrogen applications under the High-Temperature Heat energy functionality

Development stage of H_2 application / Energy-function	Exploration and study of feasibility **TRL 1-3) | market-ready in 10+ yrs**	Industrial research and experimental development **TRL 4-7 | market-ready in 3-10 yrs**	Demonstration, practical trials and market introduction **TRL 8-9 | (almost) market-ready**
	High-temperature heat		
Non-energy use	Feedstock for new chemistry: - Biobased chemistry - Waste-to-Chemicals	Feedstock for new chemistry: - Carbon2Chem (CCUS with coke and BF gas)	Default feedstock, reactant or process gas in wide range of industrial applications
Non-energy use / Energy use	Production of green(er) synthetic fuels		
Energy use: fuel for producing process heat	Alternative for natural gas if no climate-neutral option is available		Use of H_2 co-produced in industrial processes for firing

Note: The ordering is indicative; the boundaries of TRL and market maturity will be less well-defined in practice. Colour coding: level of priority for the development of activities in the Netherlands regarding the potential for reduction of emissions and opportunities for businesses in the Netherlands; green = highest priority, orange = important, but not highest priority, red = limited importance, no priority now.

Hydrocarbon symbiosis



4.3 Low-Temperature Heat energy functionality

The Low-Temperature Heat (LTH) energy functionality relates to heat for space heating and tap water in the built environment. Efforts aimed at improving the sustainability of the built environment focus primarily on avoiding demand for heat by building energy-efficient houses and buildings, and on reducing the demand for heat by insulating existing houses and buildings later on. In addition there are many alternatives to meet the remaining demand for heat in a climate-neutral manner.

All-electric heating of new, energy-efficient houses and buildings using electric heat pumps is very well possible. Furthermore, the construction or expansion of heat networks in relation to new developments is also relatively easy. However, the possibilities for this should be considered on a case-by-case basis in connection with the current and future options for feeding these networks with climate-neutral or sustainable heat, like residual heat from industry or from waste processing plants, and geothermal energy.

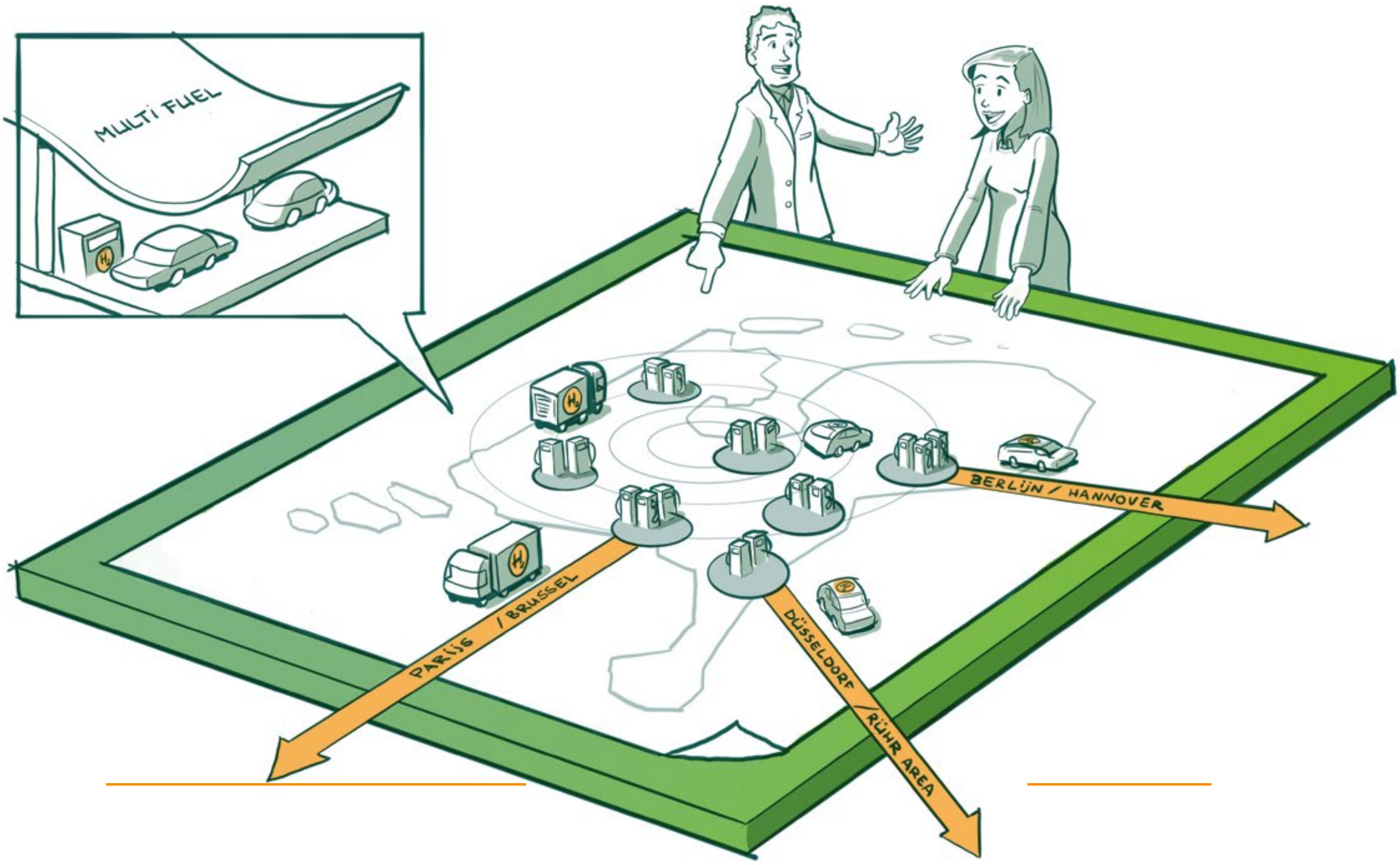
For existing buildings, however, these options are not as simple. There is huge challenge here, both regarding the number of houses and the scale of the insulation measures, and regarding the construction of new heat infrastructure or modification of the existing electricity infrastructure.

As a result, alternatives such as hybrid heat pumps are also being considered. In this case the heating is mainly performed with an electric heat pump, but the capacity required to meet peak demand for heat during the coldest times is provided by a natural gas boiler.

In addition to this, options for replacing natural gas with a different, climate-neutral gas are being considered. If the natural gas can be replaced with a climate-neutral gas that can fully or largely make use of the same gas infrastructure, this may contribute to solutions that are both socially acceptable and cost-effective. Replacement of natural gas with green gas is an option, but the use of climate-neutral hydrogen is also a possibility here.

Hydrogen can contribute to the production of this heat for houses, buildings and commercial premises. It may serve as fuel in heating boilers, but also as fuel in plants for heat networks, for example, on an urban district level. Examples of this are combined heat and power units installed in an urban district, which produce electricity locally and/or take care of balancing the power grid and also provide the required heat that can be supplied through a local heat network, as base load or only as peak load. This will depend greatly on the local alternatives.

Basic network of public H_2 refuelling points



At the moment the hydrogen option is still at a relatively low TRL level. There are many questions that still need to be answered, such as the suitability of the regional and local natural gas systems for hydrogen, questions about the safety aspects and the required safety measures, and about the modification costs to make the system suitable for hydrogen. Although a slight preference for pure hydrogen seems to be developing, the question also remains whether the transition can be completed best by gradually increasing the share of hydrogen being mixed into the natural gas or whether it would be preferable to convert the whole system at once to 100% hydrogen on a regional basis. It is important here that solutions in test beds can be tested and optimised in controlled practical conditions.

In view of the major and difficult task that has to be completed for the existing built environment and the possibly limited availability of sustainable biomass for green gas, it is crucial to explore, develop and test the options for the application of hydrogen for LTH at an early stage. The challenge here is mainly related to social and institutional issues.

Table 3 | Overview and status of hydrogen applications under the Low-Temperature Heat energy functionality

Development stage of H_2 application / Energy-function	Exploration and study of feasibility TRL 1-3 | market-ready in 10+ yrs	Industrial research and experimental development TRL 4-7 | market-ready in 3-10 yrs	Demonstration, practical trials and market introduction TRL 8-9 | (almost) market-ready
	Low-temperature heat		
Energy use/fuel		- Alternative for natural gas in existing buildings that cannot be electrified or connected to heating grids - District-level plants combined with local heating grids	

Note: The ordering is indicative; the boundaries of TRL and market maturity will be less well-defined in practice. Colour coding: level of priority for the development of activities in the Netherlands regarding the potential for reduction of emissions and opportunities for businesses in the Netherlands; green = highest priority, orange = important, but not highest priority, red = limited importance, no priority now.

4.4 Mobility energy functionality

The Mobility energy functionality is responsible for about 20% of greenhouse gas emissions in the Netherlands. For Europe the share is slightly higher, and including international aviation and shipping, transport even represents Europe's biggest climate problem with 27% of the emissions. In addition, it is the number one cause of air pollution in cities. This is why low-emission transport is high up on the policy agenda, both in the Netherlands and in Europe.

Hydrogen as fuel for electric vehicles powered by fuel cells can make a significant contribution to the low-emission fulfilment of the transport requirement for people and goods. Together with batteries, the combination of fuel cells and hydrogen offers the potential for full electrification of all road traffic. Apart from having a positive effect on greenhouse gas emissions, this leads to the prevention of emissions from non-combusted hydrocarbons , NO_x and SO_2, and drastic reductions of particulate matter and noise emissions.

Both electric vehicles (with batteries) and hydrogen vehicles (with fuel cells) are electrically driven vehicles. Although competition may occur on the market, the options generally complement each other. The advantage of hydrogen is that a relatively large amount of energy can be stored in tanks, with the weight and volume not scaling proportionally to the amount of energy, as is the case for batteries. Additionally, the tanks can also be filled up quickly with larger amounts without increased costs for improving the electrical infrastructure. The option is therefore well suited to electrification of the more energy-intensive mobility and transport applications, especially if long-term and flexible use of vehicles is required. In the current situation these are mainly diesel vehicles. Although there are fewer of these than petrol vehicles, overall diesel consumption is considerably higher than that of petrol. The figures for the Netherlands currently are about 250 PJ of diesel (18.5 Mt CO_2) and 165 PJ of petrol (11.9 Mt CO_2). The use of hydrogen vehicles could therefore have an effect on a larger share of the emissions in the transport sector than electric vehicles.

Table 4 shows a broad palette of transport applications that are in different stages of development. In the field of cars, commercialisation has already started with the introduction of three models in the larger car segments by Hyundai, Toyota and Honda. In 2018 the introduction of a plug-in fuel-cell hybrid is expected from Mercedes in response to the currently still limited availability of refuelling points. Additional models are expected from these and other manufacturers for 2020, whilst production numbers of the existing models are being scaled up to several tens of thousands a year. In the Netherlands, favourable tax relief is available for these cars. Continuation thereof in combination with support for the construction of a basic network of public refuelling points could be a solid basis for quickly developing this option in the Netherlands.

Table 4 | Overview and status of hydrogen applications regarding the Transport energy functionality

Development stage of H_2 application / Energy-function		Exploration and study of feasibility	Industrial research and experimental development	Demonstration, practical trials and market introduction
		TRL 1-3 | market-ready in 10+ yrs	**TRL 4-7 | market-ready in 3-10 yrs**	**TRL 8-9: (almost) market-ready**
Transport				
Complementary to battery-electric transport	Mobility (passengers)	- Tour boats - Ferries	Trains	- Passenger cars - Buses
		- Cruise ships - Planes		
	Transport & Logistics (goods)	- Delivery vans - Mobile equipment	- Refuse collection lorries - Road sweepers - Light-duty trucks - Heavy-duty trucks	Forklift trucks
		- Inland vessels - Cargo vessels		

Note: The ordering is indicative; the boundaries of TRL and market maturity will be less well-defined in practice. Colour coding: level of priority for the development of activities in the Netherlands regarding the potential for reduction of emissions and opportunities for businesses in the Netherlands; green = highest priority, orange = important, but not highest priority, red = limited importance, no priority now.

The development of hydrogen buses for public transport is not that advanced, but there is a lot of interest. Europe still comes out on top in the field of buses and the Netherlands has a potentially powerful player in VDL. As part of the European Fuel Cell and Hydrogen Joint Undertaking programme, efforts are being made by regions to jointly purchase hundreds of buses in order to get the costs down. In this context, 50 of these will arrive in the Netherlands during the period 2019-2020. This application has a high priority in order to meet the Dutch target of having all buses for urban and regional public transport at zero emissions by 2030. It would also appear that these developments are about to speed up, so it may be possible to benefit from this. South Korea is planning to replace 26,000 buses with hydrogen buses within a few years, and Shanghai is working on a project for 3,000 buses in 2020.

Cities are also interested in refuse collection vehicles and sweeping vehicles that run on hydrogen. In the Netherlands, various parties are active in this field. Following earlier projects with one and then two refuse collection vehicles, a project was recently started for the production of another 15 units, 9 of which will be used in the Netherlands and the rest elsewhere in Europe. These are not large markets, but due to their visibility and the role they play (cleaning) inside the built environment, they are very important markets that could contribute to the acceptance of hydrogen.

High-potential applications can be found in the field of goods transport, varying from delivery vans to heavy duty trucks. Recently the first projects with heavy duty trucks were launched in Switzerland and Norway; they are being tested in practice for the distribution of goods for major supermarket chains. In the Netherlands, projects are underway to develop prototypes for 40-tonne and 27-tonne trucks. One of the trucks will in any case go to Colruyt (a supermarket chain) in Belgium. With a number of parties that construct or convert small numbers of trucks, and with VDL and DAF to scale up the numbers, there are opportunities for the Netherlands in this field, also because of the scale of the transport and distribution sector in the Netherlands. Activities could initially be bundled around one or more major logistics hubs. Here a combination would be possible with hydrogen forklift trucks and lifting equipment already commercially available. In the United States, where several tens of thousands are already in use, they mainly appear to offer benefits in centres that operate intensively and continuously 24/7. As the costs drop, the possibilities for applications increase. This is why the option is also starting to gain a foothold in Europe.

Applications in boats and ships also provide opportunities for the Netherlands with its strong maritime sector. Part of the inland shipping fleet will have to be replaced in the near future, because the ships have been operating for a long period of time and because there are not that many moments before 2050 to start making them more sustainable. The development of hydrogen is still at an early stage here, but offers opportunities in combination with the trend to electrify drive systems, and the development of modular concepts. In this case the *power* module could initially still be a diesel generator or a generator that runs on LNG. Later on it could be replaced with a fuel-cell power source that runs on hydrogen. This should already be included when designing new ships. That is why now is the time to seriously start the ball rolling and to explore and test solutions through design studies and pilot projects.The other applications in Table 4 have a lower priority because the time is not yet right for these applications, there is little repeat potential or further growth potential within the Netherlands, or because there are no Dutch players or only a limited number on these markets.

4.5 Estimation of theoretical potential demand for hydrogen for all applications

In this paragraph we will be outlining a very rough estimate potential demand for hydrogen for all kinds of applications to get a feeling of the relevant scale. The estimates have written substantiations to include others in the line of reasoning that leads to the given results. The first column of Table 5 presents an overview of (highly indicative) estimates for the possible demand that could develop for hydrogen for various purposes to get a feeling of the extremes and the major challenge we are facing in realising the energy transition. A further substantiation of the figures is described in Appendix 2. The second column presents the same demand, but converted into megatonnes of hydrogen. By adding all the numbers, the estimates total almost 1700 PJ, which when converted comes down to over 14 Mt hydrogen. That is more than 22 times the current industrial demand for hydrogen in the Netherlands, and in terms of scale one quarter of the current worldwide production of hydrogen for industrial purposes.

Table 5 | Overview of the indicative estimates of possible demand for hydrogen in the Netherlands in a climate-neutral energy supply system with an indicative translation into amounts of offshore wind energy or natural gas with CO_2 storage required for the production of that hydrogen.

Functionality	Hydrogen demand		Offshore wind energy Electrolysis		Natural gas/ CCS Reforming	
	PJ/j	Mton/j	TWh/j	GW	PJ/j	Mton CO_2/j
High-Temperature Heat:						
- Non-energy use	50	0,4	21	4,8	67	3,8
- Process heat	100	0,8	42	9,6	133	7,5
- Sustainable chemistry	480	4,0	202	46,1	640	46,2
- Sustainable fuels	700	5,8	295	67,3	933	52,8
- Steel production	20	0,2	8	1,9	27	1,5
Mobility and Transport	125	1,0	53	12,0	167	9,4
Power and Light	115	1,0	48	11,1	153	8,7
Low-Temperature Heat	100	0,8	42	9,6	133	7,5
	1690	**14,1**	**711**	**161**	**2253**	**128**

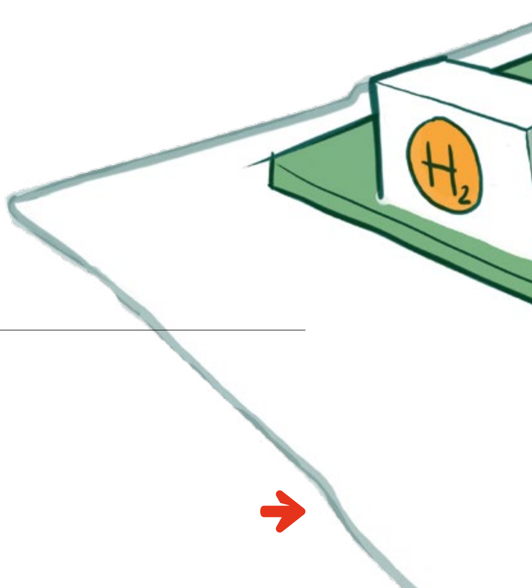
Assumptions: The energy value of hydrogen is 120 MJ/kg or 33.3 kWh/kg (LHV); the power consumption for electrolysis is 50 kWhe/kg H_2; offshore wind energy 50% full-load hours per year (4380 hours); reforming 75% efficiency (LHV); emission factor for natural gas is 56.6 Mt CO_2/PJ.

The rest of the table presents figures for the production of hydrogen. The 3rd and 4th columns show the results in case the hydrogen is fully produced by splitting water through electrolysis using offshore wind energy. The 3rd column presents a measure for the amount of energy required for production and the 4th column shows how much wind power is approximately required to harvest that amount of energy.

In 2016, net power consumption in the Netherlands was over 113 terawatt-hours (TWh). The production of hydrogen using offshore wind energy would therefore again require over 6 times as much energy. The installed capacity for offshore wind energy currently is 957 megawatts (MW), just under 1 gigawatt (GW). The result in the table indicates that this would have to be expanded more than 160 times. This is more than our own potential, which is estimated at 40 to 80 GW for the Netherlands[11]. The production of hydrogen using ‘our own’ offshore wind energy is therefore highly important, but it will be necessary to import hydrogen in the future if we want to cover the entire demand for hydrogen in a fully sustainable manner.

The 5th and 6th columns present the results in case the hydrogen is fully produced through reforming of natural gas, with the CO_2 formed during this being fully captured and stored. With the assumptions presented at the bottom of the table, the estimate for the amount of natural gas is over 2250 PJ. By way of comparison, in 2015 the total natural gas consumption in the energy supply system was almost 1200 PJ. Full capture and storage of the CO_2 requires a storage capacity of about 128 million tonnes a year. This is well above the current estimate of the Dutch potential for storage, which is 10 to 50 million tonnes a year for a period of 30 years. The possible potential for CO_2 storage therefore is a factor of 2.5 to 10 below the calculated value. For this option, a lot of storage potential elsewhere would also have to be used.

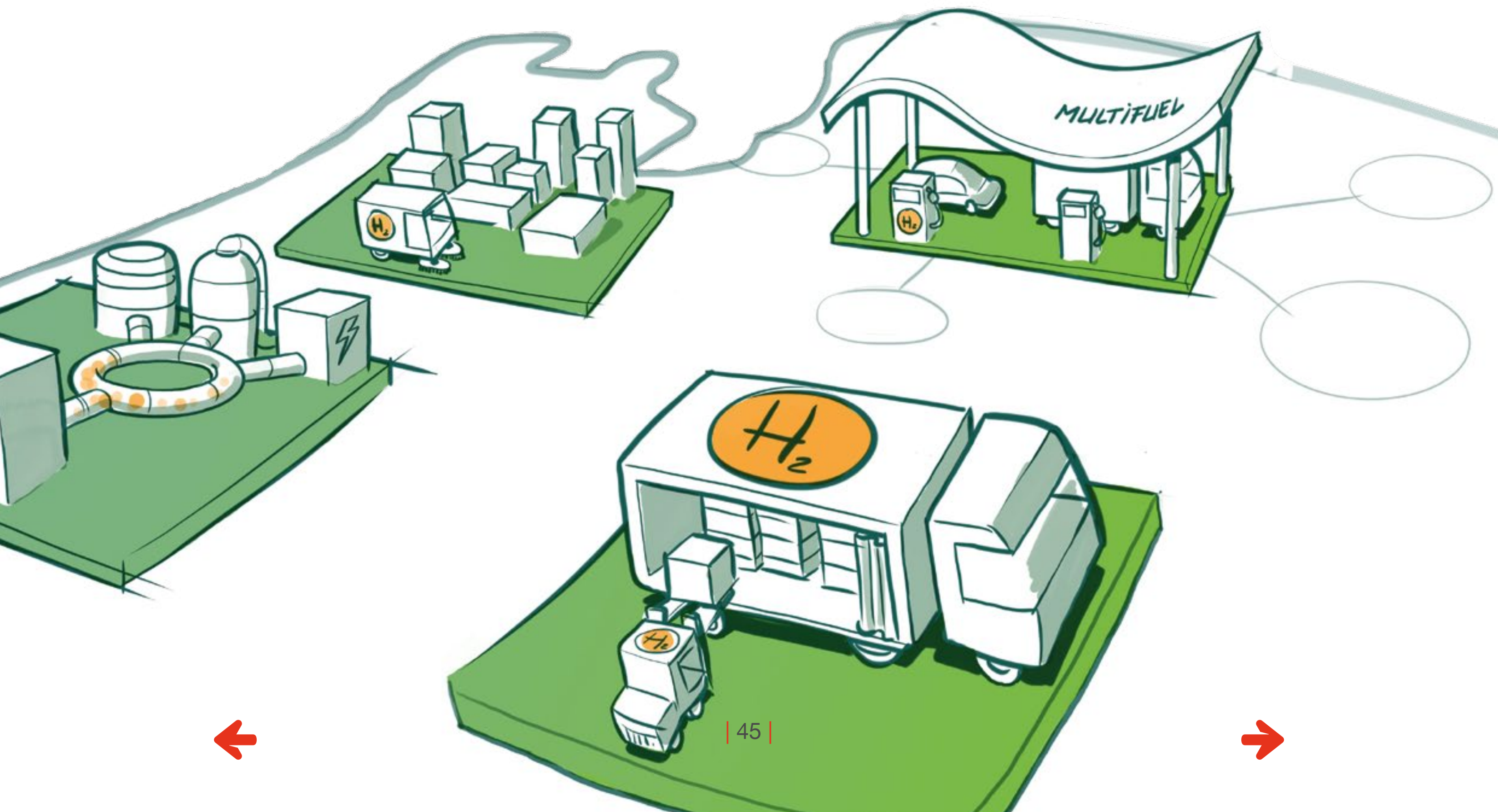
On closer inspection, however, the use of natural gas for the production of hydrogen for sustainable chemistry and (liquid) transport fuels does not appear to be an obvious option. It initially involves breaking down a hydrocarbon with capture and storage of CO_2, after which the hydrogen produced is recombined with CO_2 or carbon from other sources. For these applications, the use of sustainable hydrogen would be a more obvious choice. In that case the figures for natural gas drop to 680 PJ and a CO_2 quantity of over 38 million tonnes per year. This does fall within the bandwidth of the potential for CO_2 storage options in the Netherlands.



11 J. Ros and B. Daniëls, Exploration of Climate Objectives, PBL, 9 October 2017.

As carbon is required for the production of chemical products and materials, and for synthetic liquid fuels, the application of sustainable biomass would be (more) obvious here. If the amount of carbon here is insufficient, this will have to be topped up with carbon from waste processing (circular carbon) or carbon from CO_2 storage from the air (air capture) or extraction from water. In the aforementioned PBL/ECN study (C3), the available potential for sustainable biomass in the Netherlands is estimated at 250 to 700 PJ per year [8]. As a result of conversion losses, it will probably not be possible to use the full energy value of this for chemical products and fuels. But if this is not taken into account, the estimate for the hydrogen demand for these applications drops to 480-930 PJ. Production of this quantity of hydrogen requires 200-388 TWh of electricity, which requires about 46-88 GW offshore wind energy. This almost matches the potential estimate for offshore wind energy of 40-80 GW. However, one should realise here that use of offshore wind energy, together with onshore wind energy and solar-PV, will also be required for the production of electricity for direct use (battery-powered electric cars, trains, heat pumps, appliances, lighting, etc.).

Furthermore, when fully utilising our own potential of wind and solar energy for these applications, it will no longer be possible either to gradually replace the climate-neutral hydrogen from natural gas/CCS with hydrogen produced using our own sustainable energy. It will then have to be replaced by importing sustainable hydrogen, i.e. hydrogen produced elsewhere using energy from sustainable sources. Another (undesirable) scenario may be that the new sustainable chemical industry and the production of synthetic fuels gradually move elsewhere, leaving room for our own sustainable hydrogen, which can be used in transport applications, in the energy sector and in the built environment.



Hydrogen can be produced using a range of production routes and technologies. This chapter looks at the most commonly used technologies and provides an indication of their costs.

5 | Production routes and costs of hydrogen

Hydrogen can be produced using a range of production routes and technologies. This chapter looks at the most commonly used technologies and provides an indication of their costs.

5.1 Large-scale production of hydrogen from natural gas by means of steam methane reforming

Across the globe, large-scale production of hydrogen takes place by means of natural gas reforming. SMR entails reforming through a reaction with steam and is the most commonly used variant. A standard plant typically has a capacity of 100,000 m^3 or 9 tonnes of hydrogen per hour.[12] The process takes places in various steps, but can roughly be split into two phases. During the first phase, natural gas is reformed with steam at temperatures between 800 and 1000 °C. This yields a syngas consisting of carbon monoxide (CO) and hydrogen (H_2). The second phase is the water-gas shift, which takes place at a lower temperature. During this phase the CO from the synthesis gas reacts with even more steam (H_2O), forming CO_2 and more hydrogen.

The mixture of CO_2 and hydrogen is subsequently separated in a gas separation section and this generates a concentrated flow of CO_2 suited to CO_2 capture and storage. This is a standard industrial process that is used on a large scale for the production of ammonia and fertiliser, due to the need for CO_2 during the conversion of ammonia into urea.

In SMR, some of the natural gas is not converted into hydrogen but is instead used for the production of steam and the external heating of the reactor. This is a standard practice, which generates flue gases containing a low level of CO_2. This means it is challenging to capture 100% of CO_2 during SMR. The typical percentage captured is between 50 and 60%. Although the introduction of process modifications can increase the percentage of CO_2 captured to around 90%, this in turn reduces the efficiency around 7 percentage points.

There are two variants, Autothermal Reforming (ATR) and Partial Oxidation (POX), which allow 100% of CO_2 to be captured. During these two variants, process heat is generated at a higher temperature by allowing a portion of the natural gas to react with pure oxygen in the reactor. As a result, all of the CO_2 is retained in the concentrated process flow. However, compared with SMR this process requires a higher level of investment due to the air separator for oxygen. In order to be competitive, the processes must therefore be operated at an even larger scale.

12 IEAGHG Technical report 2017-02, Techno-Economic Evaluation of SMR based Standalone (Merchant) Hydrogen Production Plant with CCS, IES Greenhouse Gas R&D Programme, February 2017.

Even so they could offer interesting opportunities in the future if combined with hydrogen production by means of electrolysis, since this process generates oxygen.

The production costs for hydrogen from natural gas depend heavily on natural gas prices. Natural gas accounts for 70-80% of the production costs in large-scale production by means of SMR. The production costs are roughly between €1 and €1.50 per kilo of H_2.

5.2 Small-scale production from natural gas by means of SMR

The transport costs of hydrogen are comparatively high, particularly over large distances. The alternative is to produce hydrogen at the customer's premises (at the refuelling station or on the premises of an industrial client with a limited requirement). To this end, various parties (including the Dutch HYGEAR) have developed and are developing small-scale SMR units that have a typical capacity between 100 and 300 Nm^3/hour, which is the equivalent of approximately 200 to 600 kg per day.

Production in these small-scale units is based on the exact same principles that are used in large-scale production. Rather than a downscaled version of a plant, these units in fact represent fully re-designed processes for the purpose of achieving an acceptable efficiency on a small scale. The efficiency is typically between 60% and 65%. It is estimated that in the short term (2020) these units could bring the production costs of hydrogen down to €4-5 per kilo, with the prospect of a further drop to €3-4 per kilo or a little less still in the period approaching 2030. This cost level is competitive compared with a combination of large-scale production and transport.

Production units should preferably be used in continuous operation. The main market for applications is therefore currently in on-site production for small-scale industrial users. Strong fluctuations in operational conditions, as might be expected in the start-up period for refuelling stations, can cause maintenance and operational costs to increase. In addition, hydrogen production takes place at comparatively low pressures, which means a significant level of compression will need to be provided at the refuelling point. Another consideration is the space taken up on-site. A case-by-case assessment will therefore need to be carried out to determine the most practical and cost-effective option. Local availability of green gas or biogas for the production of sustainable hydrogen could also play a role here, although there is of course a possibility to link up with this through indirect means (using certificates).

5.3 Production of hydrogen by means of electrolysis

Electrolysis of water is currently regarded as the ideal technology for producing sustainable hydrogen. This is provided that sustainable electricity is used. However, the current electricity mix, which is for a large part still coal-based, means the production of hydrogen via electrolysis is even more carbon intensive than production from natural gas using SMR, although the rapid development of wind and solar energy projects will change this in the years to come. Appendix 4 provides a more detailed explanation of this. Electrolysis can be achieved through a range of methods. In all instances, electricity is used to separate water molecules and the net result is the production of hydrogen and oxygen.[13] The conventional methods of alkaline electrolysis (AEL) and proton exchange membrane (PEM) electrolysis are the most well-known and most developed variants. Both work at low temperatures of 60-70°C. Alkaline Exchange Membrane (AEM) electrolysis is a third low-temperature variant. This variant is the least developed as the technology is still at laboratory scale. A fourth variant, solid oxide electrolysis cell (SOEC), has progressed somewhat further but is also still at a low TRL. SOEC is related to high temperature solid oxide fuel cells (SOFCs) and works at temperatures of 600-800°C. Compared with low-temperature variants, this technology raises the prospect of a much higher electrical efficiency as much less energy is required to separate water molecules at those temperatures. A pre-requisite for converting this into an improved CO_2 performance is the availability of low-carbon High-Temperature Heat.

AEL and PEM are both commercially available at a scale of 1-5 MW. [14] The investment costs for AEL electrolysis are currently around €1,000 per kW. Innovation, optimisation and increased volumes could reduce this to €370-800 per kW approaching 2030. [15] The recent announcement of a contract for the delivery of a 100 MW AEL system for the equivalent of €450-500 per kW provides an indication of the scope that is still available. [16] The efficiency of the systems, which currently averages at 61% (55 kWh/kg), is expected to increase to a minimum of 67% (50 kWh/kg).

The investment cost for PEM electrolysis is currently around €1,400 per kW. An increase in the scale of systems and the numbers could bring the costs down rapidly, although market estimates for 2030 vary widely and range from €250 to €1270 per kW, with a median of €760 per kW. At approximately 60 kWh/kg, the electricity consumption of PEM systems is currently still slightly higher than in AEL. However, this is rapidly improving and the available scope is expected to exceed that of AEL, with consumption dropping to a level well below 50 kWh/kg in 2030 (efficiency >70%). Assuming the maximum number of operating hours per year and electricity costs of €70-80 per MWh, current production costs are estimated at €5-5.5 per kg and €6-6.5 per kg for AEL and PEM respectively. The costs are expected to converge in the period approaching 2030 and reach around €3-3.5 per kg for on-site production at MW scale. Large units with a capacity of 10-100 MW (4-40 tonnes a day) and possibly over will also have become available by this time and will be positioned centrally. This could see production costs drop to well below €3 per kg and possibly even to below €2 per kg. Costs would then become competitive with central production using natural gas, particularly if natural gas and CO_2 prices were to increase and production were to be combined with CCS. However, when investment costs are low, the production costs will increasingly be determined by electricity prices and there is a high degree of uncertainty as to how these will develop.[17]

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13 Along with each m^3 of hydrogen an amount of 0.5 m^3 of oxygen is produced; this translates to roughly 8 kg of oxygen for each kg of hydrogen. When production takes place at a limited scale, the market value of hydrogen is outweighed by the investments required for capture, purification and storage. Large-scale production could change this and offer interesting opportunities in combination with biomass gasification or natural gas reforming with full CO_2 capture.

14 Lymperopoulos, N. (2017), FCH JU Support to Electrolysis for Energy Applications. Presentation at the International Conference on Electrolysis 2017, Copenhagen, 12 June 2017.

15 Bertuccioli L., et al., (2014), Development of Water Electrolysis in the European Union – Final Report. E4tech Sàrl with Element Energy Ltd for the Fuel Cells and Hydrogen Joint Undertaking, February 2014.

16 http://h2vproduct.net/wp-content/uploads/2017/07/annonce-bourse-dOslo.pdf

17 A brief indication of the production costs: assuming a consumption level of 50 kWh per kg, each €10 increase in the price per MWh of electricity (the equivalent of €0.01 per kWh) translates to an increase in product costs of €0.50 per kg.

5.4 Other alternatives for sustainable hydrogen production

A recent study into alternatives for sustainable hydrogen production other than electrolysis, commissioned by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), identified a total of 11 options.[18] A subsequent review determined that the following five alternatives could have potential:

1. Biomass pyrolysis and gasification
2. Fermentation of biomass flows to biogas, combined with biogas reforming
3. Thermochemical water splitting
4. Photo-catalysis (using photo-electrochemical cells, PECs)
5. Supercritical water gasification of biomass

Biomass is the energy source for three of the pathways, with hydrogen generated in part from the biomass and in part from water. In light of the discussions regarding the availability of sustainable biomass and the many alternative uses of biomass for applications that require sustainable hydrogen as well as climate-neutral carbon, it is questionable whether the long-term objective should be to use biomass only for hydrogen production. There appears to be a greater need for uses of biomass, whether directly or via syngas, that make also use of the carbon contained in it. Consider examples such as sustainable chemical products and materials or sustainable biofuels and synthetic fuels for aviation and shipping.

The other two pathways draw their power from solar energy, with all of the hydrogen being produced from water. The thermochemical pathways require High-Temperature Heat from concentrated sunlight (by means of concentrated solar power or CSP). CSP is not feasible in many locations and is not an option for the Netherlands, but High-Temperature Heat from CSP could have a part in import scenarios. An alternative would be to use heat from nuclear reactors.

The last pathway entails the production of hydrogen using a photo-electrochemical cell. This technology is interesting as it combines the functionality of solar panels with that of electrolysis. It is in effect a type of solar cell submerged in water. Incoming light causes reactions on the surface which directly generate hydrogen. However, materials have yet to be developed that combine efficiency, durability and cost-effectiveness at a level that is sufficient to ensure a viable system. There is still a long way to go before these systems will outperform a combination of separate solar-PV and electrolysis systems. Such a combined system can be deployed flexibly in order to convert solar power into electricity or hydrogen.

The pathways have TRLs ranging from 3 for photo-catalysis, 7 for supercritical water gasification and 8 for biogas reforming. The 2030 production costs for the various pathways have been estimated using practical data and model studies. In the case of small-scale production on-site (0.2-4 tonnes per day), the costs of fermentation combined with reforming have been estimated to be the lowest, at €3.50-5.50 per kilo. The other pathways using

18 http://www.fch.europa.eu/publications/study-hydrogen-renewable-resources-eu

biomass stand at €4.50-6.50 per kilo. In the case of large-scale centralised production (>20 tonnes per day), the costs for biomass gasification, photo-catalysis and production through thermochemical cycles respectively have been calculated at €3-3.50 per kilo, €4.50-5 per kilo and €6-6.50 per kilo. Since most of the pathways still require a major R&D effort, the costs only provide a very rough indication.

5.5 Production costs and prices of hydrogen

The costs outlined relate to the cost of hydrogen productions by means of the various technologies. If hydrogen is produced internally in the context of a coherent whole of processes, as would occur at a chemical or petrochemical complex, the production costs of hydrogen will be very similar to the price of hydrogen. Use of the hydrogen elsewhere will add numerous costs to this and raise the price significantly above the production costs.

If we look at external supply for example, there will be costs for pressurising (compressing) or liquefying hydrogen for the purpose of transport and, where required, interim storage between production and transport. If a specific quality is required, additional costs for purification will be incurred. Over and above this there are costs in relation to the maintenance and certification of cylinders, tubes and facilities for on-site storage. In addition, there will also be general operating expenses and a commercial margin will apply. Lastly, there are costs involved in the transport, which are €1.50-2.50 per kilometre for delivery by truck. The ultimate price of hydrogen can vary widely and is currently heavily dependent on the desired quality, the volume and frequency of deliveries and the transport distance.

It is estimated that the total price of compressed hydrogen, as delivered to a refuelling station, is currently around €5 per kilo. If the scale increases, it is expected that chain optimisation would bring down prices to below €4 per kilo. [19] However, this price is not yet equivalent to the hydrogen price 'at the pump'. To arrive at this we must also include the cost of the refuelling point and the refuelling station, along with taxes and any levies. [20] The refuelling point is a cost element which is highly dependent on the utilisation rate. During the start-up phase in particular, this cost element could be sizeable and possibly reach a large uneconomical peak. In order to keep this peak as low and short as possible, it will be crucial to organise and bundle demand around the first refuelling points.

5.6 SMR and electrolysis compared

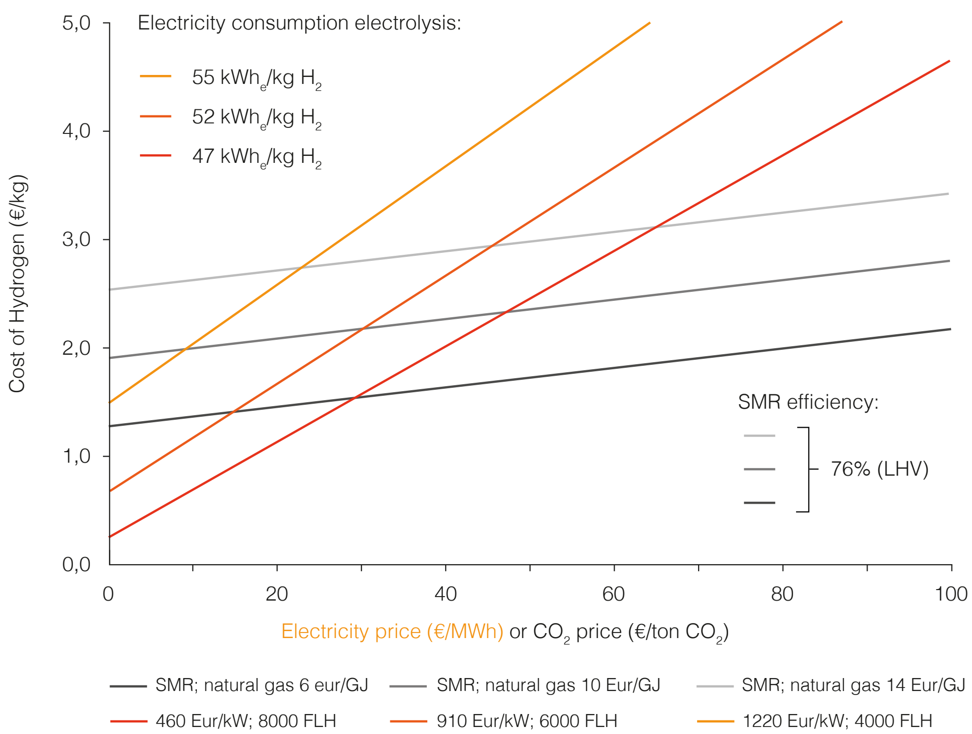
Figure 3 compares the costs of producing hydrogen by means of SMR and electrolysis for a wide range of conditions. This is an illustration of the general picture. A more in-depth discussion of the production costs for electrolysis and SMR combined with CCS is provided in Appendix 3.

19 These figures are in line with the objective that in 2023 the price of hydrogen delivered to a refuelling station should be in the range of €4.50 to €7 per kilo of hydrogen, as set out in the Multi-Annual Implementation Plan (MAIP) 2014-2020 of the Fuel Cells and Hydrogen Joint Undertaking (FCH JU).

20 This refers to value-added tax and any excise duty on hydrogen. As the current scale remains very small, hydrogen is not yet subject to any excise duty. This may change in future and could have a significant impact on the business case for refuelling points and the use of hydrogen-powered vehicles. At the same time, it is also a key tool to drive integration.

The grey lines indicate the production costs of a standard SMR plant with a capacity of 100,000 m³/h, which is operated continuously (capacity factor of 95%) and achieves an overall efficiency of natural gas to hydrogen of 76%. The production costs are shown as a function of CO_2 prices, at three different natural gas prices ranging between €6 and €14 per GJ. The current wholesale price is well below €5 per GJ [21] and the CO_2-price fluctuates at around €7 per tonne. This translates to a current production cost of around €1 per kilo. Increases in the CO_2 price cause the costs to rise, but the effect is limited. On the basis of the figures used, the production of 1 kg hydrogen results in 9 kilos of CO_2. Assuming a price of €100 per tonne, this will add €0.90 to the production cost per kilo of hydrogen.

Figure 3 | Comparison of the cost of producing hydrogen by means of SMR and electrolysis for a wide range of conditions.



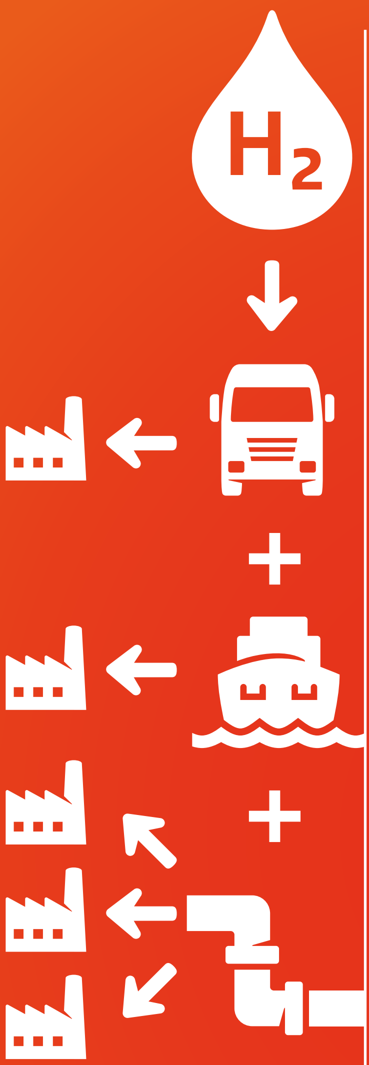
21 Over the past two years, the wholesale price of natural gas has been well below €5 per GJ. The expectation is that prices will remain low for the time being, but will begin a slow upward curve from 2020 onwards and reach approximately €9-10 per GJ in 2030-2035 (NEV 2017).

The orange lines plot the cost of producing hydrogen by means of electrolysis against electricity prices. The lines represent three different scenarios in terms of the cost of investing in electrolysis, the operating time (*the Full Load Hours or FLH)* and the specific energy consumption. The current scenario for electrolysis is closest to the topmost light orange line. This line would be approximately €0.75 per kilo lower if this had been based on an operating time of 8,000 full load hours, as was assumed for the bottom orange line. The comparison illustrates that it is currently difficult to compete with SMR, even if electricity prices are very low. Perhaps this will become possible if the most cost-effective systems are used at times when there is a surplus of sustainable electricity, reducing prices to zero. At the current time, however, the high number of operating hours that is required in order to bring production costs down sufficiently (Appendix 3 indicates this is from 4,000 hours and upwards) means the average price for the electricity supplied will quickly reach €40-60 per MWh.[22]

There is still a major effort needed in order to develop low-investment, high-yield systems that will allow electrolysis to compete with SMR where large-scale industrial applications are concerned. At the same time, this also requires electricity to be available at very low average prices. A high CO_2 price would be of some help, but only natural gas prices at a structurally higher level would truly make competition easier.

As indicated above, hydrogen for small-scale applications is significantly more expensive due to a range of additional costs. In these cases, electrolysis is able to compete with bulk production via SMR much more readily and in fact is able to do so now. In order for electrolysis to become the new standard for hydrogen production, efforts will need to be dedicated to the further development and upscaling of this technology, by using the applications listed here and by developing innovative business cases that enable electrolysis to be included as part of bulk production via SMR.

22 Over the past decade, the average cost of supplying electricity for wholesale use (150,000 MWh and over) has varied between €52 and €72 per MWh, excluding VAT and levies. True bulk consumers who trade on the APX themselves will on average pay lower rates. The supply costs are exclusive of network costs, which are relatively high for electricity in comparison to gas.



Large-scale use of hydrogen as an energy carrier will require a transport and distribution infrastructure which connects hydrogen production sites with users. Depending on the timing and the locations of producers and users, the current high-pressure natural gas infrastructure could be used for this.

6 | Infrastructure for transport and distribution

The Netherlands is not new to hydrogen as a product and has been using it as an industrial feedstock for a number of decades. Air Liquide has built a large private hydrogen network, which covers around 1,000 km in length and connects Rotterdam, Zeeland, Belgium and the north of France. A second large private network, also owned by Air Liquide, is located just across the border, in the Ruhr area. There is also a hydrogen network of approximately 140 km in the Rotterdam region, which is owned by Air Products.

However, there is no infrastructure that is well developed enough to be able to match the scale and penetration rate of the existing natural gas infrastructure. The key issue is whether hydrogen actually requires this and to what extent use could be made of the infrastructure that already exists, particularly within industrial clusters and logistical hubs.

Using gas infrastructure for hydrogen

Large-scale use of hydrogen as an energy carrier will require a transport and distribution infrastructure which connects hydrogen production sites with users. If development progresses gradually from small-scale applications, transport by truck or ship would be adequate in the early stages. In the case of large-scale application, transport by means of a pipeline infrastructure will be a critical link, as a result of factors such as the cost advantage that comes with long-term, large-scale use.

Depending on the timing and the locations of producers and users, the current high-pressure natural gas infrastructure could be used for this. DNV GL and GTS[23] have shown in a recent study that the pipes of the high-pressure natural gas infrastructure are able to cope with high percentages of hydrogen (up to 100%) and there are no significant technical or economic factors that would render the use of the natural gas infrastructure for hydrogen impossible upfront. Specific components and elements such as compressors, monitoring stations and gas storage facilities will require modification and there are aspects in terms of external security and integrity that require further investigation.

Further study will also be required in order to determine the specific pipes (sections) that could be made available for hydrogen. The availability of specific sections will be dependent on factors such as the development of the demand for natural gas, the development of the gas quality and the speed with which hydrogen will be developed. This and other information will make it possible to develop a masterplan providing insight into where and how the transition from a natural gas infrastructure to a hydrogen infrastructure might take shape over time. The DNV GL and GTS study referred to previously sets out a number of preliminary scenarios.

23 A. van den Noort *et al.* (2017), *Verkenning waterstofinfrastructuur* [Exploration of an infrastructure for hydrogen], DNV GL, OGNL.151886, October 2017.

Depending on the application, it would be possible to mix natural gas and hydrogen but this is not preferable. 'Filtering' the hydrogen from the natural gas is costly and requires additional energy. Another aspect that could pose problems is the highly variable gas quality, which is the combined effect of the filtering and variations in the flow rate throughout the year.

The hydrogen symbiosis project at Dow, ICL, Yara and Gasunie in Zeeland Flanders aptly illustrates how the natural gas network can be used for hydrogen. Here, an existing gas pipeline is used to allow Yara to access 'surplus' hydrogen from Dow and use it as a feedstock in its processes. As the use of hydrogen in industry increases, there will be scope to develop more of this type of project. It is therefore important for the statutory and regulatory provisions governing the gas infrastructure to be revised so they are not a barrier to use of the infrastructure for hydrogen. This is addressed in Chapter 8.

Another option to the use of the high-pressure natural gas network for hydrogen, could be to install hydrogen pipes in existing natural gas pipelines (known as the pipe-in-pipe solution). The scope for this option will increase when the demand for gas and the associated demand for transport capacity for natural gas decline in the future. Dual-use could be an attractive option during a transitional period and requires further study in order to establish the feasibility and practicality in terms of engineering, cost and safety.

Use of offshore assets

If hydrogen from water is produced offshore, using electricity generated through wind power, an option could be to use the current gas assets, including infrastructure, compressors and platforms, for hydrogen. Another promising option is to integrate sustainable hydrogen production on an energy island on, for example, the Dogger Bank, as recently proposed by Tennet, Gasunie and the Port of Rotterdam Authority. This could in future allow large quantities of sustainable hydrogen to be produced and transported to land, particularly to locations such as the Rotterdam region (chemical and manufacturing industry) and IJmuiden (steel production) where demand for hydrogen could be high. There are various studies which have looked at the possibilities of using existing oil and gas platforms for the conversion of electricity into hydrogen.[24] Depending on the assumptions, it would appear possible to establish a business case for this re-use in the longer term. The offshore industry has indicated it is interested in exploring this, through a pilot for example. TNO has brought together several stakeholders from the research community and industry in a project entitled 'North Sea Energy System Integration'. The idea is for this initiative to develop into a programme which focuses on the re-use of existing assets, including beneficial re-use of offshore oil and gas industry related knowledge and expertise (Human Capital Agenda).

Yet a great degree of uncertainty remains around these options and it is likely that another 10-15 years will pass before they might be ready for implementation. A key question is whether and to what extent hydrogen production should take place at sea or on land, when considering the cost, flexibility and practical possibilities for expanding the electricity infrastructure. It is

24 On the economics of offshore energy conversion, Jepma *et al*, February 2017

irrefutable that some of the opportunities presented here require more insight to be developed in future into possible variants based on a holistic approach for the countries neighbouring the North Sea and the connections to the hinterland. Areas for attention in this regard are the declining production of natural gas in the North Sea and the timeline for decommissioning these assets.

Use of local gas networks

At a local level, hydrogen could be combined with networks for distributing natural gas. This mainly relates to use in existing built environments where electrification or linking up with heating grids is not possible or feasible and hydrogen might therefore, from a social perspective, be found to be the most feasible option for 'greening' the demand for heat. This is another area where many questions are still unanswered. One aspect is whether application at home or district level would be preferable and what the optimum solution would look like in terms of cost, safety and acceptance. Further research is also required into the ways in which distribution networks could be made suitable for hydrogen. At the request of Netbeheer Nederland, KIWA has launched a study which seeks to find answers to these questions. This option has attracted the interest of a number of grid operators. Recently, a pilot exploring the application of hydrogen in the built environment was carried out on the island of Ameland. This involved adapting a care home including flats in order to accommodate a 20% level of hydrogen in natural gas. The findings show this created no barriers. The options for blending hydrogen with natural gas, or alternatively using natural gas networks exclusively for hydrogen, are also being studied by GERG, a European association of gas companies which focuses on R&D challenges. The UK has conducted a comprehensive feasibility study (H21 Leeds City Gate project[25]) into the options for switching the entire city of Leeds to hydrogen. Work on follow-up steps is currently underway.

Hydrogen infrastructure for mobility

The use of hydrogen for mobility purposes brings into play other infrastructure challenges than those outlined above. In this area, discussions mainly centre on the availability of hydrogen refuelling stations. Initially supply will predominantly be by road, with the help of tube trailers. However, where options are available and practicable, supply can also take place by pipeline, as is the case at the Rhoon refuelling station. Alternatively, production could be on-site, by means of electrolysis or small-scale SMR. A successful introduction of hydrogen in the mobility sector will also require the availability of a basic infrastructure of refuelling points. The comparatively long range of fuel cell electric vehicles (500 km and upwards) and the quick refuelling options mean that in order to achieve significant coverage and launch the market, a relatively small network will already be sufficient.

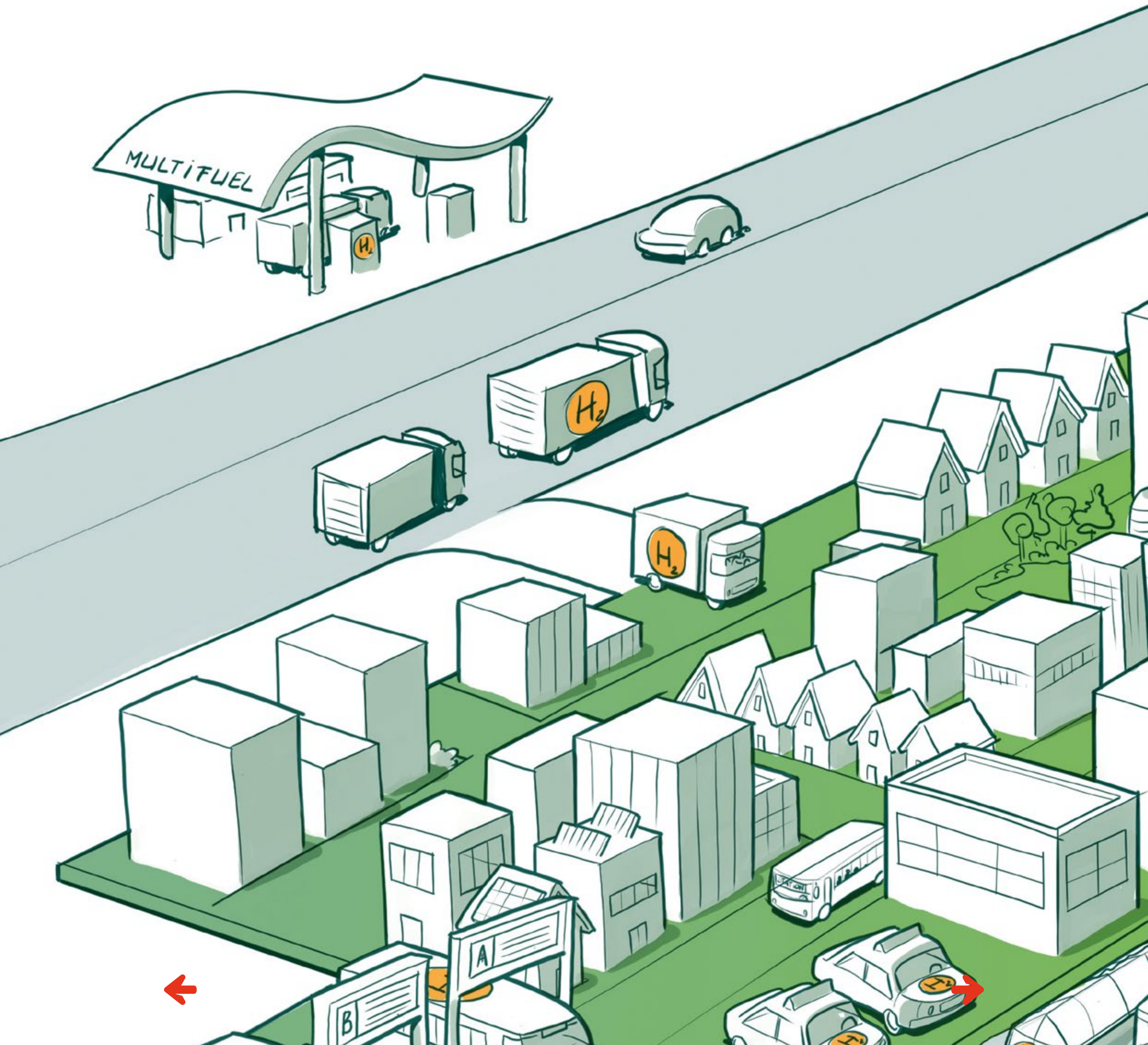
As yet the cost of a refuelling point is relatively high, which means the challenge lies in maximising utilisation in order to keep the financial gap manageable. This is why the objective for the start-up phase must be to establish the network in the best strategic locations and

25 https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/$H_2$1-Executive-Summary-Interactive-PDF-July-2016-V2.pdf

bundle as much of the hydrogen demand around these locations, by way of e.g. regional clusters where the various options for producing and using hydrogen can be combined. If vehicles are thinly distributed across a large network, this will result in a large financial gap and long-term unprofitability that will potentially cause market parties to lose interest.

Another consideration is that the start-up phase must build wherever possible on the knowledge and expertise that the market has built up over the past 15 years through a range of demonstration projects for hydrogen refuelling stations across the world. This has already contributed to a significant level of standardisation, which increases the reliability of the refuelling points. A network characterised by restrictions, frequent disruption at the refuelling points and disappointment for customers will do nothing to promote successful market introduction and development. This is why the right balance will need to be struck between refuelling stations operated by established parties and those of new entrants.

In the case of buses and goods transport vehicles, most refuelling will take place at the location the vehicles return to on a daily basis (depots). In these cases, it will be easier to select the appropriate capacity for the refuelling point since the number of vehicles will typically be known. In these circumstances, a refuelling point can be used to serve a large number of vehicles. This will significantly reduce the problem of under-utilisation and make an acceptable business case much easier to achieve. Reliability will be of major importance, not only because the increased level of dependency on the refuelling station but also because idle time for buses and lorries can have significant financial implications. Reliability and robust arrangements regarding supply security will therefore be key topics in the design of projects.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However, it is important to pay at least as much attention to non-technical aspects as experience has shown that they are often the reason why innovations are delayed or in some instances even halted.

7 | Non-technical aspects

The previous chapters discussed the technical options for the production, transport and application of hydrogen. However, it is important to pay at least as much attention to non-technical aspects as experience has shown that they are often the reason why innovations are delayed or in some instances even halted. These non-technical issues form the topic of this chapter.

Policy, legislation and regulations

Key elements are the government policy and the statutory and regulatory provisions which promote the use and production of hydrogen and address and resolve possible bottlenecks and obstacles. There have been some policy developments around hydrogen as an energy carrier but these are limited and look at cars and buses only. With respect to cars, the policy is generally tacked on to that for electric cars (no excise duties). As yet, there is no overarching and structural policy that could contribute to the development of hydrogen to its full extent.

Nor can statutory and regulatory provisions currently be said to be tailored adequately to the introduction of hydrogen. A significant proportion of safety regulations and the associated safety requirements are based on the large-scale use of hydrogen as an industrial gas and as a feedstock in the chemical industry. When compared with other options, these rules would be relatively onerous if applied to use of hydrogen as an energy source. It would be desirable to review whether it would be sufficient to develop an adapted set of requirements that meets the current standards and takes these new applications into account.

In the framework of the Dutch Gas Act, there is little scope for grid operators to take a larger role in the transport and distribution of hydrogen. An example is the hydrogen symbiosis project referenced in Chapter 6, a collaboration of Gasunie and several chemical companies in Zeeland Flanders. This project, which involves transport of hydrogen through a high-pressure natural gas pipeline, cannot be executed by the national natural gas transmission system operator (TSO) because hydrogen is not included in the Gas Act, and therefore is not part of the regulated task of the grid operators. A successful introduction of hydrogen requires incorporation of hydrogen in the Gas Act and a review as to whether and when it will be necessary to include regulations for hydrogen networks. Key aspects of this debate will the choice between private or regulated hydrogen networks and the determination when each option will offer the most cost-effective solution from a social perspective.

Subsidies

There are a number of European and national schemes which make support available for selected areas, examples of which are the introduction of fuel cell electric buses and the roll-out of a basic infrastructure of hydrogen refuelling points. In addition, innovation subsidies for hydrogen (industrial research, experimental development or demonstrations) are available through the Topsector Energy, although the limited availability of specific subsidies for hydrogen (less than 1m euro in 2017) do not yet amount to broad support for hydrogen initiatives. Funding for early phase research is made available by NWO. There is no structural support for hydrogen as yet within the Netherlands.

At European level however, support for demonstration projects is available through a range of large-scale programmes. A key programme specific to fuel cells and hydrogen is that pursued by the FCH JU (Fuel Cell and Hydrogen Joint Undertaking), a public-private partnership within the framework of the Horizon 2020 programme. In addition, support for hydrogen infrastructure is available under the TEN-E (Energy) and TEN-T (Transport) programmes. Examples in the Netherlands include the TSO2020 synergy project run by Gasunie, Tennet, Akzo and partners as well as the H2Benelux project for the development of a number of hydrogen refuelling points. Further support is available through the Interreg programmes, although the options are fragmented, not always transparent and often difficult to access.

Safety

In the area of safety, a hydrogen safety programme has been initiated by a group of stakeholders led by NEN. The initial focus is on the use of hydrogen in transport, with a review of the safety aspects within the chain as a whole. If hydrogen is produced centrally, this chain commences when the hydrogen leaves the production site. In this case, on-site safety is adequately covered under an industrial regime. By contrast, production taking place at a refuelling station would come within the scope of this programme. The chain furthermore encompasses refuelling stations and the use of vehicles, through to the maintenance and scrapping of vehicles and emergency assistance during incidents. The aim of the programme is to review systematically whether all safety aspects have been identified, whether adequate measures exist and have been put in place, and whether aspects have been addressed clearly and unambiguously in regulations.

The programme also considers safety aspects within the built environment, including the parking of hydrogen-powered cars in underground carparks or a garage belonging to a home. However, the programme does not cover the use of hydrogen as an energy carrier for heating purposes within the built environment. There are currently not sufficient arguments to do so. A specific safety programme for the built environment will, however, become crucial if development of the heating option is being considered, particularly if the hydrogen infrastructure is to be installed up to or even in the home.

While a programme specification is available and safety has been identified as a crucial aspect, implementation is still pending in anticipation of sufficient funding and industry participation. This must become an explicit component of an action plan for hydrogen.

Integration into society

Social support will be a pre-requisite for a successful roll-out of hydrogen, in particular with regard to applications such as new production sites, infrastructure, refuelling points and applications to be built that will bring consumers into direct contact with hydrogen or where interaction with consumers will be greatest.

While it cannot be assumed in advance that hydrogen will prompt much debate, it is nevertheless important to ensure citizens are well prepared for initiatives in order to avoid the emergence of resistance based on (perceived) risks and hazards. It will also be important to communicate and educate the general public in a more general sense about the benefits and necessity of new developments such as hydrogen in relation to energy supply, as well as their significance for society in relation to the climate and energy transition. This will help the general public to get used to new options and, if possible, build support for them. An aspect that may also require attention and explanation in relation to this is the current debate on abandoning natural gas.

The application of hydrogen from natural gas combined with CCS gives rise to a different scenario. Past experience has shown that citizens are, or can be, extremely critical of this and that it is essential to provide good quality information and engage them at an early stage. This is why it is crucially important to apply the lessons learned from past CCS projects. It must also be noted that even though new CCS projects are expected to use offshore storage, this is no guarantee that such projects will not meet with opposition from society. That is why it is also necessary to engage nature conservation and environmental organisations in a dialogue about this, in order to determine if and on what terms such routes would have support. This dialogue has been initiated in the context of the CCS roadmap. The first results will be available in the first quarter of 2018. It will be key to untangle these debates in order to prevent the discussion on CCS from casting a shadow over the discussion on hydrogen.

Human Capital Agenda (education and training)

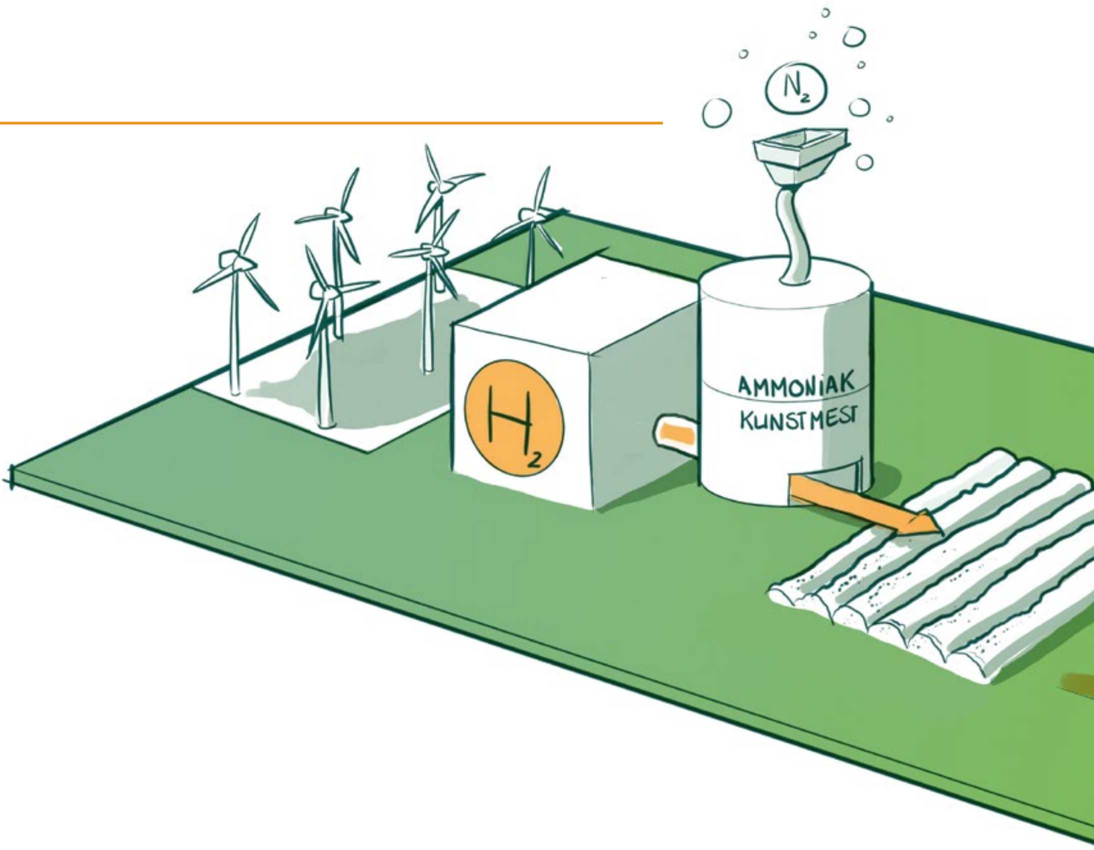
The expertise required for hydrogen is another non-technical aspect. While hydrogen is not a new development, the application thereof in new markets, such as mobility or the built environment, and the development of new production methods will create a demand for qualified staff. The ability to produce hydrogen offshore will also place specific demands on the expertise and skills of staff. Large-scale application of hydrogen means the required personnel will need to be available. This means focus must be placed on developing technical competencies among new entrants to the labour markets and workers completing lateral transfers, and also among those workers that could upskill or retrain from occupations that are less in demand.

This will be a major challenge in view of the scarcity of technically qualified staff across all levels and the expectation that the shortages will increase further. Part of the reason for this is that many aspects of hydrogen require specific expertise in the areas of mechanical engineering, electrical engineering, chemistry and physics. It is therefore recommended to include hydrogen in the curriculum of basic education programmes.

Hydrogen trading

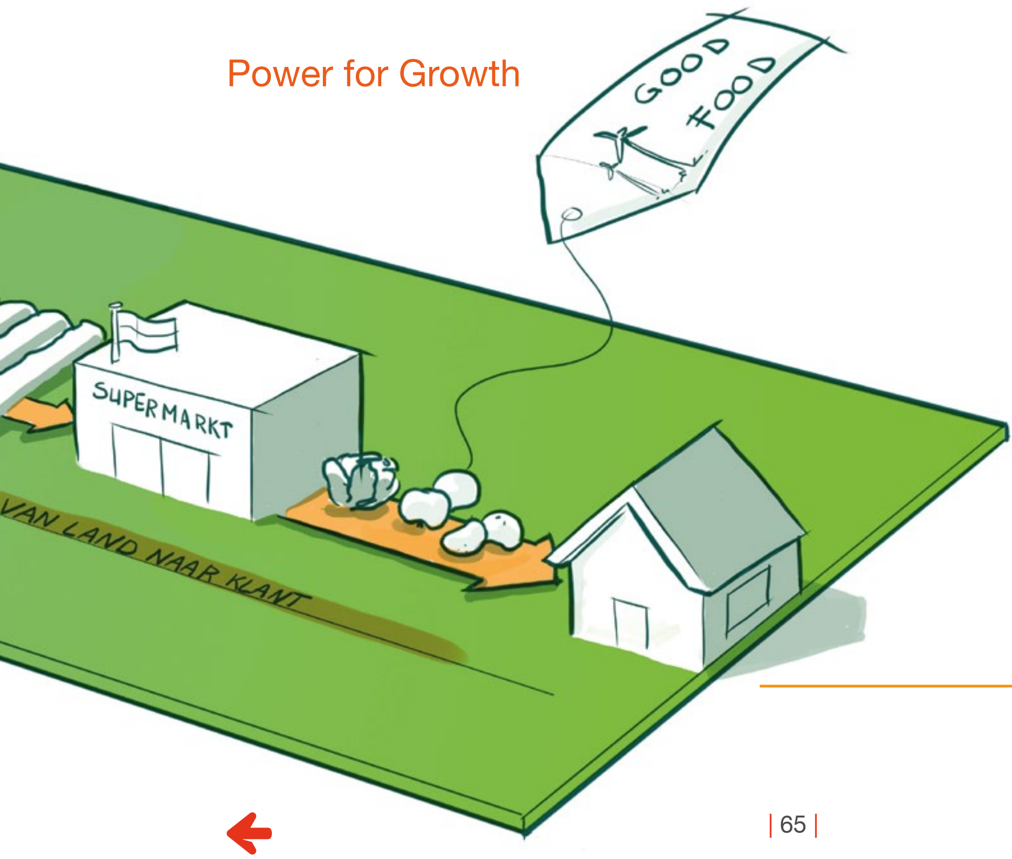
The possible development of hydrogen into a widely used energy carrier raises the question as to how the trade in hydrogen might be organised. One possibility would be to organise trade by means of an open trading platform, which would enable producers to offer hydrogen for sale, users to purchase hydrogen and any party wishing to play a role in hydrogen trade to make sales or purchases. The Dutch gas market, which is organised around the TTF, provides a template for such a trading platform.

For now, the establishment of such a hydrogen trading platform might still be premature. Even so it is important to identify and consider the benefits and drawbacks of a trading platform at an early stage, whilst taking into account the experiences of how the current market for natural gas has come about. A transparent and well-functioning market could significantly accelerate the development of hydrogen as an energy carrier.



In this regard, the specification of the product to be traded is a key question that will eventually need to be resolved. Where individual contracts are concerned, the producer and user can agree between themselves what specification would be mutually acceptable. They can reach agreement on a purity grade which the producer is able to supply and which the user is able to handle. In the context of an open trading platform, however, purity is something all stakeholders must be consulted on and agree to. If the independent transporter is to handle any and all exchanges of products within the platform, all producers must ensure their supplies comply with the same minimum standard of purity and all users must be capable of handling the same purity standard.

Power for Growth



The inventory includes initiatives that are currently in the implementation phase, projects that were recently concluded and for which a follow-up is being considered, and initiatives that are in the conceptual or planning phase.

8 | Hydrogen initiatives in the Netherlands

In the context of this hydrogen roadmap, a third party was commissioned to create an overview of all current initiatives, plans and applications.[26] The inventory includes initiatives that are currently in the implementation phase, projects that were recently concluded and for which a follow-up is being considered, and initiatives that are in the conceptual or planning phase. The focus is mainly on the next five years, although there are a number of plans with a longer timeline that feature prominently in ongoing discussions and that were included for that reason. The inventory also outlines how the various stakeholders and initiatives expect the role of the government and their own strengths, ambitions, ideas and courses of action to develop in the next five years.

Initiatives and projects exist in abundance. They are over a hundred in number, although this varies a little depending on how the boundaries between initiatives are chosen (e.g. should each filling station count as a separate initiative?). The initiatives have been classified based on their energy function, with R&D in relation to sustainable hydrogen production and solar fuels and supporting projects for market development and policy forming additional categories. Most initiatives relate to ideas, plans and feasibility studies. There are also a significant number of R&D projects for technology development, many of which through EU programmes, where Dutch actors are achieving a good measure of success.

Apart from established industrial applications of hydrogen, projects that involve practical applications mainly concern projects in the area of mobility and transport (refuelling stations, buses, passenger cars, goods vehicles and similar). Parties developing business cases for hydrogen often look to mobility as a sector where hydrogen can potentially generate maximum added value, although fleets are still small and this is reflected in sales volumes. There are specific plans for the coming years which look to expand the number of refuelling stations from 3 to 10-12 by 2020 and there are specific plans to increase the number of hydrogen-powered buses to 60 over the same period. Work is also underway to establish a small fleet of refuse collection lorries and lorry prototypes in the 27-40 tonne class.

There are three initiatives that focus on producing hydrogen in bulk for use in gas-fired power plants and generation of High-Temperature Heat and feedstock for the petrochemical industry, by combining natural gas and CO_2 capture and storage. Two of the three initiatives take the form of an exploratory study and are referred to as the H-Vision project and the 'Berenschot study' respectively. The latter is a non-case specific analysis of the concept. The H-Vision project envisages how the concept might be implemented on the Maasvlakte, using insights into CO_2 storage gained in connection with the ROAD project.

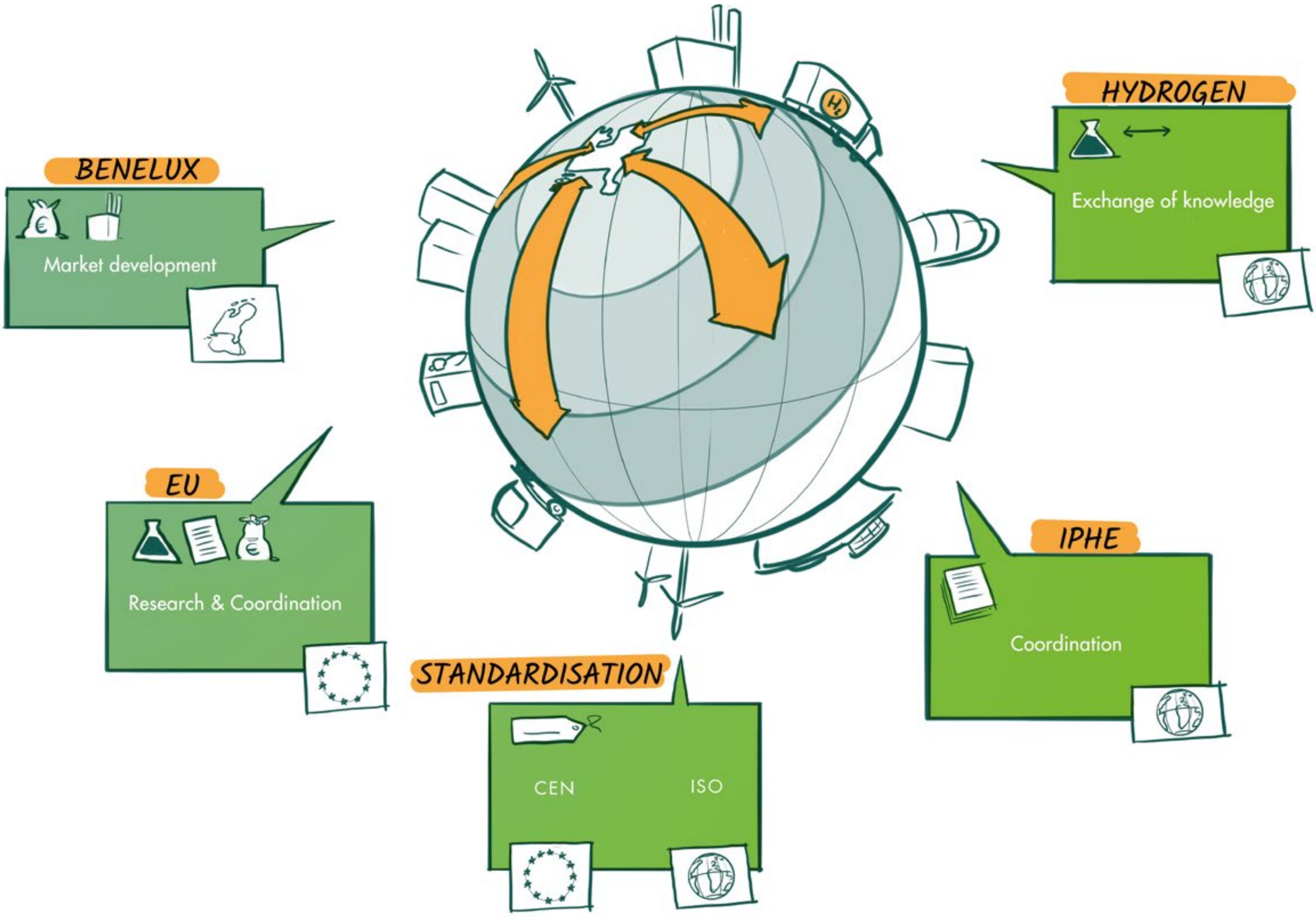
26 *Overzicht van Nederlandse waterstofinitiatieven, -plannen en -toepassingen* (Overview of hydrogen initiatives, plans and applications in the Netherlands). Dwarsverband (R. Hoogma), November 2017. Please see https://topsectorenergie.nl/en/tki-new-gas.

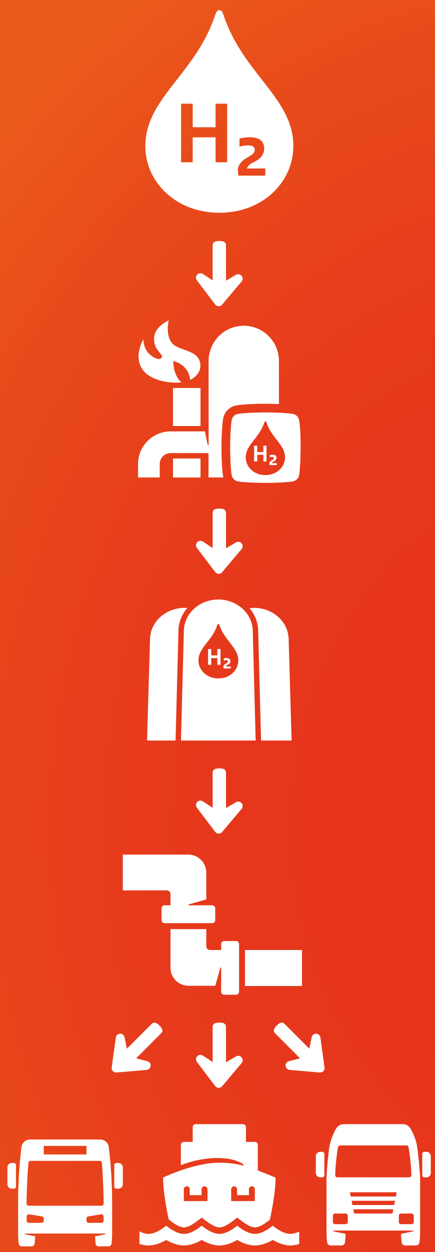
The initiative relating to the Magnum power plant in Eemshaven represents the most concrete application. Led by the potentially powerful alliance between Nuon, Statoil and Gasunie, implementation is scheduled for 2023. The concept derives its strength from its scale, which would make it possible to achieve a significant reduction in CO_2 emissions subject to a sufficient number of operating hours. It also justifies the development of infrastructure for transport by pipeline and seasonal storage in salt caverns. At the same time, the scale gives rise to challenges. Both the cost of investment and the cost of hydrogen for producing electricity are high, which means the production would rank below natural gas in terms of merit. The implementation of the project and the operation of the power plant will require significant financial support.

Regions working on hydrogen initiatives are the Northern Netherlands (implementation with considerable potential in Eemshaven and applications in Chemiepark Delfzijl, among other locations), Rotterdam/Goeree (existing hydrogen industry, combination with CCS initiatives and energy production island), the Southern Netherlands (product development with the regional manufacturing industry in a cross-border collaboration with Flanders, initiated and coordinated by WaterstofNet) and Arnhem/Gelderland (SME cluster for hydrogen involved in many EU projects). There is one substantial project in Zeeland (Green Deal on Hydrogen Symbiosis). The Amsterdam/North Holland region is currently lagging behind, but this could soon change. Initiatives for refuelling stations can be found across the Netherlands.

Developing a market for climate-neutral and sustainable hydrogen as a feedstock and an energy carrier (fuel) requires not only that technology and business cases are developed and production capacity and an infrastructure for transport and distribution are built. Suitable regulations, norms and standards governing safety, sustainability certificates (Garantuee of Origin) and procedures for granting permits must also be in place. The position of hydrogen in the Gas Act is one of several recurring themes highlighted in the various initiatives. As part of the national and international energy system, hydrogen has yet to receive the levels of attention that have been paid to natural gas and electricity within statutory and regulatory frameworks. Yet this will play a crucial role in ensuring the successful development of hydrogen. Some of the questions emerging here will be similar to those raised in relation to natural gas and/or electricity over the past years. In addition to this, new aspects can and must be raised in view of the enormous potential for growth in the market and the opportunities for reusing existing infrastructure. Other issues that will play a role include operating subsidies for low-carbon instead of renewable energy carriers, joint communication on the role of CCUS and extended support facilities for RD&D. Work is therefore underway to address issues such as the harmonisation of regulations, the development of certification for sustainable hydrogen and the development of standards for measuring the quantity and quality of hydrogen delivered at a refuelling station.

International aspects of hydrogen





This chapter discusses several innovation challenges in relation to hydrogen, which cover the entire chain from production, storage and transport to distribution and end-use.

9 | Innovation challenges

This chapter discusses several innovation challenges in relation to hydrogen, which cover the entire chain from production, storage and transport to distribution and end-use. Where production is concerned, the emphasis is on electrolysis. Storage, transport and distribution are characterised by a wider range of topics, which relate to all components forming part of the current storage and pipeline infrastructure for natural gas and also to infrastructure for the distribution or supply of hydrogen for applications in the area of mobility and transport.

The key technologies for end-use applications are fuel cells and burners. Innovation challenges in this area include the development, implementation and testing of systems, in particular fuel cell systems for practical applications such as in buses, lorries, mobile machinery and ships. The discussion regarding these elements will focus on the broad outlines. Specific innovation challenges in relation to the various elements have been discussed in greater detail elsewhere[27].

Hydrogen production (and the link with CCS)

The process for generating hydrogen for industrial non-energetic applications from natural gas is standardised, is being applied on a large scale and has already been optimised to a large extent. The challenge with regard to this application is how to decarbonise current production and how to replace current production with hydrogen produced from non-fossil sources, using energy from sustainable energy sources. One way to achieve decarbonisation is to capture and store CO_2. This again is a standardised process, which industry already applies extensively at sites where there is demand for a concentrated flow of CO_2, such as the production of urea and carbonated drinks. The associated costs are passed on as part of the product cost. However, in places in which such a demand is currently absent, CO_2 capture is driving up costs compared with the existing scenario. In order to minimise cost rises, there is a need to optimise CO_2 capture processes further and develop new, more efficient and cheaper processes.

Research into CO_2 capture is currently treated as part of CCS, a field which investigates methods for *post-combustion*, *oxy-fuel* and *pre-combustion* capture. Capture during hydrogen production is in effect a *pre-combustion* process. Carbon is removed from the natural gas before it is used in the form of hydrogen, although the hydrogen produced is not yet used to fuel *combustion* processes[28]. Innovations relating to *pre-combustion* technologies and concepts involving natural gas must be addressed as part of an innovation programme.

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27 1. Topsector Energy and Topsector Chemie, *Elektrochemische Conversie en Materialen* (Electrochemical Conversion and Materials), September 2017; 2. Fuel cells and Hydrogen Joint Undertaking, Multi-annual Workplan 2014-2020, June 2014, and subsequent workplans for 2015, 2016 and 2017; and 3. US DOE, H2@Scale RD&D – Opportunities and Challenges, DRAFT, 2017.

28 A distinction can be drawn here between (1) the thermochemical conversion of hydrogen in burners using oxygen in order to produce High or Low-Temperature Heat, electricity or a combination of both (CHP), and (2) electrochemical conversion of hydrogen in fuel cells using oxygen with electricity as the primary product.

A number of alternatives exist for the production of sustainable hydrogen, with electrolysis of water using sustainable electricity being the main option. Other options are biogas reforming, gasification of sustainable biomass and waste, and supercritical water gasification of residual biomass flows. In all of the latter options, (sustainable) carbon plays a role alongside hydrogen. In view of the anticipated future demand for sustainable carbon for chemical products and materials as well as for sustainable synthetic liquid fuels, biomass is likely to be more relevant for the production of sustainable syngas than for the production of hydrogen alone. The focus for hydrogen is therefore on electrolysis.

In terms of cost, hydrogen production by means of electrolysis is currently only able to compete with conventional production of hydrogen from natural gas under specific conditions. Although systems are available on an MW scale, the cost of the technology must be reduced and systems must be scaled up towards GW capacity. Upscaling will already translate into cost savings by itself, since the proportional increase for peripheral equipment is less in larger systems than in electrolytic cells and stacks. It is also necessary to optimise systems and replace expensive materials with cheaper alternatives, whilst increasing efficiency and durability further.

Storing, transporting and distributing hydrogen

The key innovation challenges in connection with storage, transport and distribution concern the use of the current natural gas infrastructure for hydrogen. Key questions in this regard are: what conditions must be fulfilled to make this possible, whilst maintaining the minimum safety requirements? What technical modifications will be needed and how much will they cost? This applies to the national high-pressure network as well as the regional transport networks and local distribution networks. It is also necessary to quantify the need for storage and determine where and in what form storage must be built. Possible options include pure hydrogen in the form of a compressed gas (e.g. in salt caverns), in the form of a liquid (in above-ground tanks) or storage as a nitrogen compound (ammonia), a carbon compound (methanol, formic acid) or perhaps bound to a liquid organic hydrogen carrier (LOHC).

Another aspect that needs to be elaborated is how to shape the switchover in gas quality and the conversion of the infrastructure. Will the switch to pure hydrogen be immediate or be brought about using gas mixtures in which the hydrogen concentration is gradually increased? What role will green gas play? And what phases and speed should be adopted with regard to the conversion of the natural gas infrastructure or parts thereof? The declining demand for transport capacity for natural gas also creates scope for considering dual-use solutions which involve the installation of flexible gas-tight composite pipelines for hydrogen in existing pipelines.

Key innovations specific to mobility and transport relate to elements of refuelling stations which can presently create obstacles. More accurate flow measurements are needed, as well as equipment and procedures for the calibration and periodic inspection of flow meters.

There is also a major need for reliable and cost-effective methods and equipment for the (online) measurement of contamination at ppm and ppb level, in order to safeguard the required hydrogen quality. Innovations are also needed that help to significantly reduce investment and operating costs. There is still room for improvement on numerous components, including compressors, filler hoses, refuelling nozzles and high-pressure tanks, as well as methods enabling vehicles to refuel as quickly as possible within the stipulated safety parameters.

With regard to small-scale solutions for storing hydrogen in vehicles, transport by truck or ship and storage at refuelling stations, new materials are needed for the production of stronger, lighter and cheaper high-pressure tanks in a range of sizes and pressure ratings (350-700 bar). Materials for vehicle tanks should preferably allow refuelling to take place within a wide temperature range (-60 °C up to 100 °C). With regard to cars, there is a need to optimise the geometry of tanks, reduce component sizes and integrate valves and pressure regulators within tanks, in order to allow them to be fitted more easily into a vehicle. Alternative methods for storing hydrogen (including in powder form) are also in development, but their potential is presently unclear.

End-use of hydrogen

End-use of hydrogen will benefit from innovations which promote the development and introduction of energy-related applications in the area of mobility, transport and logistics, industry and the built environment. Although the development of new processes using hydrogen as a feedstock will certainly be an important field for industry, this is beyond the scope of a hydrogen roadmap.

The key technologies for the application of hydrogen are burners and fuel cells, for the production of heat and electricity respectively. Fuel cells and fuel cell systems constitute the greatest innovation challenges in this area. The innovation needs are similar to those for electrolysis, although a key difference is that it is not necessary to work towards scaling up fuel cell systems to capacities of hundreds of MW. If needed, capacity at that level could also be provided by means of hydrogen-powered gas turbines.

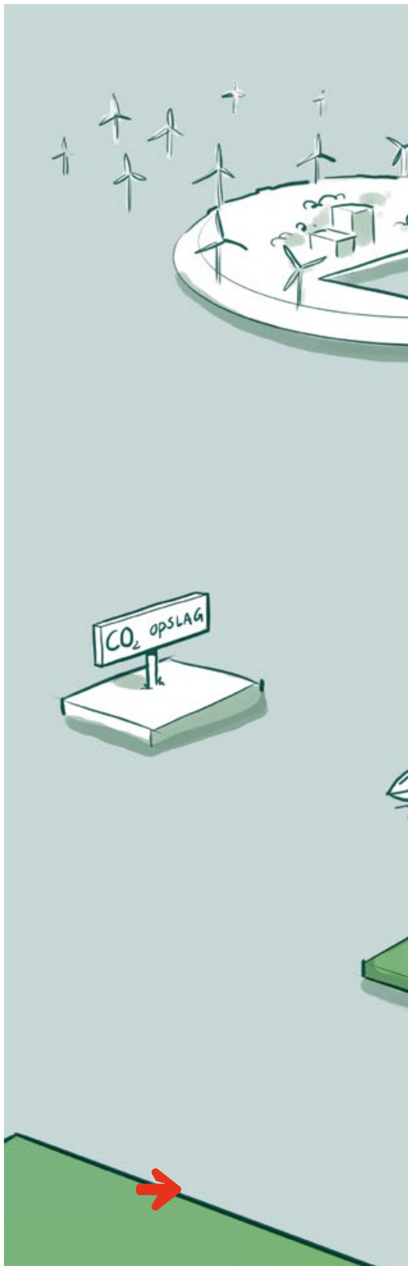
A key area for the application of fuel cells is in mobility and transport. Here, the Netherlands could play a significant part in the development of hydrogen-powered lorries and buses for public transport, as well as specialty vehicles such as refuse collection lorries and road sweepers. In addition, there is a wide range of mobile equipment in ports and airports that might be well suited to hydrogen applications. Possible applications can also be found in the maritime sector, examples being tour boats, ferries, inland vessels and the wide range of vessels used to deliver port services (inspections, tugs and similar).

Aside from mobility and transport, the built environment is another area that could offer concrete opportunities for applications of hydrogen. To clarify whether application is possible and if so what form it could take, there are a great number of questions that need answering.

Options include bringing hydrogen into homes or installing it up to the boundary of the home of perhaps just the district, whilst combining it with local heating grids operated at comparatively low temperatures. For the foreseeable future, this area will offer scope for research into the suitability of the local gas supply network, the safety aspects that are involved and the costs associated with modifications. This may in turn create a need for innovations relating to the use of hydrogen in central heating boilers and hybrid heat pumps and the development of small-scale CHP systems powered by fuel cells.

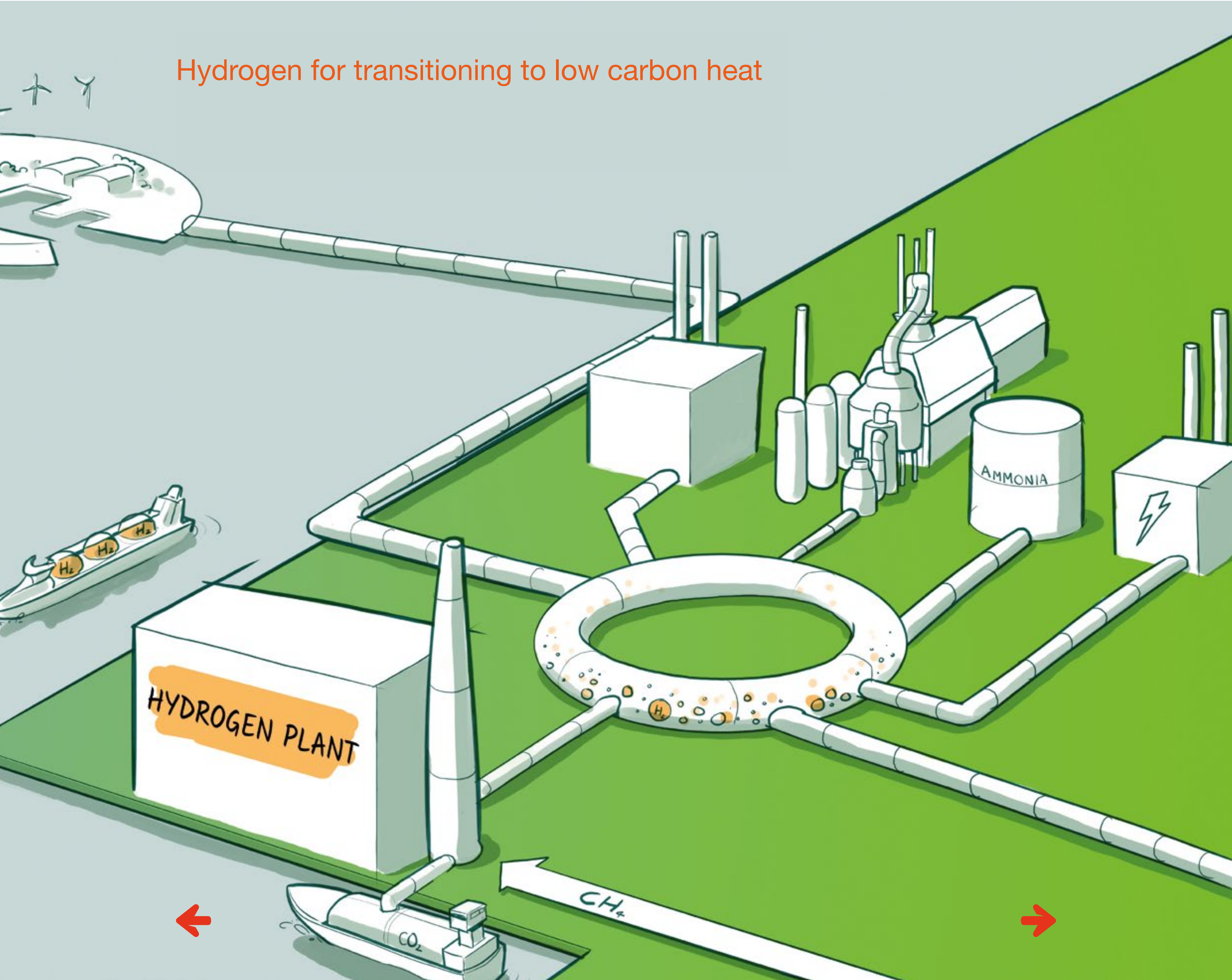
Overarching aspects and innovation challenges

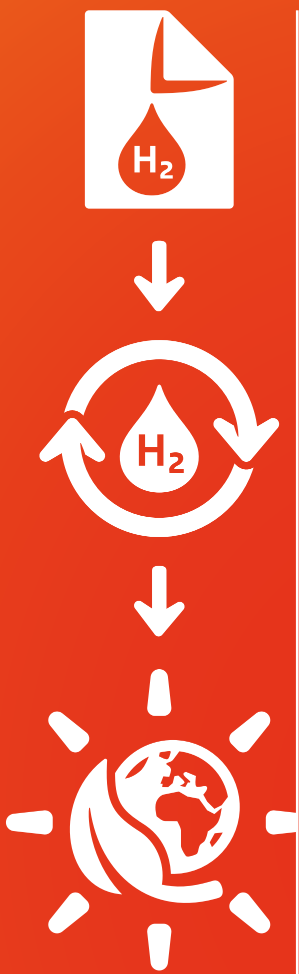
The manufacturability and standardisation of the technology and systems are key aspects that must be considered early on in relation to all developments, especially in the area of electrolysis, fuel cells and high-pressure tanks. It must be possible to manufacture standardised high-quality products in large quantities and at a sufficiently low cost. The Netherlands has strong international capability in this field, through companies such as ASML.



In addition to innovation challenges in relation to technology, there are also a number of innovation challenges that are more generic in scope. One example of this is timely communication with the general public on the benefits, necessity and specific features of hydrogen, in order to increase the chances of a successful introduction of this new energy carrier. Another innovation challenge concerns the development of suitable norms and standards in relation to hydrogen and the inclusion thereof in all relevant laws and regulations. Topics for such norms and standards could include the safe use of hydrogen and the standardisation of the quality of hydrogen if it is to be delivered to a range of customers for a range of applications by means of a public infrastructure. In this context, the development of a transparent market for hydrogen could be seen as another innovation challenge.

Hydrogen for transitioning to low carbon heat





The intention is to advise on an approach for developing and promoting hydrogen over the coming years, in order to begin laying the foundations for the introduction of hydrogen as a climate-neutral and sustainable pillar of the energy transition.

10 | Action plan

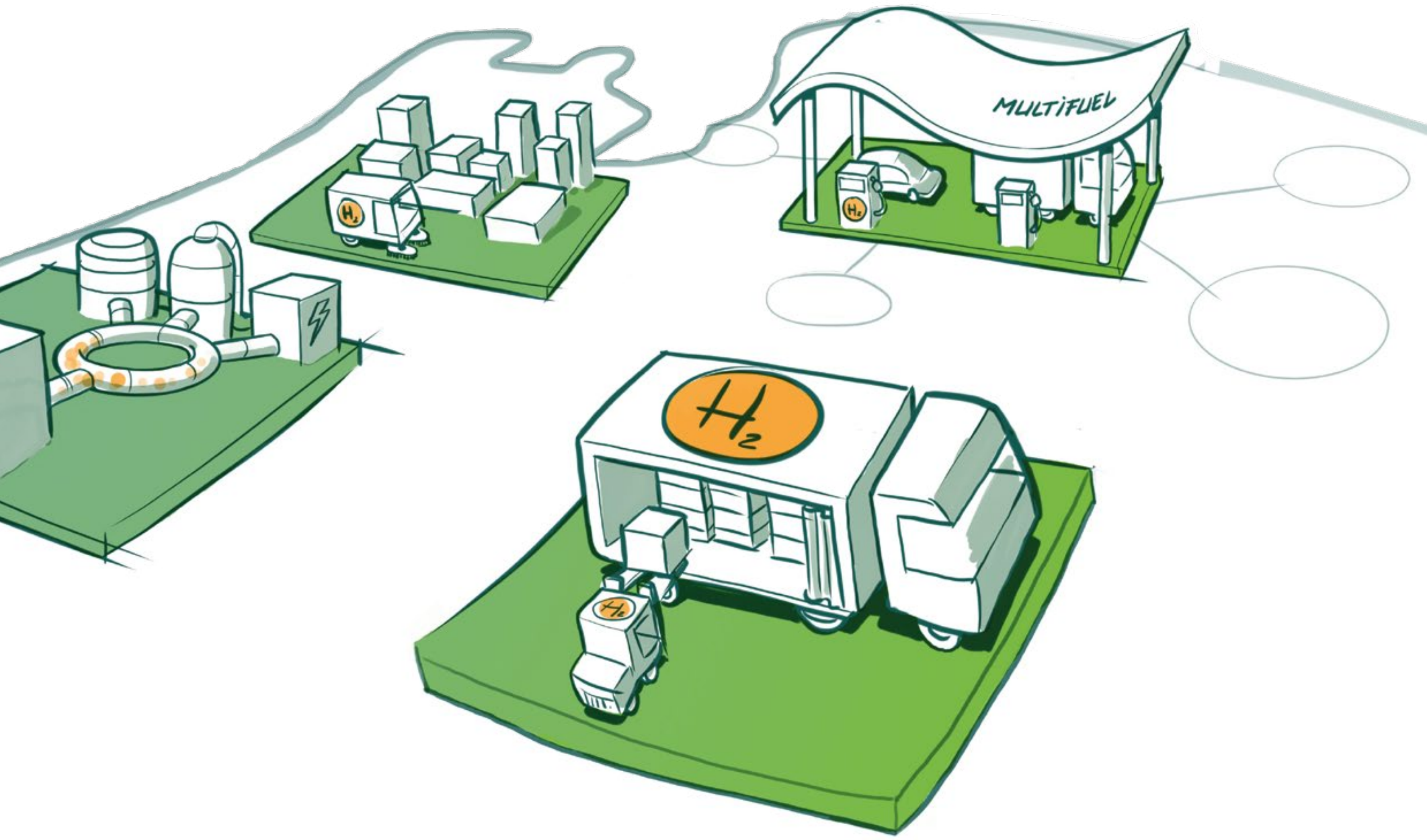
This chapter describes the outlines of an action plan for hydrogen. The intention is to advise on an approach for developing and promoting hydrogen over the coming years, in order to begin laying the foundations for the introduction of hydrogen as a climate-neutral and sustainable pillar of the energy transition. The introduction of hydrogen must be launched *here and now*. There is every urgency to do so: climate change presents an enormous challenge and hydrogen has solid potential as a climate-neutral fuel and feedstock in scenarios targeting a dramatic reduction in CO_2 emissions through extensive decarbonisation of fossil sources and optimum use of the potential of wind and solar energy.

Hydrogen from fossil sources has played a major role in industry for several decades now. The challenge lies in a slow but steady transition to what must ultimately become fully sustainable hydrogen. Considering the time that remains to achieve a dramatic reduction in emissions, the limitations on the speed of implementing sustainable energy and the scaling-up that is yet to be accomplished for production technologies for hydrogen, a pathway based on climate-neutral hydrogen from natural gas combined with CCS (also known as blue hydrogen) appears indispensable in this context, so that upward momentum can be established. This pathway has the additional advantage that it can quickly operate at high volumes and provide a business case for converting the natural gas infrastructure to hydrogen.

When hydrogen is initially deployed as an energy carrier, there could also be a role for fossil-based hydrogen as it would provide an easily accessible source of hydrogen at reasonable prices for projects aimed at building practical experience and at market introduction. This could certainly be true for applications where even the use of fossil-based hydrogen will immediately contribute to lower emissions compared with the reference scenario, an example being use as a transport fuel for fuel cell electric cars and buses. However, the objective in the period approaching 2050 must be the production and application of *sustainable* hydrogen. The sustainability objective will need to be incorporated explicitly in the development route for hydrogen in order to avoid fossil sources becoming locked in.

A multi-track approach will be necessary to ensure a successful introduction and scaling-up of hydrogen. Hydrogen will require a system change and will enter many new areas of application. This means projects can only lead to successful and representative outcomes if they have the minimum size or critical mass required. There will also be variations in the speed and objectives of developments. For instance, the application of climate-neutral and/or sustainable hydrogen will have the most urgency and promise in industry and the transport sector (since they represent energy-intensive applications requiring the long-term and flexible deployment of vehicles). This is why these applications should form the main focus of activities. While a slower speed might be possible where the built environment is concerned, it will still be desirable to explore the potential role of hydrogen – including through a small number of small-scale pilots – in view of the enormous challenge that exists in making the existing built environment fully sustainable. As regards electricity generation using hydrogen (or hydrogen-based alternatives such as ammonia), the focus could be placed on the exploration and demonstration of the future need for flexible capacity management in scenarios dominated by wind and solar power.

Such projects will require a high level of investment that cannot be supported by industry and the business community alone, not least due to the present lack of a level playing field for climate-neutral and sustainable alternatives. In order to initiate this system change and ensure it succeeds, strong commitment is required on the part of industry, the business community and the government, based on a long-term collaboration between these parties and with contributions from knowledge institutions and social organisations.



Proposal for an action plan

Partly on the basis of consultations in the field (see Appendix 1), this roadmap describes in broad outlines the role climate-neutral and sustainable hydrogen could fulfil in a sustainable supply of energy and feedstock for the chemical industry and the transition towards this. Better insight into and management of this role must be achieved through an approach which includes the three elements listed below as a minimum and which addresses them simultaneously and in an integrated manner:

1. Integrated formulation of visions and plans for the coming years in relation to hydrogen

The objective is to formulate visions and plans for the optimum development, application and integration of hydrogen in conjunction with other solution strategies, with the aim of making our system for energy and raw materials carbon-free and sustainable as fast as possible, using the emission reduction targets for 2030 and 2050 and the reliability and affordability criteria as a guiding framework. This will allow us to address important issues in order to increase our understanding and management of the potential of hydrogen, of synergies with related developments such as CCS and the use of biomass for biofuels and biological raw materials, and also of the manner in which these aspects can impact on and reinforce each other. It will also be necessary in this regard to carry out scenario analyses in order to build a picture of a number of developments in our system for energy and raw materials. Developments that must be investigated as a minimum are:

- The development of and link with offshore wind power. The issues at play here include the necessity of and opportunities for conversion in the context of integrating sustainable electricity, offshore hydrogen production, timing aspects, link with plans for the integration and production of sustainable hydrogen in other countries bordering on the North Sea (which may include one or more energy islands), the need for electricity storage, price developments and costs/revenue models and similar.

  - Analyse how offshore wind power on the North Sea will develop over the next years and decades, taking account of the plans in other countries bordering on the North Sea and the development of the electricity infrastructure on the North Sea and in the relevant countries. This must establish the timeframe within which hydrogen could provide the required flexibility and meet the need for conversion and storage. This analysis must also consider the development and any phasing-out of gas assets on the North Sea and the extent to which they could be used for hydrogen. A natural choice would be to assign the role of coordinating these efforts to Tennet.

- The link with climate-neutral production of hydrogen from natural gas combined with CCS (blue hydrogen), importing climate-neutral hydrogen (similar to the Norway solution) and any spin-offs relating to sustainable hydrogen production, such as infrastructure developments that are relevant for both routes.

  - Prepare an implementation plan for the development of CCS, based on the forthcoming CCS roadmap. This must provide insight into how CCS might develop over the coming years, and in which industry sectors and at what cost. A factor in this regard will be the availability of infrastructure and storage locations, as recently mapped out by EBN and Gasunie. This information will make it possible to determine how CCS can or must contribute to bringing about the transition. There will be a strong role in this for the chemical sector.

- The link with ‘greening’ the chemical and manufacturing industry, such as the demand for hydrogen in connection with the switch from fossil sources to circular carbon, biobased chemicals and CO_2 from air capture combined with sustainable hydrogen. Factors in this regard are the timeframe for a gradual switchover and the impact on the demand for sustainable hydrogen.

  - Use the roadmap(s) for ‘greening’ industry to illustrate in what areas sustainable and/or climate-neutral hydrogen could play a significant role, what demand for hydrogen this will generate and how this demand can best be met, how this links up with CCS and biomass, also considering geographical aspects (locations, supply routes in the event that sustainable hydrogen is used, etc.). Use this information to develop regional action plans for energy clusters and, where possible, to come to more general decisions.

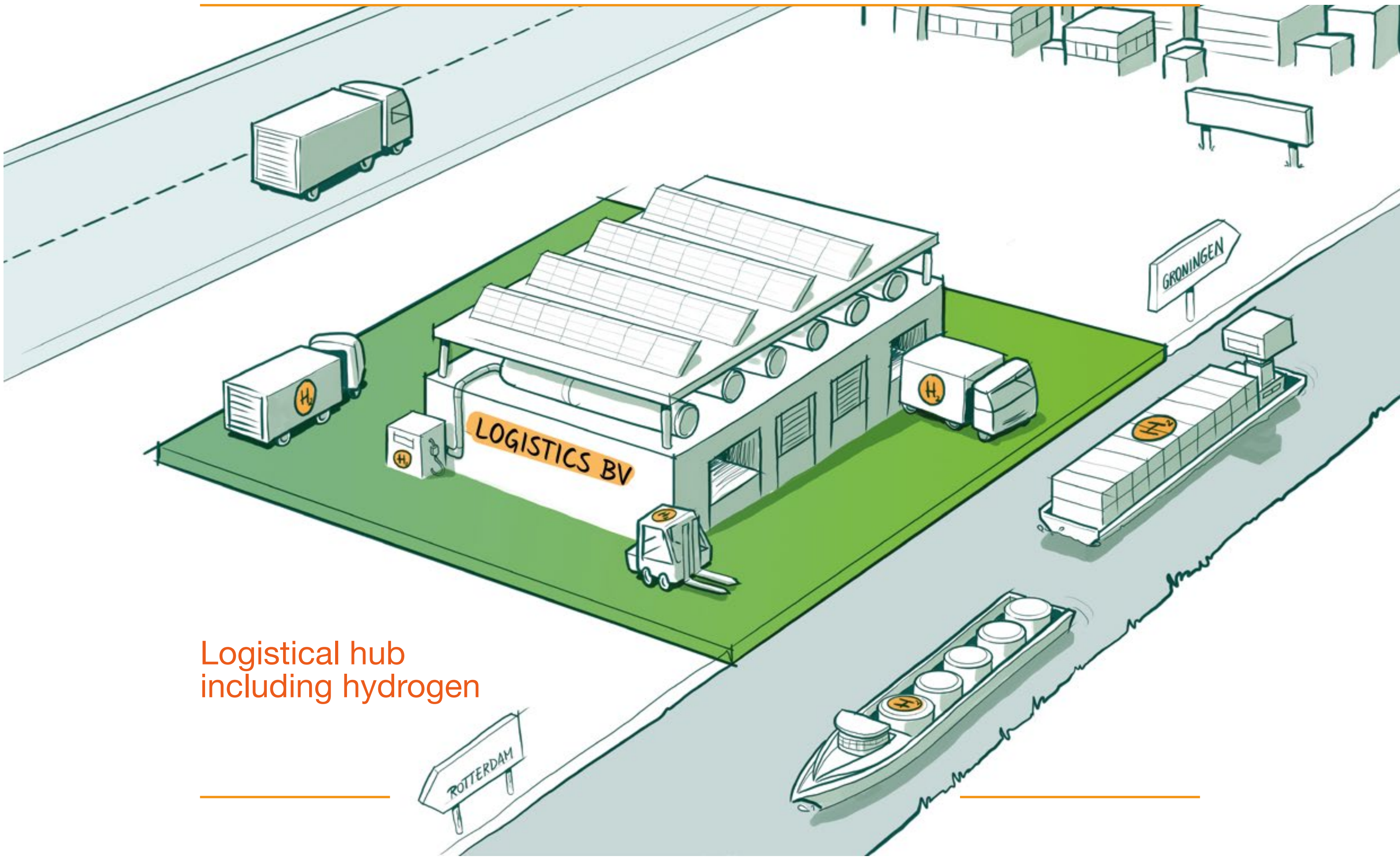
- The role of biomass. Continuing on from the previous item, it will be important to build a picture of the role that biomass, including when imported, could play in the various applications referenced in this report, in particular those in industry, transport (of persons and goods) and the built environment.

  - Illustrate how biomass could be used, including options for importing biomass and support for this in society and among politicians. The ‘Green Gas Roadmap’ being prepared by Groen Gas Nederland and TKI New Gas may be of assistance here, along with other publications.

- The manner in which demand for hydrogen as the fuel for fuel cell electric vehicles might develop, as a result of tighter European CO_2 emission standards for vehicles as well as the pressures due to the increasing number of green zones in cities and Dutch government objectives in relation to zero-emission mobility and public transport. Consideration should also be given to the demand for hydrogen that might be created by synthetic fuels for use in the international aviation and shipping industries.

  - Develop projections around the possible use of hydrogen for mobility and transport applications, using insights from sources such as the Green Deals on Zero-Emission Public Transport Buses and Urban Logistics, the outcomes of the development of the Fuel Vision and the objective that new cars must be zero-emission cars from 2030 onwards.

- Infrastructure aspects, in particular the re-use of assets in the natural gas sector (pipelines, compressors, measurement and control systems, reservoirs) and offshore installations for hydrogen, and the link with other activities, such as CCS, natural gas transport and green gas, timing aspects, risks and regulation.
  - Create a master plan for re-use of the Dutch natural gas infrastructure for the purpose of hydrogen, which covers the offshore infrastructure and timing aspects. Also include the establishment of one or more energy islands in this. Other aspects to be covered are the position of and planning in relation to CCS and the import of blue and sustainable hydrogen. Gasunie and Tennet could take the lead in this effort.
- Integration of the previously listed topics, in order to build a picture of the structural role hydrogen could fulfil, including the levels of flexibility and storage provided and the peak output required in future.
  - Use the above action items and other information to analyse the demand for flexibility and storage, the level of the demand for hydrogen that will be created and the ways in which these demands can best be met. The market development of hydrogen also forms a part of this. The government could take on a steering role in this.

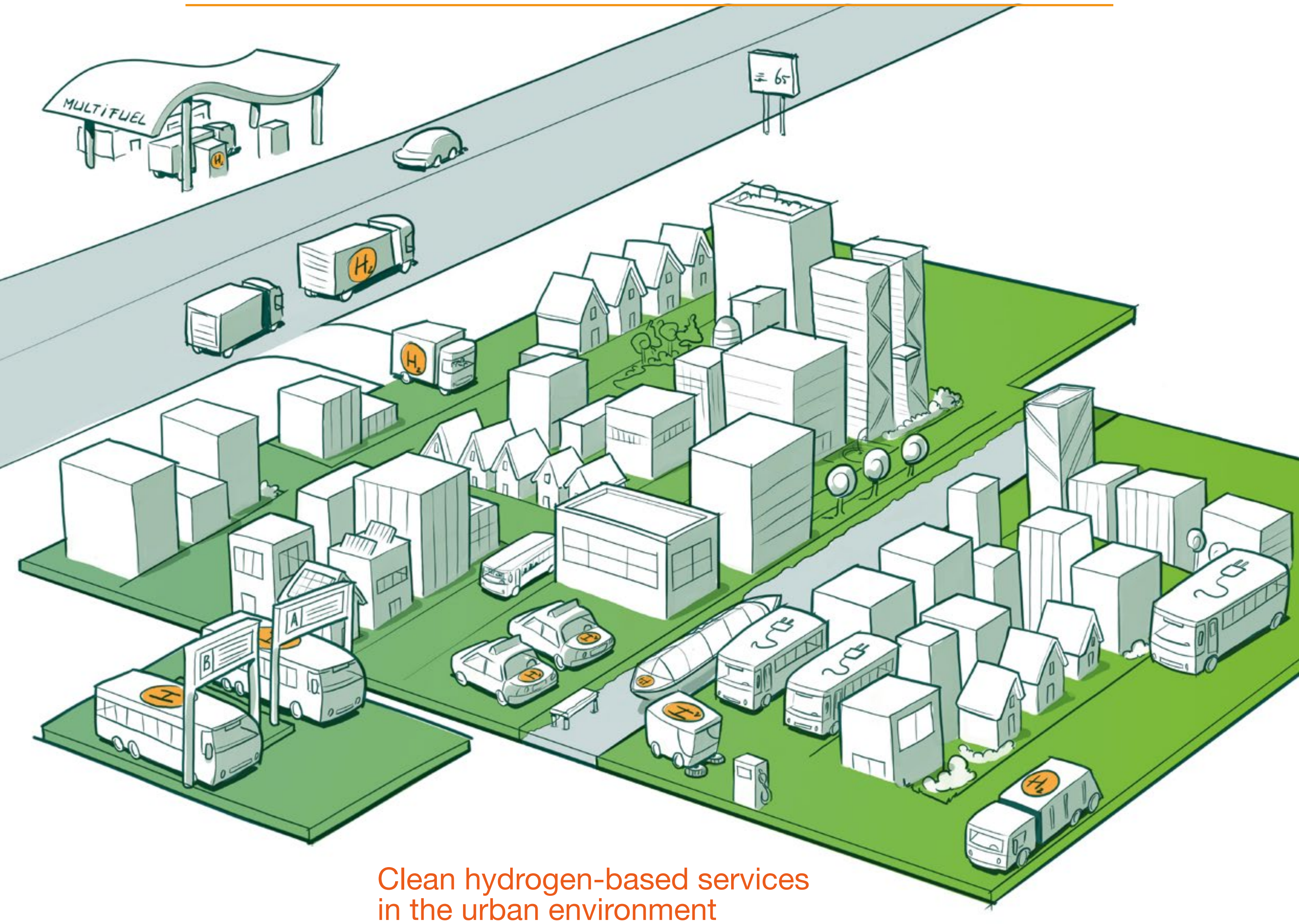


Logistical hub including hydrogen

The desired outcome is a package of clear, widely supported visions and detailed (master) plans for the subtopics which, in the context of the system, clarify the significance and development of hydrogen as a replacement for fossil fuels in our system for energy and raw materials and for the integration of sustainable energy. One possible way to achieve is through a coordinated top-down process, which involves all relevant stakeholders in order to establish how they could facilitate the implementation of hydrogen through joint efforts. Aspects of this process that still need to be elaborated include the best method and place for conducting these discussions with the support of experts and the required supporting calculations, in order to ensure outcomes with genuine value. The Climate and Energy Agreement that will be drafted in 2018 will be the ideal forum for developing the meta issues listed here, since they will have a direct bearing on the substantive arrangements made in the agreement. Research into the possibilities is therefore proposed, with a view to safeguarding that the topics are addressed as part of this process.

The theme around vision formulation is also closely linked with the CCS roadmap, which a wide cross-section of stakeholders, guided by consultancy agency De Gemeynt, is currently preparing at the request of the Ministry of Economic Affairs and Climate Policy. The expectation is that this roadmap will be completed in the first quarter of 2018. This link is the reason why the hydrogen roadmap includes a number of references to the topic of CCS but no detailed elaboration. A thorough stakeholder consultation and the required subject-related expertise have already been arranged in the context of the CCS roadmap. The outcomes of this work will be of major significance for the pathway based on blue hydrogen.

Work is also underway to develop a Green Gas roadmap, the focus of which is the production of renewable gas from biomass. The details are being elaborated by Groen Gas Nederland, in close collaboration with TKI New Gas and stakeholders. This roadmap also shares links with the hydrogen roadmap due to overlapping areas of application, including industry (supply of fuel and feedstocks) and the built environment. In this area, there could be a mutually beneficial relationship between hydrogen and green gas/biomass, one reason being that biomass is able to supply the required green carbon. This will require elaboration and further alignment during the creation of the two roadmaps.



Clean hydrogen-based services
in the urban environment

2. Putting hydrogen into practice over the next 3-5 years

In addition to the formulation of visions and plans, a key focus for the next three to five years will be to start production and put applications of hydrogen into practice in compelling examples that are able to illustrate long-term perspectives. This will be essential in order to introduce hydrogen and build practical experience in preparation of a broad (or broader) market introduction. The outcome must be a well-balanced project portfolio covering all aspects, along with excellent organisation within and between projects to ensure mutual learning and sharing of experiences.

To achieve this, there must be a coordinated bottom-up process that allows local or regional initiatives to flourish in line with the vision for development of hydrogen in the Netherlands. Demonstration projects will generate valuable information that must be shared with others, so that learning is optimised and follow-up projects can build on that experience. In addition to technological aspects, efforts must also be dedicated to economic aspects/business models, market development, social support and laws and regulations. This is because past experience has shown that it is precisely these aspects that can act as strong barriers to implementation and wide deployment. They must therefore be addressed at an early stage.

As regards implementation projects, it is self-evident that follow-up projects are key and management will be required to maximise the effect at the individual and overall level. A case in point is hydrogen-powered transport: refuelling infrastructure must be interconnected in a logical manner and joint purchasing can generate benefits, including in the area of cost. This means the option could quickly come within reach, with fewer risks for all participants.

Examples of promising projects in industry that could be initiated in the short term:

- One or several scale-up projects for water electrolysis in an industrial environment, based on technology used by AkzoNobel, PEM electrolysis or alkaline electrolysis, for example. The 20 MW electrolysis project by AkzoNobel and its partners is a good example of this. Other chemical companies have also shown interest in launching similar projects.
- Stress testing for large-scale electrolysers in an industrial environment, including under a fluctuating supply of sustainable electricity.
- Pilots exploring replacements for fossil fuels for the supply of High-Temperature Heat in industry.
- Re-use of industrial residual gas combined with hydrogen.
- A proof-of-concept study into the development of a GW-scale electrolysis plant.
- Feasibility of using sustainable hydrogen to replace fossil-based hydrogen, in oil refining or ammonia production for example.
- Supply chain study for (storage and transport of) hydrogen when combined, for example, with offshore/remotely produced hydrogen (e.g. from the Sahare region, Middle East and Australia).

Examples of promising projects in the area of transport and mobility that could be initiated in the short term:

- The building of a cost-effective basic network of public hydrogen refuelling points, with the maximum possible flexibility for supporting other uses (such as public transport, refuse collection lorries and goods lorries).
- Buses and the construction of the related refuelling infrastructure and elaboration of a plan based on concession and replacement schedules in the run-up to 2030.
- Setting up 3-5 urban areas for practical trials around initial concessions for hydrogen-powered buses, which serve as test areas for new hydrogen applications such as refuse collection lorries and road sweepers. These areas should preferably also form part of the basic network of public refuelling points, opening up the possibility of combinations with taxis and minivans.
- Setting up one or more locations for practical trials around the introduction, demonstration and testing of hydrogen-powered vehicles for cargo and logistical applications, such as forklift trucks and lifting equipment. Suitable locations would be those that operate on a 24/7 basis and use a wide range of vehicles (including tractor-trailer combinations, sided lorries of various sizes and delivery vans). Another interesting possibility would be to link up with hydrogen-powered electric inland shipping at a main waterway.

Examples of promising projects for climate-neutral electricity generation:

- Plans are being prepared in Rotterdam and Eemshaven for climate-neutral electricity generation combined with CO_2 capture and storage. Similar plans in Groningen are concentrated around the Nuon-Vattenfall plant Magnum. Plans are currently being elaborated in the Rotterdam region.

Examples of promising projects in the built environment:

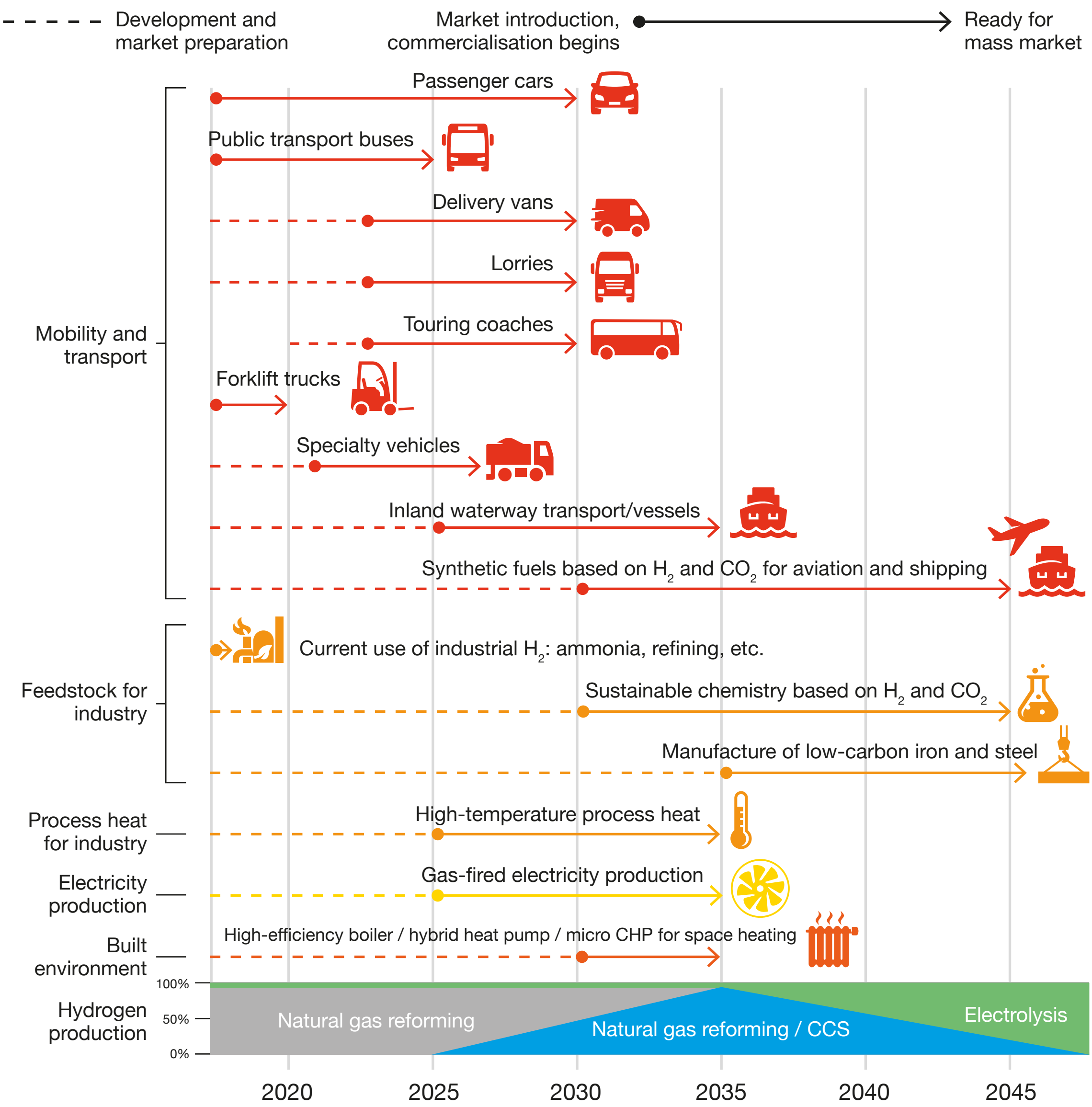
- The possibilities for using hydrogen in the built environment should be explored in a controlled environment, in view of the social implications and the many questions that surround hydrogen. Examples of such environments include Green Village at TU Delft, whose testing ground provides the opportunity to conduct experiments under controlled, real-life conditions.

As explained in the introduction to this chapter, applications in relation to industry and mobility are prioritised over applications in the built environment and electricity generation. This is not so much to say that the latter two applications should not be included, but rather that support should be given at a different intensity compared with industry and mobility.

Many of the projects referred to here will require preparatory work, including the forming of consortiums, project planning and implementation, scheduling, financing, policy-related support, communication and social engagement. This could be arranged in 2018 and it is recommended in this regard to seek links or collaboration with the 100-plus existing initiatives.

Figure 4 has been included to illustrate the possible scheduling and implementation of the various applications. The indicated pathways are approximations, describing hydrogen applications in broad outlines. The figure is intended to show the key routes, rather than provide a comprehensive picture. It is evident from the figure that a number of applications are already available and suitable for practical implementation now. Other applications require technology, but systems in particular, to be developed further. This therefore constitutes the third element of this proposed action plan.

Figure 4 | Outline schedule of implementation processes for a range of hydrogen applications.



3. Research, development and demonstration for key topics in relation to hydrogen

In addition to vision formulation and the practical implementation of hydrogen through specific projects, it will be important to dedicate efforts to R&D issues in the field. The objectives are to reduce the cost of producing and implementing hydrogen, increase the efficiency of the technology, develop new processes, promote the application of more widely available resources and present innovations through pilots and demonstration projects. The ultimate goal is to contribute to a sustainable, reliable and affordable supply of hydrogen. This focus area also links to the practical trials listed under section 2, as they will represent ideal opportunities for testing and demonstrating innovations.

The outcome must be a robust RD&D portfolio which delivers cost reductions and improved performance of hydrogen across the board (in production, applications, etc.). The report of the ECCM committee previously referred to in this memorandum provides a comprehensive overview of the innovation challenges in relation to the technology for producing and applying hydrogen.

Innovation will also be important for aspects beyond technical components and for combining different technologies that are already available. This track is about reducing the cost of hydrogen and related technologies, delivering innovative demonstration projects, testing new combinations of concepts and technology, and developing or enhancing components and systems. It is anticipated that the Topsectors for Energy, Chemistry, HTSM and Water will take the lead in this. TKI New Gas and TKI Energy and Industry, which form part of the Topsector Energy, began joint work on a hydrogen programme line in 2017. The aim is to formulate a multi-annual mission-driven, programme-based strategy for hydrogen in 2018, which will be implemented by means of a subsidy scheme.

We will highlight two innovation tracks:

1. long-term track focused on researching and developing technology for hydrogen production and use of hydrogen as an energy carrier and raw material (TRL 2-5/6)

It will be crucial to link up with relevant national and international industrial sectors, in order to achieve the best possible exploitation of outcomes and discoveries. Key research topics are as follows:

- reducing the use of scarce resources
- improving reliability and robustness
- increasing efficiency
- increasing life spans
- reducing costs
- improving manufacturability
- developing new technologies and processes

2. Demonstrations of technology and development of new and improved products, systems and (production) processes (TRL 6-8/9)

Examples of systems and applications include fuel cell systems and power trains for buses, lorries, delivery vans and vessels. A promising option in connection with production processes is the production of hydrogen from natural gas and/or biomass combined with CCUS. A key area in the built environment is the application of hydrogen at e.g. district level.

Management and facilitation of hydrogen (cross-cutting activity)

In addition to the subject-related focus areas above, we have also identified that hydrogen requires management and broader facilitation. Management must be focused on safeguarding the interconnection between all the hydrogen activities, making adjustments as required and monitoring developments regarding hydrogen in the context of a sustainable energy and raw materials system. This topic in effect provides the management function, which aims to achieve objectives efficiently and effectively, prioritise themes, coordinate matters between projects, programmes and regions, as well as ensuring open communication and accountability to stakeholders. This also includes management at regional level, as organised through the Northern Innovation Board in the Northern Netherlands and through Deltalinqs and the Port of Rotterdam Authority in the Rotterdam region. Cooperation at regional level reinforces separate, local initiatives and enables them to increase their critical mass, momentum, resonance and ability to attract funding.

Other key topics are:

- The safety of hydrogen, which could take the form of a national safety programme
- Integration into society (including information, awareness raising, public perception and public acceptance)
- International harmonisation and collaboration, including through collaboration within the Benelux region, with Germany and the EC/Brussels (H2020, HFC JU)
- Connecting strategies and projects, targeting optimum learning and creating added value, and developing forward-looking plans and programmes so that projects are in line with the long-term vision
- Progress monitoring: where are things at, to what extent are objectives being achieved, what do the achievements tell us, what else is needed, how can experiences be embedded
- Determining the respective roles of the authorities and businesses and building commitment and support within society

The challenge will be to cast this management function in an effective (*lean and mean*) form that functions in a targeted manner and avoids creating a great deal of overhead that will in turn delay matters. The H_2 Platform could be a suitable candidate for taking up this role in the area of mobility. Where industrial applications are concerned, this role could be assigned to a platform led by industry or an industrial cluster, as an outcome of understandings reached in the context of the Climate and Energy Agreement for example. The fine details of this will need to become clear in the months ahead.

Appendicies

Appendix 1 | Individuals and organisations interviewed

In August to December 2017 personal interviews were conducted in the context of the consultation, gathering input from organisations including:

AkzoNobel, Gasunie, Tennet, Greenpeace, WaterstofNet, Shell, GasTerra, Stichting Natuur en Milieu, Stedin, Eneco, Alliander, Netbeheer Nederland, H_2 Platform, Port of Amsterdam, TU Delft / Green Village, the Netherlands Enterprise Agency, the Ministry of Economic Affairs and Climate Policy, the Ministry of Infrastructure and Water Management, TU/e & Differ, TKI Energy & Industry, VEMW, Statoil, Port of Rotterdam Authority, SCW Systems, Noord-Nederland/ Northern Innovation Board, Energy Valley, E&E Advies.

In addition, the three workshops organised on 28 September, 24 October and 5 December in the context of the H_2 Platform had an approximate attendance of 40, 45 and 30 participants respectively, with participants representing a wide cross-section of stakeholders. Their input has also been incorporated wherever possible.

The contractor responsible for the inventory of hydrogen initiatives (see Chapter 8) held talks with a wide range of projects. The roadmap also includes the input from these discussions.

During the Topsector Energy working conference on 29 November in Nieuwegein, we organised two workshops on hydrogen for mobility (approx. 45 participants) and industry (approx. 50 participants). The input these workshops yielded has been incorporated as much as possible.

Two sessions were organised with the TKI New Gas management in order to receive their input with regard to the draft roadmap. And lastly there were several individuals who provided comments on the final draft of the roadmap.

Appendix 2 | Basis for estimates regarding the future use of hydrogen

This appendix explains the basis for the (highly indicative) estimates relating to the future use of hydrogen as an energy carrier and as the building block for chemical products and synthetic fuels, over and above the current non-energy use of hydrogen in industry. The estimates outline the potential from a theoretical technical perspective and are not based on economic considerations, cost optimisation or restrictions arising from competing demands for resources. The estimates, which are intended as a first exercise in order to get a sense of the order of magnitude, look in turn at each energy function as identified in the Energy Agenda.

High-Temperature Heat

The High-Temperature Heat energy function is entirely interlinked with industry. This function encompasses the use of energy carriers for the production of high-temperature process heat, defined here as temperatures in excess of 250°C. The function also covers the non-energy use of energy sources for the production of chemical products and materials. With regard to hydrogen, a further distinction is made between the current non-energy use and the possible future use in the event that industry is required to not only switch to climate-neutral and sustainable energy, but also to sustainable raw materials. Then there is a further category that could be classified as both energy-related and non-energy use. This refers to the use of hydrogen for the production of sustainable synthetic fuels and the use of hydrogen for the reduction of iron ore in low-carbon processes for steel production.

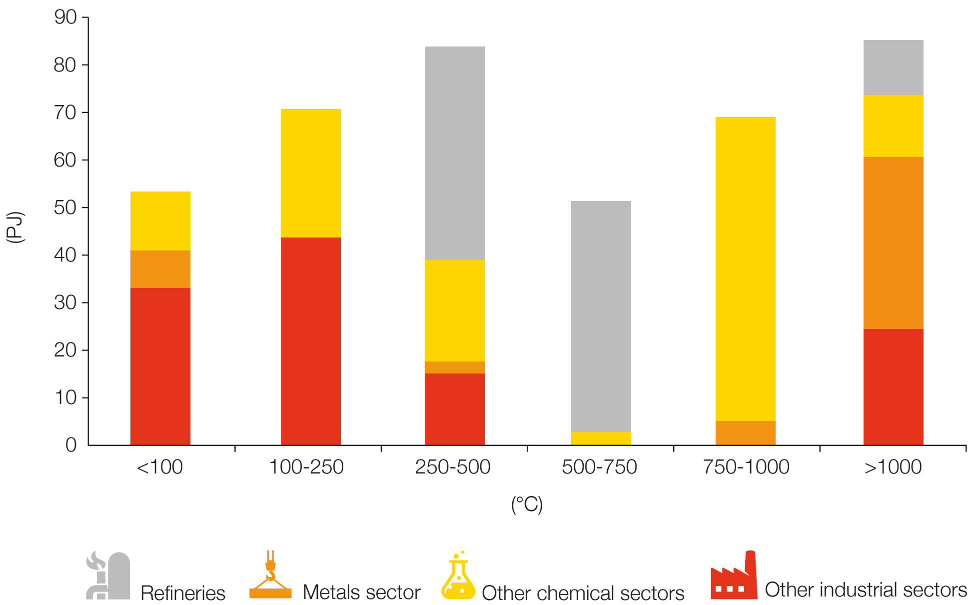
Non-energy industrial use of hydrogen

Non-energy use of natural gas in industry and refineries currently amounts to approximately 100 Petajoule (PJ), more than 80 PJ of which is used in industry and just under 20 PJ of which in refineries. The equivalent in hydrogen is 75 PJ if we assume a conversion efficiency of 75%. The distribution at global level is slightly different, with the chemical industry accounting for approx. 50%, refineries for 40% and other industrial sectors for 10%. Increased electrification in road transport will reduce the demand for fuel from refineries, which are therefore expected to see their need for hydrogen drop. It is possible that the demand among refineries may not disappear altogether as a result of a residual demand for fuel from sectors such as Dutch and international aviation and shipping. Although the current scenario in the Netherlands deviates from the global average, the estimate made here is conservative in nature. It is assumed that the current demand for industrial hydrogen will drop to around 50 PJ.

Use of hydrogen for High-Temperature Heat in industrial sectors and refineries

The chemical industry and refineries use a wide range of residual gases from refining and cracking processes in order to produce High-Temperature Heat. This is likely to remain the case while petroleum is used as the raw material, unless methods are discovered that allow residual gases to be used for higher-value purposes in a cost-effective manner. The estimate given here for the quantity of hydrogen that could be used for the production of high-temperature process heat is based only on replacement of the natural gas currently used for energy production. In 2014, industry consumption for this use amounted to 202.6 PJ, of which 40.6 PJ in CHP plants and 52.9 in refineries.[29] If we assume that roughly two-thirds of the natural gas used in CHP is converted into heat, the total use of natural gas for heat comes to 242 PJ. Using an indicative distribution by temperature level of the demand for heat in industrial sectors and refineries, it is estimated that the demand for heat at relatively low temperatures, up to 250°C, will be 124 PJ (see Figure 5). At present, most of this demand will be met through the use of natural gas. It is assumed that there are good opportunities for electrification of this demand and that natural gas will not be required in future. Assuming a conversion efficiency of natural gas to heat of 80-90%, a heat demand of 124 PJ will require 138-155 PJ of natural gas. This brings the portion of natural gas that is used for High-Temperature Heat to approximately 100 PJ. If future growth and savings within the sector cancel each other out and the conversion efficiency of hydrogen is equivalent to that for natural gas, the potential use of hydrogen for High-Temperature Heat will therefore total 100 PJ.

Figure 5 | Distribution of the heat demand in Dutch industry by temperature level (Data in PJ for 2010 based on the distribution in 2006. Source: *Warmte en koude in Nederland* (Quantifying heat and cold in the Netherlands), RVO, 2013



29 Based on the background data in the National Energy Outlook 2016.

Hydrogen as a feedstock for sustainable chemical products and materials

Aside from the current non-energy use of hydrogen in industry, in particular in the chemical sector, the demand for hydrogen could increase sharply as a result of industry's need to phase out the use of carbon from fossil sources in the longer term. A switch to sustainable chemistry would be possible through climate-neutral carbon, produced from sustainable biomass for example or carbon dioxide (CO_2) derived from air (air capture) or water. Production of chemical products and materials would then take place using climate-neutral carbon combined with sustainable hydrogen. Over the past years, industry has used the equivalent of approximately 480 PJ in petroleum for non-energy uses each year. A portion of this petroleum could be replaced by biomass. With regard to the Netherlands, it is assumed that the potential of sustainable biomass is around 250 to 700 PJ per year. A portion of this is currently used to produce biogas/green gas and biofuels and also to generate heat and electricity in the built environment and in power plants. If the fossil carbon used in the chemical sector is replaced in its entirety by products based on CO_2 or hydrogen, all energy would be produced from hydrogen. This would translate to a demand for hydrogen around 480 PJ, provided the size of the sector and the production efficiency of chemical products and materials remain the same. The actual figure will depend on the extent to which biomass is able to replace petroleum as a feedstock, the availability of biomass and the energy demand of alternative production routes and processes for the required chemical products and materials.

Hydrogen for producing sustainable fuels

Aside from the direct use of hydrogen as a fuel in fuel cell electric road transport, hydrogen could in future also be used for the production of sustainable synthetic fuels. A need for this could arise in sectors where electrification is not feasible, not practical or only possible at an extremely high cost. Examples could be the aviation and shipping industries, especially in the case of long-distance (intercontinental) travel and shipping. Such fuels should preferably be based on climate-neutral carbon, produced from sustainable biomass for example or carbon dioxide (CO_2) derived from air or water. This carbon would then be combined with sustainable hydrogen (power-to-fuels and also solar fuels). In the Netherlands, fuels bunkered for international shipping and aviation over the past 5 years represent an average of about 70PJ each year. [30] Some of this fuel could be produced from biomass. Such use would likely be in competition with the use of sustainable biomass as a raw material for industrial sectors. If the fuels are replaced in their entirety by products based on CO_2 or hydrogen, all energy would be produced from hydrogen. If the size of the sectors and fuel utilisation efficiency remain the same, the demand for hydrogen will be at least 700 PJ in this scenario. The actual figure will be higher due to conversion losses during the production of the fuels.

30 While fuels bunkered for international shipping and aviation in the Netherlands are included in the statistics for Dutch energy supply, they are excluded from the data used to calculate national greenhouse gas emissions. This means the fuels do not directly count towards Dutch efforts to increase sustainability and reduce CO_2 emissions. Not all of this fuel is produced in the Netherlands either. From time to time, the balance tips towards a net import. However, at this time the bulk of the fuels originates from Dutch refineries. Ultimately, these fuels too will need to become climate-neutral and this is why, by way of indication, the total bunkered value has been included here as a sustainability challenge.http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=80101NED&D1=13,21,43,46&D2=l&D3=240,257,274,291,308,325&HDR=G1,G2&STB=T&VW=T

Steel

The current process for manufacturing crude iron and steel is carbon intensive. Steel can in principle be manufactured without the use of carbon, although this does require alternative processes. The Direct Reduced Iron (DRI) process is an example of this. DRI is an existing process, with reduction currently based on a reductive gas mixture consisting of carbon monoxide (CO) and hydrogen produced through natural gas reforming. Such gas mixtures are referred to as syngases in the chemical industry. The reduced ore is shaped into briquettes and converted into steel using electric smelters. Reduction can also be achieved using exclusively hydrogen. If sustainable hydrogen is used, a low-carbon process can be established, the only CO_2 emissions of which would be those from the ore itself. In this method for iron ore reduction, each tonne of crude iron requires approximately 570 Nm^3 of hydrogen. [31] The Netherlands currently produces approximately 7 million tonnes of crude iron a year (Mt/y). If we assume that half of the produced volume could be reduced through recycling and the remainder (3.5 Mt/y) is produced through hydrogen-based DRI, the annual demand would amount to 2 billion cubic metres of hydrogen, which is roughly equivalent to 20 PJ.

Transport energy function: Mobility and Transport

Final energy consumption in the form of petrol and diesel currently stands at around 165 PJ and 250 PJ respectively. As a fuel, petrol is mostly used in privately owned vehicles. Diesel tends to be used in goods transport, light commercial vehicles (delivery vans) and by those who travel extensively for business purposes. While electric vehicles offer a good alternative to most petrol cars, hydrogen is currently a better match for the characteristics of diesel-based categories. The expectation is that the energy consumption of (future) electric vehicles powered by hydrogen fuel cells will be 50% less than the average of current diesel-powered vehicles. This means the total of 250 PJ will be halved and that the hydrogen demand is estimated at 125 PJ.

Power and Light energy function

The increased implementation of onshore wind energy, offshore wind energy and solar PV means a reduction in the natural gas required for electricity generation. However, the phasing-out of coal and the closure of Borssele will have the opposite effect. Adjustable capacity will be required in any event, in order to balance the variable and insecure supply from wind and solar energy with the demand for electricity. At present, electricity production uses well over 150 PJ in natural gas and approximately 200 PJ in coal. Recent analyses show that once coal and nuclear energy have been phased out and onshore wind energy, offshore wind energy and solar PV have increased to 7, 16 and 19 GW respectively, the need for use of natural gas will be approximately 230 PJ[32]. Other analyses indicate that if offshore wind energy is increased extensively, the use of natural gas for electricity will be reduced by half, although this is in a system where nuclear energy and coal can also still play a role.[33] Combining these outcomes leads us to estimate that even a very substantial expansion of offshore wind energy will leave a demand of around 115 PJ in gaseous fuel for use in gas-fired power stations. This then corresponds with a potential demand for hydrogen in the amount of 115 PJ.

31 J.P Birat, Steel & Hydrogen, IEA Hydrogen Roadmap meeting, 9-10 July 2013, Paris
32 M. Weeda, K. Smekens, *Verkenning Energievoorziening 2035* (Energy supply in 2035 - an exploratory study), ECN-E--17-026, July 2017.
33 M. Weeda, M. van Hout, *Verkenning Energie-functionaliteit Energie-Eilanden Noordzee* (Energy function of energy islands in the North Sea - an exploratory study), ECN---17-064, November 2017.

Low-Temperature Heat energy function (built environment)

The National Energy Outlook 2016 indicates that in 2035 natural gas consumption will amount to 240 PJ in households and 80 PJ in the services sector. A simplistic extrapolation of the trends for the period up to 2050 would yield outcomes of 190 PJ and 50 PJ respectively. A further reduction ought to be possible by stepping up efforts in home insulation, solar thermal heating, etc. Whether gaseous fuel could be eliminated completely is a topic for debate and further study. To facilitate reflection, we will simply assume that the demand for natural gas could be reduced by half again. It must be possible to phase out the use of natural gas for heating purposes in the period up to 2050. Reduction by half would leave a demand for gas in the amount of 120 PJ, which after rounding down could result in a demand for hydrogen in the amount of 100 PJ. This is roughly equivalent to 2 million homes with an average annual consumption of 1500 m^3 of natural gas. Apart from using hydrogen directly in the central heating boilers of homes, hydrogen could also be used in hybrid heat pumps and as a fuel in plants supplying (local) heating grids.

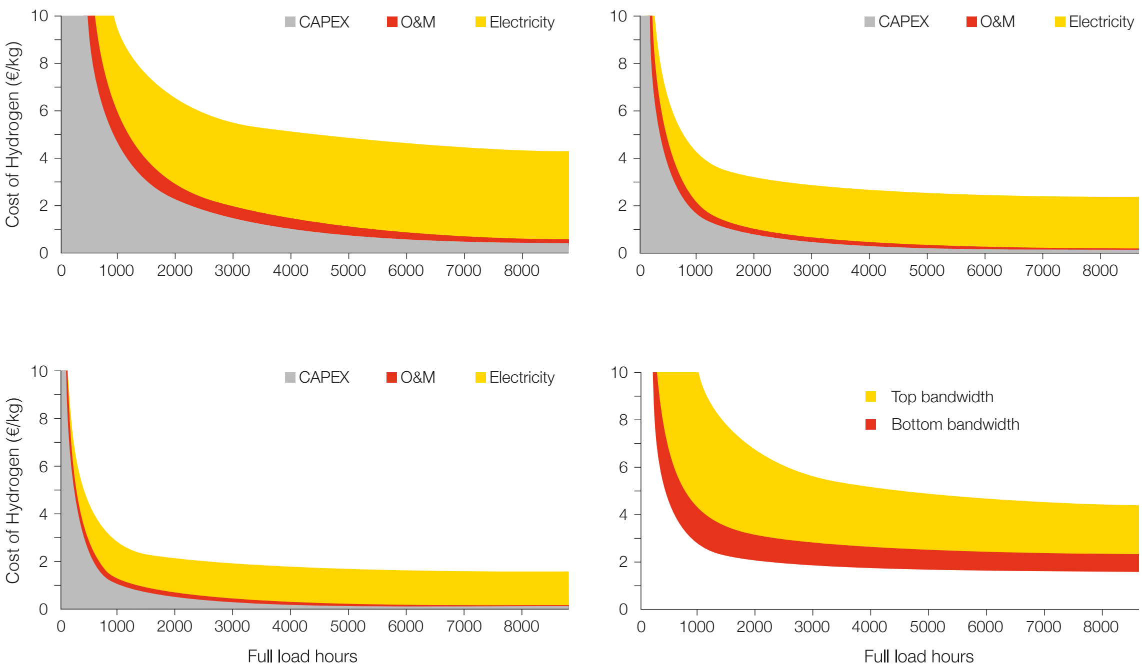
Appendix 3 | Explanatory notes to the cost of producing hydrogen by means of electrolysis and comparison with SMR

This appendix contains a more detailed explanation of the cost of producing hydrogen through electrolysis and SMR.

Figure 6 indicates the cost of hydrogen based on the investment cost for an electrolysis unit (including delivery and installation), the fixed maintenance and running costs and the cost of electricity. [34] The figure shows that the share of the investment cost (CAPEX) in the production cost of hydrogen depends heavily on the operating hours of the plant. Today's high investment cost, as illustrated in the figure at the top left, means that up to approximately 5,000 operating hours this share amounts to €1 per kilo or more. As the investment cost decreases, this point shifts to a lower number of operating hours and the production cost of hydrogen is increasingly dominated by the cost of electricity. The share of the CAPEX drops below €1 per kilo if the investment cost is €300 per kW and the number of operating hours exceeds 1000. The share drops off rapidly, with the cost profile remaining flat from 2-3000 hours onwards.

34 The investment cost excludes civil engineering costs and other costs for specific engineering, permit applications, etc. Initial and start-up costs have not been factored in, nor have the costs for spare parts. The fixed maintenance and running costs are 2% of the initial investment cost of the plant. No account was taken of stack replacement. The full calculations were based on a technical life of 20 years. Financing is based on 70% borrowed capital and 30% equity capital. WACC is 8%, with the investment being repaid over a ten-year period.

Figure 6 | Cost of producing hydrogen by means of electrolysis as a function of the operating time, for a wide range of conditions in relation to investment costs, efficiency and electricity prices;
Top left: 1220 €/kW, 55 kWhe/kg H_2, 70 €/MWh; Top right: 460 €/kW, 47 kWhe/kg H_2, 45 €/MWh; Bottom left: 300 €/kW, 47 kWhe/kg H_2, 30 €/MWh; Bottom right: bandwidths based on the highest and middle variant (Top bandwidth) and on the middle and lowest (Bottom bandwidth).



The bottom right figure summarises the other three and indicates the bandwidth of the cost for producing hydrogen in current and future scenarios. The production costs only fall below the bandwidth when the average electricity costs are well below €30 per MWh. Future electricity prices represent a large unknown factor. Some expect prices to decrease significantly in response to an abundance of cheap sustainable electricity. Others wonder what the revenue model would look like if prices were that low and expect the market to be more balanced, with prices not changing significantly from current levels.[35]

35 Calculations in the context of the National Energy Outlook 2017 indicate that current electricity prices are at a historical low due to an excess supply of capacity. This will continue for a little while longer, but the withdrawal of capacity from the market is expected to drive wholesale prices up to €32 per MWh in 2020 and €48 per MWh in 2035. These figures do not yet include the closure of all coal-fired power stations by 2030, as proposed in the coalition agreement entitled ‘Confidence in the Future’.

Figure 7 | Cost for producing hydrogen through electrolysis as a function of electricity prices.

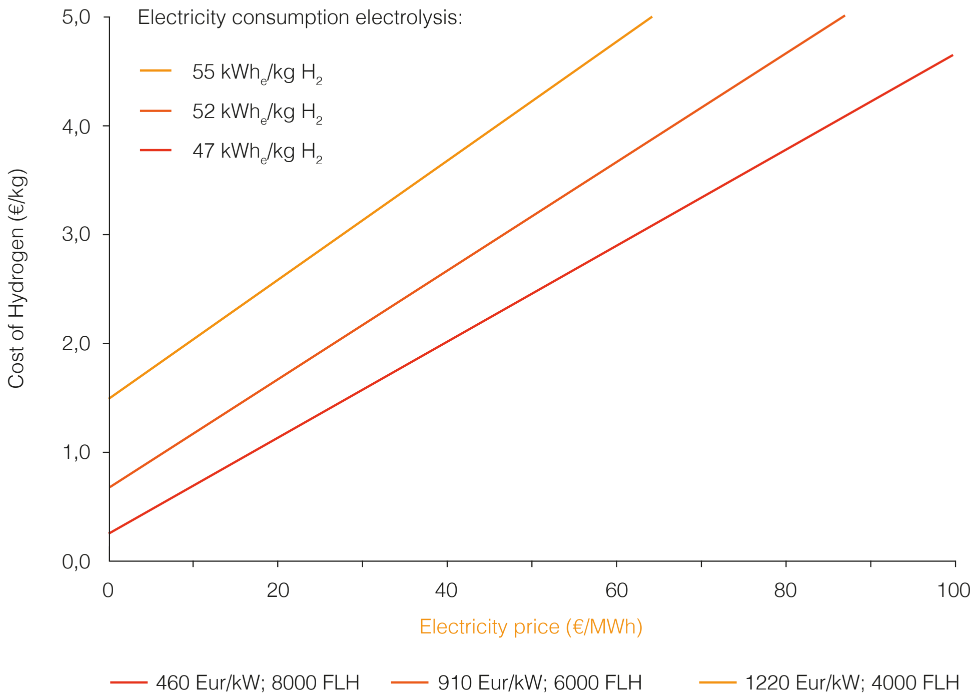
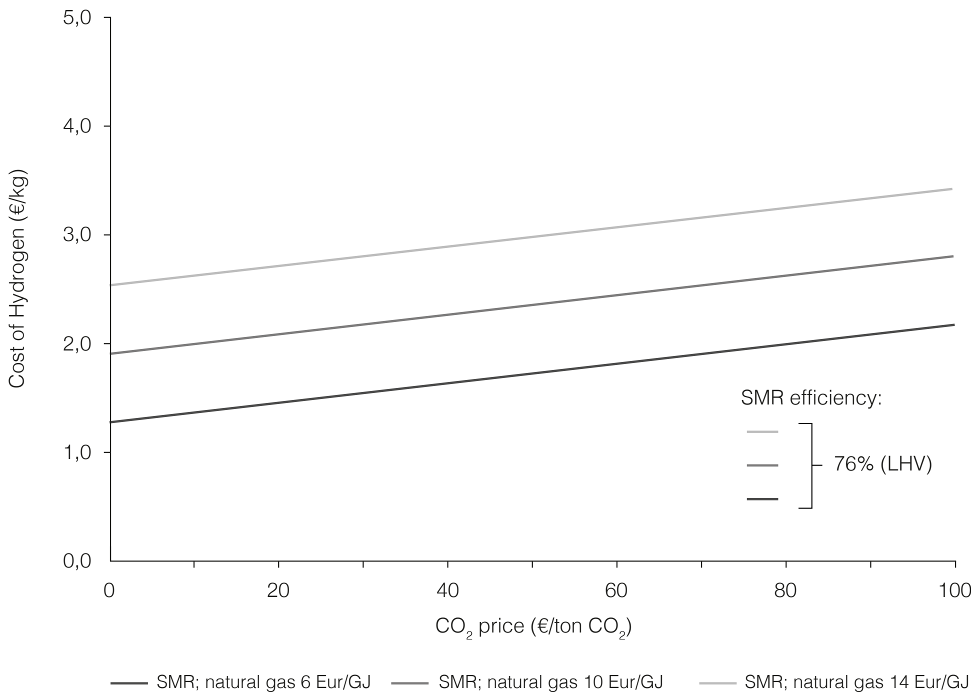


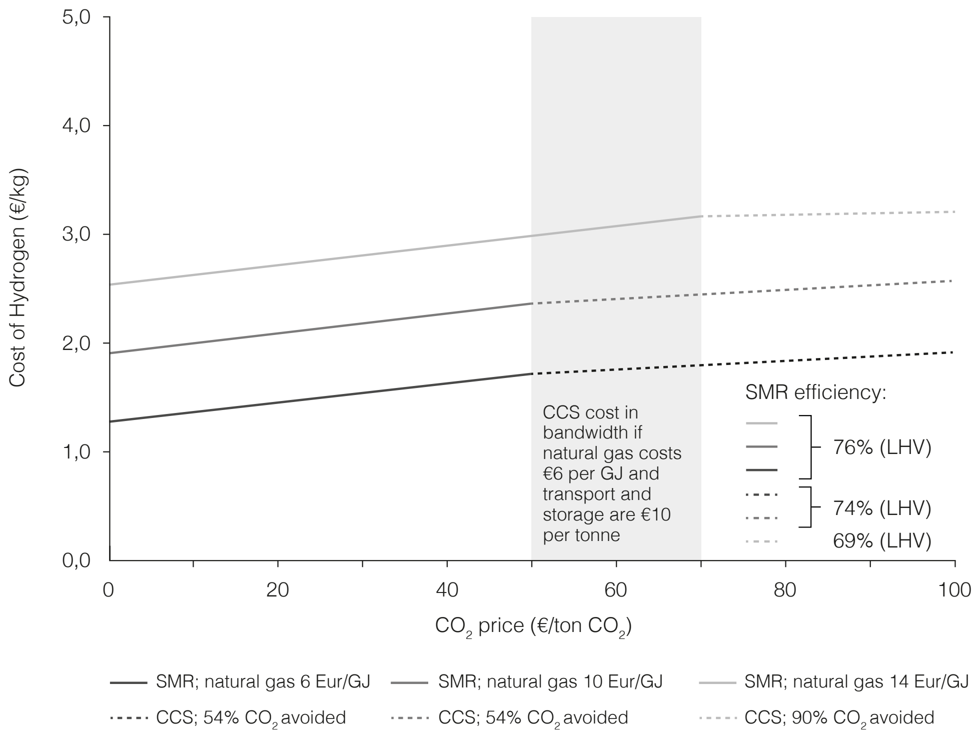
Figure 7 shows the production cost of hydrogen as a function of electricity prices for electrolysis units with different investment costs, yields and operating times. The top line most closely represents the current scenario for investment costs. If transaction prices for electricity are at €40-60 per MWh, the production cost of hydrogen is expected to be around €4-5 per kg. A decrease in electricity prices would also translate to a decrease in the production cost.

Figure 8 shows the cost of hydrogen produced from natural gas by means of SMR. The costs have been shown as a function of CO_2 prices at three different price levels for natural gas. The bottom line in this figure is the most representative. In fact, wholesale prices for natural gas are currently well below the price level of €6 per GJ on which the bottom line is based.

The left part of the figure only shows outcomes that are exclusive of CCS. It is anticipated that this option will be employed once the CO_2 price reaches levels which exceed the cost for capturing and storing CO_2. The process can be implemented in different forms, each of which has a different impact on the investment cost, the operating costs, the percentage of CO_2 emissions prevented and the yield of the hydrogen production. The rule of thumb is that the higher the targeted percentage of prevented CO_2 emissions, the higher the investment and operating costs and the lower the yield. The standard variant with the lowest cost achieves a percentage of prevented emissions of approximately 54%. The maximum variant is able to achieve around 90% in the case of SMR. The lower levels of CO_2 emissions remaining after capture mean the production cost of hydrogen will rise more slowly if CO_2 prices increase.

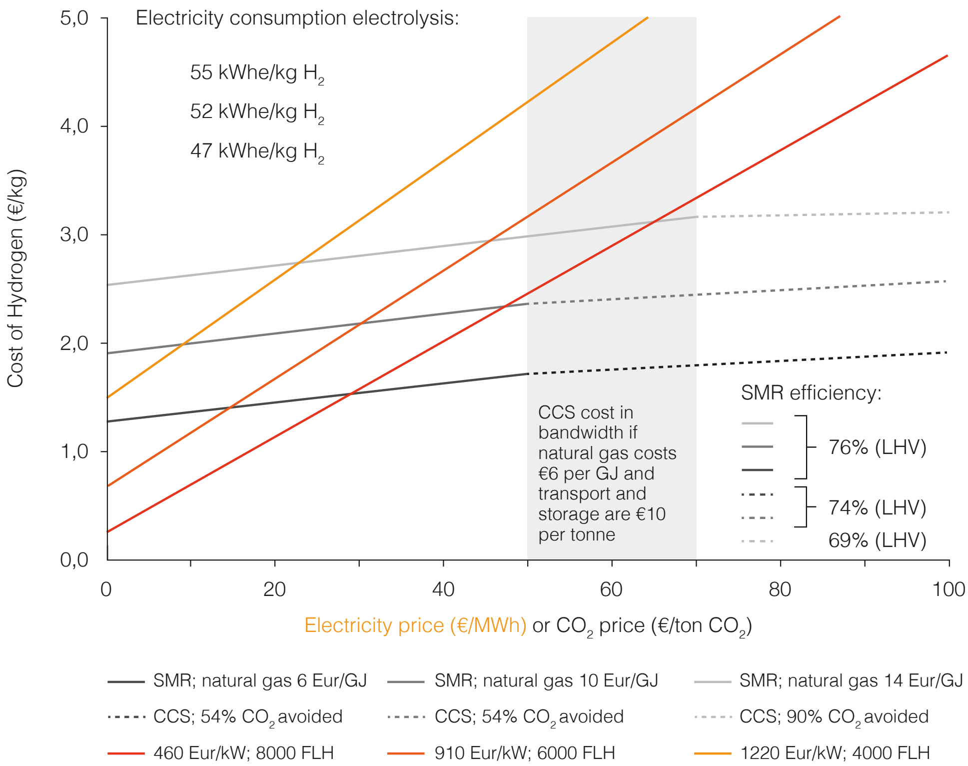
Figure 8 | Production cost of hydrogen from natural gas by means of SMR as a function of the CO_2 price, with and without CCS at various natural gas prices.
Left: SMR excluding CCS; Right: SMR including CCS once CO_2 prices exceed the cost for capturing and storing CO_2.





And lastly Figure 9 combines Figure 7 and Figure 8 to produce a comparison between the production cost of electrolysis and those of SMR. The comparison illustrates that even at very low electricity prices, it is currently difficult to produce at a lower cost than SMR. It is clear that there is still a major effort needed in order to develop low-investment, high-yield systems that will allow electrolysis to compete with SMR as far as large-scale industrial applications are concerned. At the same time, this also requires electricity to be available at a very low average prices. A high CO_2 price would be of some help, but only if natural gas prices were also to increase to a structurally higher level would competition truly become easier.

Figure 9 | Comparison of the production cost of hydrogen by means of electrolysis and SMR, with and without CCS, for a wide range of current and future conditions.



Appendix 4 | Hydrogen emission factor

The production of hydrogen from natural gas by means of SMR generates roughly 9 kilogrammes (kg) of CO_2 for each kilogram of hydrogen. This means emissions amount to 9 kg CO_2 per kilo H_2 if CO_2 is not captured and stored (CCS). The capture or recovery of CO_2 from the raw product gas is a standard industrial process, which is used, for example, during the production of hydrogen for ammonia. The CO_2 is made to react with ammonia on a large scale, in order to produce urea. The temporary capture of CO_2 in products or fuel (Carbon Capture and Utilisation or CCU) only reduces the direct emissions; the CO_2 will ultimately be released somewhere. The application of CCS means the emissions of the standard process are reduced to approximately 4.1 kg CO_2 per kilo of H_2. Variants also exist that allow the emissions to be reduced to 1.0 kg CO_2/kg H_2, although these do increase energy consumption and costs.

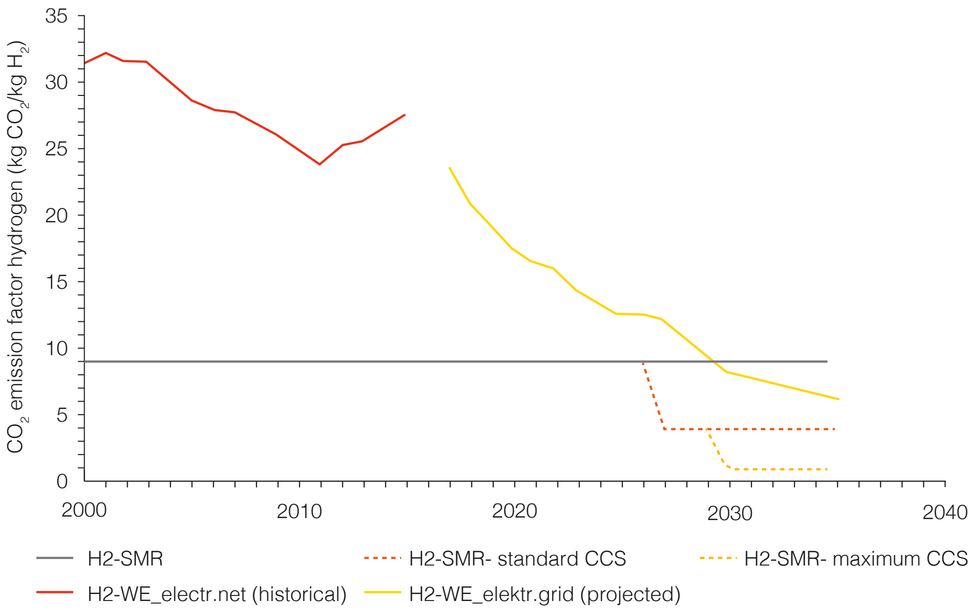
If electrolysis takes place using sustainable electricity produced from wind and solar energy, the hydrogen will have an emission factor that is in principle (virtually) zero (0 kg CO_2 per kilo of H_2). There is, however, an issue at system level here. The result is only zero overall if there is no other possible use for the electricity. Hydrogen production by means of electrolysis generates a demand for electricity that is additional to the conventional demand from appliances, lighting, etc. If sustainable electricity is used to meet an additional demand, that electricity is no longer available to make the conventional demand more sustainable. The conventional demand then needs to be met by coal or natural-gas fired power stations. This system effect means that, in terms of energy supply as a whole, the calculation of the emission factor of hydrogen from electrolysis must be based on the emission factor of the average kWh of electricity produced in the Netherlands, unless the wind or solar farm is used exclusively for hydrogen production and there is no exchange with the public grid. The same applies to scenarios where the limiting factor is the infrastructure and a link to hydrogen production could provide a solution.

In the case of electrolysis, the top-performing units currently require approximately 50 kWh to produce one kilo of hydrogen. This means that in order to outperform SMR without CCS, the emission factor of the electricity used must be less than 180g CO_2 per kWh (9 kg CO_2/50 kWh). If we draw a comparison with SMR including CCS based on a standard capture process, the emission factor must be less than 82g CO_2 per kWh in order to achieve a better CO_2 performance at system level compared with electrolysis.

As recently as 2015, the emission factor for electricity stood at 527g CO_2 per kWh in the Netherlands. This means that if the current hydrogen production from natural gas were to be replaced on a large scale with production from water by means of electrolysis, there would be a de facto increase in CO_2 emissions rather than a decrease. Figure 10 illustrates this in greater detail by comparing the emission factor for hydrogen produced from natural gas by means of SMR and that of hydrogen produced from water through electrolysis.

Figure 10 is based on the assumption that the electricity consumption for electrolysis will gradually reduce from 52 kWh/kg in 2000 to 47 kWh/kg in 2030, and remain stable thereafter. For the period up to 2015, the emission factor for electricity has been established using historical values. For the period from 2017 to 2035, use was made of the values as estimated in the National Energy Outlook 2017 (NEV 2017) on the basis of adopted and proposed policies. It is evident from the results that if the implementation of wind and solar energy does not surpass the forecasts in the NEV 2017, it will not be until 2029 that hydrogen from electrolysis will generate fewer CO_2 emissions than hydrogen from natural gas through SMR.

Figure 10 | Comparison of the CO_2 emission factor of hydrogen from electrolysis and that of hydrogen from natural gas through SMR.



The cost of CO_2 emissions prevented through CCS range from approximately €50 per tonne for the standard variant to €70 per tonne for the maximum variant. The NEV 2017 projections indicate an increase in CO_2 prices from approximately €5 per tonne in 2017 to €25 per tonne in 2035. This would not give the market sufficient financial incentive to implement CCS. The figure also includes the impact of CCS on CO_2 emissions in the event that supplementary policies are introduced that promote CCS. Hydrogen from natural gas is not sustainable. However, this option and combinations of this with CCS will, for the time being, have a lower CO_2 emission factor compared with hydrogen from electrolysis.

Colofon

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