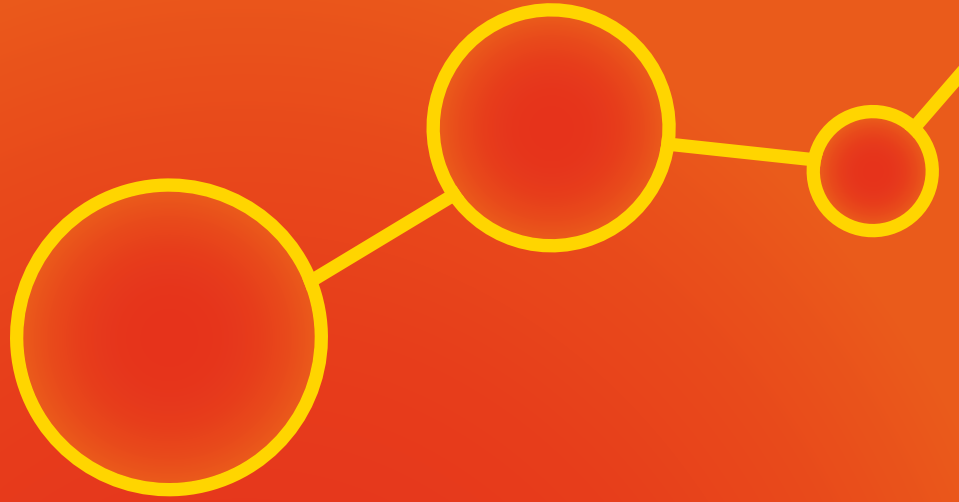


**TKI NIEUW GAS**  
Topsector Energie

A programmatic approach for Hydrogen innovations in the Netherlands  
for the 2020-2030 period

# Hydrogen for the energy transition

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# Summary

## Introduction

### Hydrogen is a robust element in the energy transition

All around the world people are getting excited about hydrogen. The Netherlands is no exception, with new hydrogen initiatives announced almost every week. Alongside the varied energy and non-energy applications for hydrogen in the transport sector, industry and the built environment, attention is also focused on the systemic role that hydrogen can play in the energy system. This means a role as flexible storage and transport medium for an intermittent supply of electricity generated from renewable energy sources (with emphasis on wind and solar), and the interface function that hydrogen can take on between the electricity sector and the gas sector. Hydrogen expands our capacity to utilise wind power and solar energy, and this puts hydrogen in a strong position alongside other sustainability options such as energy conservation, electrification (non-hydrogen), the use of biomass and bio-based fuel sources, geothermal energy, and fossil fuels in combination with reuse and storage of CO<sub>2</sub>.

### The programmatic approach creates a shared playing field for hydrogen

A Multi-year Programmatic Approach for Hydrogen (MPAH) has been proposed in response to the emerging developments in hydrogen technology in the Netherlands and the innovation needs that this dictates. The objectives of the MPAH are defined as follows:

- Creation of a shared, cross-sector approach to facilitate successful development, demonstration, implementation and scale-up of innovations in hydrogen across multiple sectors that contribute towards the achievement of the goals of the National Climate Agreement.
- Acceleration of implementation so that hydrogen technologies are substantially embedded by 2030.
- Leveraging of synergies by taking a cohesive approach to multiple themes, such as safety, the human capital agenda and societal acceptance.
- Profiling of the Netherlands internationally as an interesting incubator for hydrogen technologies, showcasing our knowledge and industrial activities in the field.

### An approach that is both programmatic and adaptive, for a dynamic field

This programmatic approach for hydrogen is neither a rigid document nor a detailed roadmap showing the exact route to take us directly to the desired destination as fast as possible. The field of hydrogen technologies is extremely dynamic, both in this country and at the international level, and it spans multiple innovation and value chains. This means that players in it need to respond adaptively, fast and flexibly when new developments so require. Against the background of this dynamic environment, the approach for the coming 3-5 years is described in much more concrete and robust terms than for the period thereafter. Achievement of the results we strive for in terms of significant reductions in CO<sub>2</sub> and nitrogen emissions, and the energy transition as a whole, as effectively and economically as possible, will depend on systematic evaluation of the approach and adjustments based on the results.

## National Climate Agreement, top sectors policy and industry dictate a programmatic approach

There are three factors that have dictated this programmatic approach. The first is the National Climate Agreement, which was prepared in 2018 and presented on 28 June 2019. This agreement puts hydrogen in a prominent role in various sectors of our energy system and as a supporting pillar of the “system” as a whole. The cabinet’s letter accompanying the Climate Agreement announces an “ambitious hydrogen programme, with a focus on research, pilot studies and demonstration projects, infrastructure and varied hydrogen applications”. The importance that the Climate Agreement places on hydrogen calls for a broad, programmatic approach. It is worth noting that as this approach was drafted, an additional argument for an emissions-free energy supply became abundantly clear: the “nitrogen crisis” that suddenly brought the Dutch agricultural and construction sectors to the streets in protest of government policy measures. Secondly, and following on from the Climate Agreement, came the Integrated Knowledge and Innovation Agenda (IKIA), published in March 2019 and elaborated in more detail in the months thereafter. This document was developed around thirteen “Multi-year Mission-driven Innovation Programmes” (MMIPs) for the sectors Electricity Generation, the Built Environment, Industry, Mobility and Agriculture. Hydrogen is a theme that cuts across all sectors and interfaces with multiple MMIPs because it is (potentially) poised to have a significant impact on virtually all sectors of the Climate Agreement. Because of this cross-sectoral relevance, an integrated programmatic approach for hydrogen is called for. Thirdly, the industrial activities surrounding hydrogen are relevant; it is a field generating major interest, and developments in it have shifted into high gear, as is evidenced by the vast body of studies, companies, research groups, consortia and initiatives with a will to get into hydrogen. The drivers behind all of these are looking for an approach that sets out clear paths to follow into the future, so they can start efficiently and effectively developing tomorrow’s hydrogen-based technologies and functions.

## Process and coordination

### Hydrogen as overarching theme spanning multiple sectors of the Climate Agreement

The core team assembled to design this programmatic approach first drafted consultation documents to serve as a basis for the dialogue with a broad group of stakeholders, who were consulted in face-to-face meetings, workshops and email updates. This structure gave all parties the opportunity to actively contribute, and so generated a broad base of support for the programmatic approach. The initiative for the coordination of the multi-year programmatic approach has been placed with the Top Sector Energy (TSE) as the coordinating “top sector” for the societal challenge “Energy Transition and Sustainability”. For the five sectors Electricity Generation, the Built Environment, Industry, Mobility and Agriculture, “mission teams” were set up and tasked with the substantive direction of the approach. Having interfaces with virtually all missions and MMIPs, hydrogen is clearly an overarching theme, so a separate hydrogen steering group will be formed consisting of representation from all relevant sectors and missions plus representatives of private-sector companies, public-sector bodies and knowledge institutions. The hydrogen steering group will be part of the governance as defined by the five missions. In the Top Sector Energy, TKI Nieuw Gas is responsible for the coordination of this hydrogen steering group. The governance structure will be detailed going forward.

## Programmatic approach

### A structure in five parts

The multi-year programmatic approach for hydrogen is elaborated in five separate but interrelated components:

#### 1 From vision to policy-making

The focus here is on vision-building and programme development, with the goal of surveying the options for achievement of the energy transition, the roles that hydrogen can play in this transition, and the policy support and market regulation that success will require.

#### 2 Practice: demonstration projects (pilots, demos and implementation)

This component is about the practical projects that must be ready for implementation in the 2025-2030 period, and so must be experimented with and demonstrated in the short term. These projects serve multiple purposes, such as: accelerating the introduction of hydrogen-based solutions, organising integral hydrogen chains, testing and developing business cases, and working towards embedding in society through practical examples suitable for future upscaling. Short-term R&D projects will also be a part of this.

#### 3 Creating the conditions

Various overarching themes must be addressed cohesively, and tackled with a cohesive approach, to get the most out of existing synergies, resolve any problems as efficiently as possible, and ensure that the activities proceed expeditiously. The focus is on the areas that are urgent in the short to medium-term, like legislation and regulations, safety and risk management, standardisation, and the need for infrastructure.

#### 4 Research for the longer term

This is research and development activities (lower TRLs) for the longer-term solutions that may be important going into 2030 and beyond, and/or the robust elements for achieving the energy transition approaching 2050. A good example is the co-electrolysis of water and carbon dioxide into a syngas that can serve as a basis for the production of climate-neutral chemical products and materials (plastics) and synthetic fuels.

#### 5 Supporting and accompanying activities

This refers to activities oriented towards removing impediments and addressing topics relevant to developing and upscaling hydrogen applications, such as information campaigns, the human capital agenda, development of supporting tech applications, embedding in the regions, and international partnerships.

For these elements, priority activities have been identified that will be necessary to successfully achieve the ambitions of the Climate Agreement in the coming years and to make hydrogen a mature technology. These are described elsewhere in this document.

## **1 From vision to policy-making**

For a successful implementation and upscaling of hydrogen technologies, a clear policy vision and insight into scenarios and analysis will be indispensable.

### **1A. Hydrogen policy vision**

A government draft of a policy vision for hydrogen must provide the desired clarity on the incentives for hydrogen and broad implementation going into 2030. There is a need for stable long-term policy, including aspects such as the taxation of hydrogen for mobile and non-mobile applications (excise duties and energy tax) and support of the operational costs of hydrogen production through (for example) a production subsidy. This will make it possible to define business cases for projects. Certainty is also needed during the upscaling phase, in order to bring down the investment cost for the technology in real terms. This, too, is principally a task for the government; consultation with stakeholders to understand their plans and needs should be sought.

### **1B. Studies and analyses for programme development**

It is important to show what technological advances will have an impact on hydrogen technology and hydrogen's position in relation to alternatives at the national and European levels; this can be done with scenario analyses, which will also make clear where hydrogen is most desirable and in what time horizon. Other important aspects are the relationship with existing and additional sustainable electricity generation capacity, the position of blue hydrogen (including the CCS option) and the potential for imports. Insight into the functioning and applicability of new market models will help assess and shape policy.

## **2 Demonstration in large-scale projects with real-world applications**

A consideration of the Climate Agreement and the consultation on this programmatic approach results in the following prioritisation of practical projects that can count on broad support from stakeholders and which will be robust for the energy transition. The years and scales indicated are ambitious but, in view of the speed of the developments at the international level and the need to reduce CO<sub>2</sub> emissions rapidly, it makes sense to set the bar high. For many of these projects, combinations may be possible and worthwhile. This is relevant for a number of reasons: cooperation, coordination and clustering (local and regional, and national and international) accelerates knowledge development and increases the base of support, produces shared infrastructure and advantages of scale, and increases the chances of effective policy and adequate financing options.

For these large-scale practical projects, development plans should be detailed in the coming months to define what needs to happen when, what will be needed to achieve this in terms of R&D, what issues (legislation/regulations, permits, safety, availability of funding, etc.) will need to be dealt with and what the financing plan will look like.



Bottlenecks that have already been identified and those that come to light over the course of the development of these projects will be the basis for a research agenda in the short term.

It will also be important to gain a view to the consortia that could be created to implement the development plans. A number of consortia already active in the regions (such as the HEAVENN consortium the north of the country, the project consortium around H-Vision in Rotterdam, and the project initiators in Stad aan 't Haringvliet) could serve as models. The challenge is to keep the focus on “big themes” that strong consortia would want to attach themselves to.

## **2A. Achievement of large-scale production of hydrogen at GW scale in 2030**

A number of project instigators have launched plans for an expansion to 3-4 GW in 2030 moving from the initial installations of 20 MW (now in preparation) through projects of 50, 100 and 250 MW up to this gigawatt scale. This will require electrolysis technology. The obvious choice would appear to be to organise this upscaling around applications for which there is already a high demand for hydrogen (existing industrial applications) or which could generate a high demand for hydrogen, such as new industrial applications and replacement of natural gas with renewable gas. If the cumulative upscaling moves towards many hundreds of megawatts and the gigawatt scale, this will absolutely have to be considered in relation to the extra efforts required for achievement of sustainable electricity production in order to attain actual CO<sub>2</sub> emissions reductions in the Netherlands. This will require a programmatic approach to be worked out by parties in industry and government (both national and international) in order to achieve the desired growth path. Alongside green hydrogen, “blue” hydrogen remains an option for maintaining availability of large quantities of climate-neutral hydrogen in the relatively short term, for example for industry and flexible electricity generation. The first initiative in this area is the H2Magnum project (project partners: Vattenfall, Gasunie and Equinor; project location: Eemshaven). Elsewhere, there is an ambitious plan (H-vision) for the production of blue hydrogen from natural gas in the Port of Rotterdam.

## **2B. Construction of a “hydrogen backbone” to connect the Netherlands’ major industrial clusters by 2030, including large-scale underground hydrogen storage**

Once hydrogen is produced on a large scale, the construction of hydrogen infrastructure will be needed to provide the various production and consumption clusters with green and blue hydrogen. This means establishing a “hydrogen backbone” at the national level to which hydrogen storage (such as gas fields and aquifers) is directly connected, plus hydrogen in distribution networks for the built environment and local applications. In addition, large-scale underground hydrogen storage in salt caverns will be needed to keep sufficient quantities of hydrogen available and to create a buffer between production and use. Of course, the necessity of infrastructure for transport and storage will depend on the production and demand for hydrogen, but this cannot be allowed to be the limiting factor.

## 2C. Dispatchable, flexible hydrogen-based power stations in 2030

Keeping sufficient quantities of climate-neutral electricity available with the requisite flexibility and peak capacity in an electricity system increasingly dominated by intermittent (wind and solar) capacity will ultimately require converting gas (and potentially coal) power stations to handle hydrogen. A good example is the Magnum power station at Eemshaven, where the potential for conversion for hydrogen is investigated. Ultimately, these dispatchable power stations, and additional local variants, will be necessary to achieve fully carbon-free electricity generation heading into 2050 with the capacity to cover shortfalls in the supply of wind and solar where other flexibility options are inadequate or more expensive.

## 2D. Demonstration of 3-5 pilots with hydrogen in the built environment, by 2025

There are a number of possible options for sustainability in the built environment. Use of green hydrogen is, alongside green gas, an attractive option for homes and communities where other options such as heat networks and electrification are not feasible. Achieving the desired sustainability in the built environment must start in the short term with research, testing and demonstration of how hydrogen can be used for these applications, such as examples of the situations in which and the scales (block, community, district, etc.) at which hydrogen can best be used in the built environment (existing buildings), including a survey of what legislation and regulations need to be changed in order to make this possible.

In addition, the development of a number of representative projects in various configurations (different situations, proportions of hydrogen and end-user applications) will be needed to gain the broad experience needed and to define the conditions under which retrofitting, application and potential further rollout after 2030 can happen effectively, efficiently and safely. This means:

- Mixing into the natural gas grid in an existing community, for example combined with local generation.
- Use of 100%-hydrogen solutions in an existing community.
- Application in individual homes.
- Application in collective heat systems (vertical construction and regional nets).

## 2E. Rollout of hydrogen-powered mobility, including refuelling stations in 2025

Much of the technology required (including the cars and fuelling stations) is already available but needs improvement and optimisation at both the component level and the system level. The ambitions formulated in the Climate Agreement are 50 hydrogen refuelling stations at public service stations and 15,000 fuel cell cars and vans/light commercial vehicles plus a further 3,000 heavy duty fuel cell vehicles (buses, trucks waste disposal vehicles) on the roads in 2025, including refuelling stations, and 10-20 demonstrations with hydrogen-powered inland waterway vessels. To these targets should be added: 10-20 demonstrations with mobile heavy equipment in construction, agriculture, industry and ports.

## **2F. Start of pilot and demonstration projects with new industrial applications for hydrogen in the 2025-2030 period**

Alongside the present large-scale application of hydrogen in industry, there are a number of options to use green and blue hydrogen as a replacement for the energy needs currently provided by natural gas and liquid fuels, and the production of raw materials and products. These projects are along the same lines as those under “2A. Achievement of large-scale production of hydrogen at GW scale in 2030” (which specifically names the production of hydrogen) because the need for hydrogen for these applications is potentially huge. Because the financial feasibility in industry is extremely important from the perspective of international competition, the main efforts will be towards pilot projects and demonstration projects, with upscaling and transition to large-scale applications expected to follow later. Examples include:

- Supply of hydrogen from a 20 MW water electrolysis plant in Delfzijl to BioMCN for the production of green methanol.
- Use of hydrogen from a 100 MW electrolysis plant for production of fuels and/or base chemicals with the carbon monoxide (CO) and carbon dioxide (CO<sub>2</sub>) in the exhaust gases from the cokes and steel production at TATA.
- Use of electrolysis hydrogen for refining deep-frying fat into sustainable kerosene and bio-propane in the SkyNRG initiative.
- Production of green methanol from hydrogen and syngas generated from gasification of waste (Enerkem, Nouryon, others)
- Production of synthetic kerosene in the North Sea Channel area on the basis of green hydrogen in the Port of Amsterdam.

## **2G. Introduction of local sustainable electricity from hydrogen in 2025 with completion of pilot and demonstration projects.**

At a number of locations, there are limitations in the power network capacity, as a result of which the introduction of locally generated electricity from solar and wind is not possible or is not always possible. This means that at these locations, projects do not get off the ground or move forward only slowly. In the coming years (up to 2025), there is a need to set up pilot projects and demonstration projects to assess the possibilities of water electrolysis in relation to the introduction of local sustainable electricity generation and remove bottlenecks in the electricity network. Concepts include potentially linking hydrogen filling stations or applications of hydrogen in the built environment like mixing hydrogen into the local or regional natural gas network.

## **2H. Design and construction of a “test energy island” combined with offshore wind and hydrogen production for 2030**

Due to the great interest in offshore wind as a basis for future electricity production (the “Green Powerhouse North Sea”) and the expected challenges and bottlenecks with respect to transport and landfall of this electricity, a test of the complete system for offshore “wind hydrogen”, on a limited scale and under realistic conditions, and including the required infrastructure such as offshore hydrogen pipelines, is desired.

This can be a means of gaining experience in how this option can be applied efficiently and reliably in the future. There are already plans in development for multiple large “energy islands” in the North Sea where hydrogen could be produced using wind power.

### **3** Creating the conditions

This component refers to the issues that are of critical importance for the large-scale rollout of hydrogen. These include legislation and regulations, safety, standardisation, suitability and modification of natural gas infrastructure for transport and distribution of hydrogen, gas quality (including mixing of hydrogen in natural gas), import of hydrogen, and system integration of onshore and offshore electricity generation. Some of these issues will be necessarily addressed by the practically oriented projects, while others are still in the “study phase” with the best options, methods of application, costs, and time frame still under consideration.

### **4** Research for the longer term

This component is oriented on the longer-term research needed to develop the full capacity of hydrogen for a broad spectrum of applications. The separation between research for the long term (after 2030) and the period up to 2030 is not always cut-and-dried. Some results will be needed earlier but demand more fundamental solutions that will take more time. This need will also depend on the speed at which developments in hydrogen move in the shorter term.

For the more fundamental and technological research needs, there are a number of industry MMIPs that have outlined the research themes in relation to hydrogen, such as industry MMIP 6 (Circularity) and industry MMIP 8 (Electrification). The ECCM programme also provides a description of the research themes, including priorities. There have also been a number of projects in various areas launched within this programme already. It should be noted that drawing a strong connection between the research themes and the opportunities for industry in the Netherlands (including, in particular, the manufacturing industry) is desired.

R&D questions with a near-term horizon will have to be handled quickly and effectively to ensure that hydrogen projects can be carried out and scaled up into the longer term. The expectation is that the practical projects will also give rise to new research questions. Ideally, this dynamic should be organised around calls for project proposals, combined with practical projects where possible. Right now, hydrogen is at a very early stage of development, and there are a great many technical improvements and optimisations possible in terms of production and application.

## **5** Supporting and accompanying activities

This refers to peripheral areas that will be necessary to successfully develop hydrogen projects: for example, certification, development and application of measurement methods, embedding in society, the role and involvement of regions, tech applications, and the human capital agenda. Many of the activities this covers can be make-or-break for implementation, which is why these activities should ideally be addressed in the practical projects. Future projects, and future funding, should be made contingent on an integral approach to these.

### **5A. Certification of hydrogen**

Development and application of a uniform European system for Guarantees of Origin for hydrogen and green hydrogen, certificates for green hydrogen and hydrogen with a low fossil/carbon footprint.

### **5B. International coordination and cooperation**

With respect to development and harmonisation of norms and standards for hydrogen technology and applications, it is recommended that the Netherlands opt to approach this strategically and place key experts on significant working groups to ensure that the Netherlands is represented and plays an active role on the policy side.

### **5C. Miscellaneous: Regional Cooperation, HCA, Tech, SRI, etc.**

There are a number of non-technological themes that will be relevant and contributory for the successful development and upscaling of hydrogen technologies. These will require ongoing attention in relation to the other activities. These are themes such as regional cooperation, the human capital agenda, tech applications and socially responsible innovation.

# Summary overview

The development of hydrogen demands major investments from all stakeholders

The Table below gives a summary overview of the five components of the approach, including timing and an initial, very general indication of the expected budget needs. It must be kept in mind that this overview is very explicitly for indicative purposes, because it is still impossible to make a precise assessment. Some of these components have already been identified, prioritised and budgeted in the relevant MMIPs. There will be coordination with these MMIPs on an ongoing basis to maximally facilitate the development of hydrogen technologies.

Subject	Timing (when ready)	Estimated budget (€ x 1,000,000)
<b>1 From vision to policy-making</b>		
<b>1A.</b> Hydrogen policy vision	Early 2020	None
<b>1B.</b> Studies for programme development	Ongoing	Annually, 0.2-0.5
<b>2 Demonstration in large-scale projects with real-world applications</b>		
<b>2A.</b> Realisation large-scale hydrogen production on GW scale	2030	1,000+
<b>2B.</b> Construction of hydrogen backbone infrastructure in the Netherlands and hydrogen storage	Around 2030	Partially public
<b>2C.</b> Utilisation of controllable, flexible hydrogen-based power stations	2030	250+
<b>2D.</b> Demonstration of 3-5 pilot studies with hydrogen in the built environment	2025	10-20
<b>2E.</b> Rollout of hydrogen-powered mobility, including filling stations	2025	10-20
<b>2F.</b> Hydrogen pilot projects and demonstration projects in industry (partly falls under 2A)	2025-2030	50-100
<b>2G.</b> Introduction of local sustainable electricity generation using hydrogen	2025	10-20
<b>2H.</b> Design and construction of test energy island	Before 2030	100+
<b>3 Creating the conditions</b>		
Various subjects, to be worked out in detail in the coming years (safety, legislation/regulations, gas quality, standardisation, etc.)	2020-2021	10-20
<b>4 Research for the longer term</b>		
Implementation of medium to long-term R&D agenda	2020-2030	Annually, 5-10
<b>5 Supporting and accompanying activities</b>		
<b>5A.</b> Certification of hydrogen	2020-2021	Limited
<b>5B.</b> International coordination and cooperation	Ongoing	Limited
<b>5C.</b> Miscellaneous: Regional Cooperation, HCA, Tech, SRI, etc.	Ongoing	Limited
<b>TOTAL</b> <i>(very rough estimate for 2020-2030 period)</i>		<b>Order of 1,500-2,000</b>





# Chapter 1



# 1 | Introduction: a multi-year programmatic approach for hydrogen as link between sectors and regions

## 1.1 Background

In March 2019, the Integrated Knowledge and Innovation Agenda for Climate and Energy (IKIA)<sup>1</sup> was published. This document describes the innovations that will be required in all sectors of the Climate Agreement and throughout the entire innovation chain in order to reach the targets of 49% reduction in CO<sub>2</sub> emissions by 2030 and (effectively) 100% reduction in CO<sub>2</sub> emissions by 2050. The innovation needs are described in 13 MMIPs (Multi-year Mission-driven Innovation Programmes), which were further elaborated in the first half of 2019. In line with the Climate Agreement, these MMIPs are “sectorally” oriented and describe the innovations that will be required in the sectors Electricity Generation (MMIPs 1 and 2), Built Environment (MMIPs 3-5), Industry (MMIPs 6-8), Mobility and Transport (MMIPs 9 and 10), and Agriculture (MMIPs 11 and 12). In addition, there is an overarching MMIP 13 for system integration that describes the connecting, fundamental themes in this area. The Top Sector Energy has primary responsibility for the coordination of this IKIA but coordinates with other top sectors in specific theme areas (e.g. Chemistry, HTSM (High-Tech Systems & Materials), Logistics, and Agro & Food).

For the past few years, activities in the field of hydrogen technology have been on the rise<sup>2</sup>, as evidenced by a broad array of studies, consortia and initiatives on the initial activities around hydrogen technology or indicating an interest in exploring this domain<sup>3</sup>. These activities are focused on specific sectors, such as the use of hydrogen as a source of energy in industry, mobility and transport, the built environment and electricity generation, and as a sustainable building block in combination with green CO<sub>2</sub> as a replacement for petroleum in the production of synthetic fuels and chemical products and materials. At the same time, activities like the production of hydrogen, infrastructural themes, flexibility, and storage technology are also outspokenly cross-sectoral.

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1 “Innovation with a mission” report; See [www.klimaatakkkoord.nl/themas/kennis--en-innovatieagenda](http://www.klimaatakkkoord.nl/themas/kennis--en-innovatieagenda).

2 “Hydrogen” is an overarching concept that refers to the use of hydrogen as a source of energy, hydrogen produced from renewable resources and in combination with CCS, and renewable hydrogen as a building block for sustainable chemistry and synthetic fuels.

3 Examples: Green Hydrogen Coalition, Green Hydrogen Economy in the Northern Netherlands, Green Hydrogen Economy in the Province of Zuid-Holland, SDR hydrogen plans, H-vision, MW testing centre (Hydrohub), GW plan, HyChain, various initiatives for 10-250 MW electrolyzers. For a full list, see the annex to this report.

On 28 June 2019, the government presented the Climate Agreement<sup>4</sup>, which defines a prominent role for hydrogen in the sectors named above and as an overall reinforcement of the “system” (see Table 1). The cabinet’s letter accompanying the Climate Agreement announces an “ambitious hydrogen programme, with a focus on research, pilot studies and demonstration projects, infrastructure and broad hydrogen applications”. The importance that the Climate Agreement places on hydrogen calls for a broad, programmatic approach to hydrogen technology, including a broad-spectrum innovation programme. In consideration of the sector-based approach of both the Climate Agreement and the IKIA, there is a risk of fragmentation of the innovation needs and activities within the hydrogen domain if efforts within individual sectors prove inadequate or inadequately coordinated, or if they do not make adequate use of the advantages of synergy to be gained from the programmatic approach. This is another reason why a broad-spectrum programmatic approach is critical.

**Table 1 | References to hydrogen in the Climate Agreement**

Sector	Goal (What?)	Approach (How?)
Industry	<ul style="list-style-type: none"> <li>• Installation of 3-4 GW electrolysis in 2030 (500 MW in 2025)</li> <li>• Reduction in investment costs for electrolysis by 65% between now and 2030</li> </ul>	<ul style="list-style-type: none"> <li>• Hydrogen programme with €30-40 million/year for pilots and demos within national funding</li> <li>• Research for inclusion of hydrogen in SDE+(+), use of EU funds, involving financial sector institutions like InvestNL</li> </ul>
Electricity Generation	<ul style="list-style-type: none"> <li>• For flexibility of electricity system, development of CO<sub>2</sub>-free dispatchable production, potentially up to 17 TWh in 2030, for which CO<sub>2</sub>-free hydrogen is an option</li> <li>• Development of Green Powerhouse North Sea (up to 60 GW in 2050) with partial conversion to hydrogen</li> </ul>	<ul style="list-style-type: none"> <li>• Timely modification of existing infrastructure for hydrogen and construction of new infrastructure to link industry clusters</li> <li>• Establishment of a national government vision of market regulation and energy transition, with updating of legal frameworks by 2021</li> <li>• Development of green hydrogen certificates (EU)</li> </ul>
Mobility and Transport	<ul style="list-style-type: none"> <li>• In 2025 50 filling stations, 15,000 fuel cell cars and 3,000 heavy vehicles; in 2030 300,000 fuel cell cars</li> <li>• Reduction in investment costs for filling stations by average 10% per year</li> <li>• Hydrogen contributing to at least 150 emissions-free inland waterway vessels in 2030</li> </ul>	<ul style="list-style-type: none"> <li>• Covenant with stakeholders to promote hydrogen-powered mobility</li> <li>• Tax incentives and use of EU funding</li> <li>• Government as launching customer (sustainable procurement by national and local authorities)</li> <li>• Zero-emissions zones for city logistics in 30-40 largest municipalities</li> <li>• National Agreement on Zero-Emissions Bus Transport</li> <li>• Green Deal on sea shipping, inland waterways and ports</li> </ul>
Built Environment	By 2030, clear picture of how hydrogen can contribute to achievement of 2050 goal, including for buildings and communities that are difficult to make sustainable otherwise	Lay foundation in legislation & regulations and community-focused approaches for pilots and demos in the coming years

4 Climate Agreement, 28 June 2019 (search term: [www.minezk.nl](http://www.minezk.nl), Klimaatakkoord).

The MPAH (Multi-year Programmatic Approach on Hydrogen) presents a shared perspective on a broadly supported approach to hydrogen. It identifies the innovations needed and presents an organisational and implementation framework. The programme also endeavours to optimally leverage the advantages of synergy to accelerate the development and upscaling of hydrogen technology as much as possible. This puts the programmatic approach squarely behind the government's announced hydrogen programme. The programmatic approach for hydrogen was developed in cooperation between the MMIP teams and the various relevant sectors<sup>5</sup>. Goals, approach and desired results are explained in the following.

## 1.2 Objectives

The objectives of the MPAH are:

- Create a shared, cross-sector approach to innovations to replace fossil carbon-based fuels with sustainable and/or climate-neutral hydrogen and facilitate successful development, demonstration, implementation and scale-up of innovations in hydrogen across multiple sectors that contributes towards the achievement of the goals of the Climate Agreement.
- Accelerate the implementation of hydrogen as an energy source/fuel in our energy landscape to a substantial level in 2030, and the increase of sustainability through the use of hydrogen as a raw material.
- Maximally leverage the advantages of synergy in the development of hydrogen as one of the central energy carriers in the energy system by identifying overlapping themes and addressing them in a coherent approach in (for example) production, transport, distribution and storage. These advantages of synergy may be economic in nature (cost savings, shared procurement) but can also take the form of joint development and demonstration (bundling of innovative strengths) so the implementation and upscaling of hydrogen can be accelerated.
- Create ownership for overarching themes that can benefit all sectors, such as institutional aspects relating to safety, societal acceptance, development of supporting tech applications, the human capital agenda and policy aspects.
- Work together (in collaboration with the regions) to put forth a strong joint policy of the Netherlands internationally as an interesting incubator and location for activities associated with the development of hydrogen as one of the key energy sources in the energy system, including showcasing our knowledge and activities in the field.

The result is a programmatic approach for hydrogen that outlines an effective and cost-efficient trajectory for the research, demonstration, implementation and upscaling of hydrogen that will be needed across the various sectors in 2030 and 2050. The programme offers a multi-year approach for the coming years with the central object of accelerating the implementation of hydrogen technology towards 2030, achieving the required upscaling and identifying and executing the innovation tasks for the short (period up to 2025), medium (to 2030) and long term (to 2050).

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5 Hydrogen is a component of a number of different MMIPs, including 1, 4, 5, 6, 7, 8, 9 and 13.

## 1.3 Approach

In March 2018 the Top Sector Energy released a Hydrogen Roadmap<sup>6</sup>. A joint action by the Ministries of Economic Affairs and Climate Policy and Infrastructure and Water Management in collaboration with a large group of stakeholders in industry, knowledge institutions, the public sector and civil society organisations, it sets out initial innovation needs categorised around the themes of power and light, low-temperature heat, high-temperature heat, and mobility and transport. The programmatic approach MPAH is the bridge from this roadmap to the IKIA and the Climate Agreement.

A core team was put together to draft the MPAH (see annex E for the team's composition); this team was responsible for the end result and the process, which was structured as follows:

- The core team drafted consultation documents that served as a basis for meetings and workshops with stakeholders.
- The core team held “bid rounds” in which the innovation needs were presented to interested parties such as the MMIP teams inventoried from among the hydrogen community at an earlier stage.
- These were followed by “collection rounds” that were organised by the core team for the individual MMIP implementation teams to deliver their innovation products for their incorporation into the programme.
- The core team organised generic workshops on specific subjects to coordinate input; these included the H<sub>2</sub>Platform on mobility and transport, and industry consultation via MMIP 8.
- In July 2019, there was a broad consultation workshop for the discussion of the definitive concept and for setting priorities. All documentation was also presented on the Top Sector Energy website for consultation, in order to maximise the reach of the results.
- In September 2019, there was another open, broad consultation with the hydrogen community conducted via email and on the TSE website.

All documents written in this process remained public and available to all stakeholders throughout the process. The structure of the process gave all parties the opportunity to actively contribute, and so generated a broad base of support for the programmatic approach.

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6 Hydrogen Roadmap: <https://www.topsectorenergie.nl/sites/default/files/uploads/TKI%20Gas/publicaties/20180514%20Roadmap%20Hydrogen%20TKI%20Nieuw%20Gas%20May%202018.pdf>





# Chapter 2

## 2 | Hydrogen: robust element in the energy transition

### 2.1 The way forward: meeting societal challenges

Limiting the impact of major global warming-driven climate change will require drastic and immediate reductions of greenhouse gas emissions. Success will demand fundamental changes in the way we generate energy and in the industrial applications of fossil-based resources. Alongside these climate-related challenges, the world is facing a number of other closely related societal challenges, some with respect to creating a liveable world for future generations, and others with respect to the sweeping changes that tackling the climate challenge will bring. Some examples of these include:

- a clean living environment, in which emissions into the air, soil and water are minimal.
- a safe living environment, based on energy and raw materials that present the minimum possible risks.
- a high-quality public space, with a minimum of environmental impact.
- an inclusive energy transition that preserves quality employment and profitability within our economy, including a highly skilled working population.

Looking at the direct living environment, there are four major sectors around which these societal challenges are clustered:

- industry, which must keep its operations clean and safe, with the lowest possible emissions, while making a positive contribution to society.
- the built environment, which must offer high quality of life and low emissions at an acceptable cost.
- the energy sector, which must produce sustainable, reliable (with flexibility) and affordable electricity and also provide the conversion from primary to secondary energy sources (e.g. refineries), which must be made climate-neutral.
- mobility and transport, which must be clean, silent and efficient, while (ideally) not presenting any restrictions on freedom of movement.

Taken together, these sectors comprise the 'system' within which hydrogen has a role to play.

## 2.2 Permanent need for molecules in a sustainable system

Achieving the emissions reduction targets will depend on success in several areas, such as: reduction of energy demand, use of renewables, and electrification. But even with a high level of electrification, a sustainable energy supply will also have an ongoing (and significant) need for liquid and gaseous energy carriers. Estimates of the share of this permanent need of molecules in a sustainable energy supply vary but are of the order of 40-60% in 2050 (current: approximately 80%).

Liquid and gaseous energy sources will remain necessary as fuel in applications for which an electricity and battery-based energy supply alone is insufficient or inefficient: consider examples like fuel for the aviation and shipping industries, road transport with heavy, energy-intensive and demanding use patterns, or generation of high-temperature heat for certain industrial processes. In addition, molecules will remain necessary in the process industry for the synthesis of chemical products and materials. Hydrogen is already an important basic element in the chemical industry, and its importance is expected to grow, especially considering that in the foreseeable future all chemical products and materials that are now produced from fossil hydrocarbons (coal, petroleum and natural gas) are to be replaced by sustainable and/or circular forms. Finally, liquid and gaseous energy sources will be needed for the large-scale storage and transport of energy needed to ensure that the supply and demand of energy are in balance, always and everywhere.

## 2.3 Roles of sustainable hydrogen

To ensure that we do not become dependent solely on the limited supply of sustainable biomass as an alternative source for our expected high demands in liquid and gaseous energy, it is critically important for this task to also be able to draw on the ample potential in renewable energy sources solar and wind power. This can be done in a number of ways, for example the production of hydrogen from water using electrolysis, powered by sustainable electricity generated from solar and wind power. In this process, electrical energy generated from solar and wind is converted into chemical energy stored in hydrogen.

This hydrogen can be used directly as a fuel to replace natural gas (heat for domestic heating or electricity in gas-driven power plants), or for the production of onboard electricity for fuel cell-based electrical equipment and vehicles. It can also be used indirectly by combining the hydrogen with sustainable forms of carbon for the production of synthetic liquid fuels and chemicals (for example as a replacement for fossil kerosene). And alongside carbon and nitrogen, hydrogen is the basis for virtually every chemical product and material.

This means that hydrogen is not only the key to large-scale storage of sustainable electricity from solar and wind for reuse during periods of inadequate supply of solar and wind or for off-grid electrical applications such as electric vehicles, but it also provides the option to use solar and wind power to increase the sustainability of the molecules side of the energy system and of raw materials for the chemical industry.



That breakthrough opens the door to vastly larger-scale use of solar and wind energy than using those resources alone for sustainable electricity generation. Hydrogen's vast potential for large-scale storage of energy will go a long way towards resolving one of the most problematic issues inherent to solar and wind energy, reconciling the variation in supply of energy generation from these sources with the variation of the demand. An additional advantage of hydrogen and hydrogen-based energy sources like methane, ammonia and methanol is that these are relatively simple to transport in large quantities and over great distances via pipelines and tankers, making it possible to import sustainable energy from faraway locations with high potential and under better conditions for the production of sustainable electricity, and at lower costs, than can be done in places like the Netherlands.

The options for storage, transportability, convertibility into electricity and the broad range of potential applications make hydrogen a major source of flexibility for the energy system at the central and local levels. One major example of this flexibility is the capacity to regulate electrolyzers for the production of hydrogen (adjustable capacity for positive and negative demand response) in order to adjust to the variable supply of electricity from solar and wind generation to support the stability of the electricity network. All in all, these components offer the prospect of a future energy system that is sustainable and based largely on solar, wind and hydroelectric power. An alternative is the direct production of hydrogen using solar energy, i.e. without involving electricity as an intermediate step. The limitation of this option is that it is not an answer to the need for flexibility in the electricity system<sup>7</sup>, but it does add flexibility to the energy system.

To conclude, hydrogen offers significant added value for reducing CO<sub>2</sub> emissions, as a climate-neutral fuel and raw material, and for important systemic solutions like flexibility, transport and storage. These roles are broadly recognised, as evidenced by various publications of the Hydrogen Council, the IEA and the European Commission, as well as studies by Gasunie and TenneT<sup>8</sup>. An illustration of the relationship between these functions is provided in Figure 1.

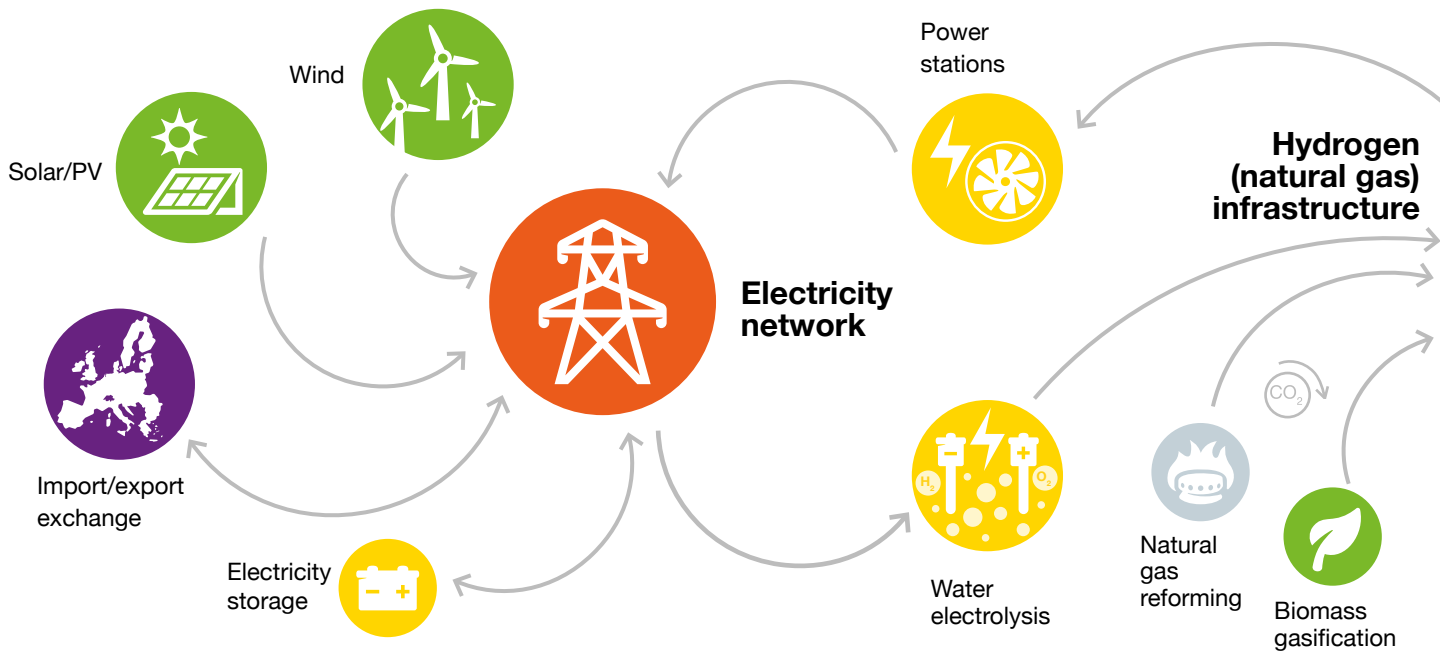
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<sup>7</sup> To some degree, this option reduces the potential for electrolysis as a source of flexibility for the electricity system (it leaves less capacity for production of hydrogen by electrolysis).

<sup>8</sup> Examples of good reports include: [ec.europa.eu/energy/sites/ener/files/documents/final\\_draft\\_asset\\_study\\_12.05.pdf](https://ec.europa.eu/energy/sites/ener/files/documents/final_draft_asset_study_12.05.pdf); [ec.europa.eu/clima/sites/clima/files/docs/pages/com\\_2018\\_733\\_analysis\\_in\\_support\\_en\\_0.pdf](https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf); [www.iea.org/hydrogen2019/](https://www.iea.org/hydrogen2019/); <http://hydrogencouncil.com/study-how-hydrogen-empowers/>; [www.klimaatakkoord.nl/documenten/publicaties/2019/02/22/tennet-gasunie-infrastructure-outlook-2050](https://www.klimaatakkoord.nl/documenten/publicaties/2019/02/22/tennet-gasunie-infrastructure-outlook-2050)

Figure 1 | Schematic of potential functions of hydrogen

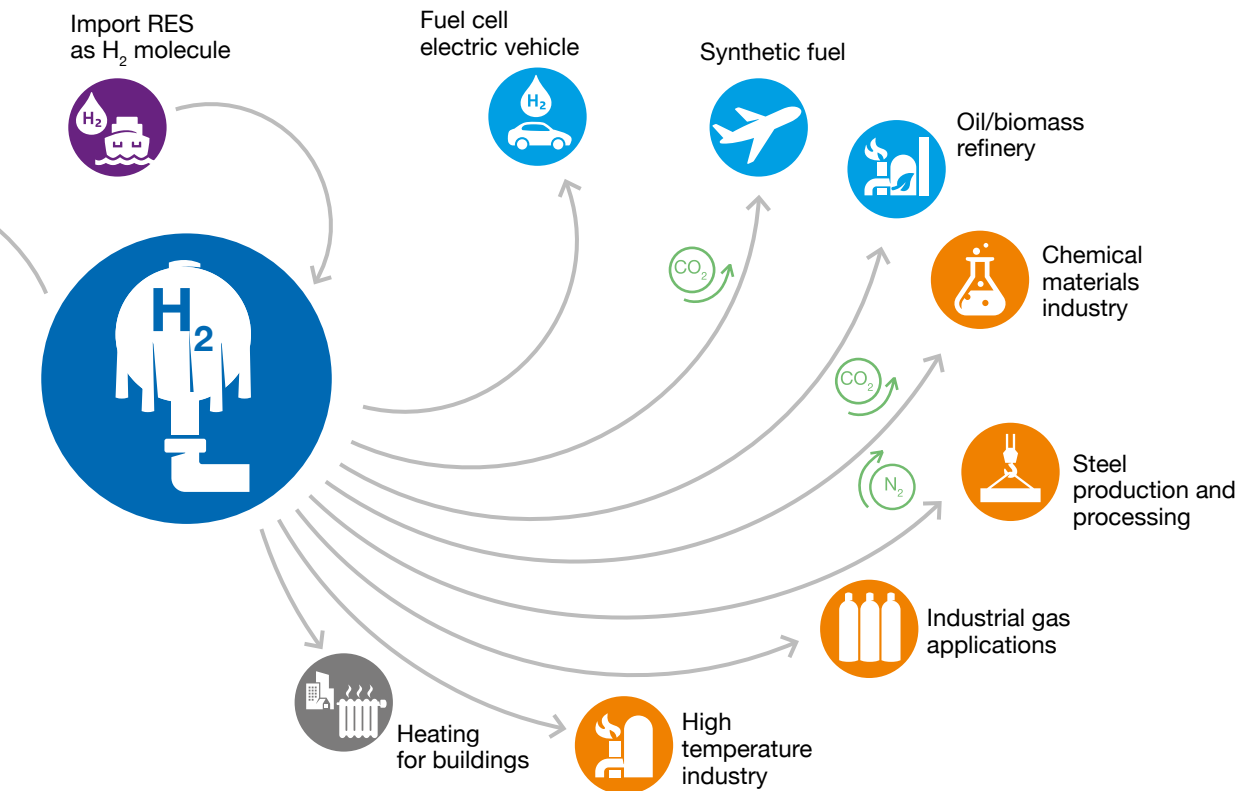
(source: Hydrogen Roadmap).



## 2.4 Transition and the role of green and blue hydrogen<sup>9</sup>

The production of green (sustainable) hydrogen from water via electrolysis depends on the availability of sustainable electricity. Expanding the capacity for sustainable electricity takes time, and despite steady growth, not enough new capacity in sustainable electricity is expected to become available in the short term to allow sustainable hydrogen to make a significant contribution towards achieving the greenhouse gas emissions reduction goals for 2030. On the other hand, the potential of green hydrogen may help accelerate the rollout of offshore wind power by 2030, because utilisation of this electricity via hydrogen is not dependent, or much less dependent, on the expansion of the transmission capacity of the onshore high-voltage network. Conversion to hydrogen can happen upon landfall on the coast or will soon even be possible at sea, in combination with the transport of hydrogen by existing or new pipelines, which will reduce the transport and system costs.

<sup>9</sup> Definitions: Green hydrogen is hydrogen generated from renewable electricity or sustainable biomass. Blue hydrogen is hydrogen generated from fossil fuels, with the CO<sub>2</sub> emissions captured and reused or stored. Grey hydrogen is hydrogen of fossil origin without the capture and reuse or storage of CO<sub>2</sub>.



Blue hydrogen can be used as a step-up to green hydrogen. As it looks now, the drastic reduction in emissions that will need to be achieved by 2030 will be very difficult without the use of CO<sub>2</sub> capture and storage (CCS). This involves a choice between “end-of-pipe post-combustion CCS” (the capture of CO<sub>2</sub> after the combustion of fossil energy) and the source-oriented “pre-combustion” CCS, in which decarbonisation of fossil energy sources happens before they are used for energy purposes; the result after decarbonisation is blue hydrogen. This makes the latter form more “future-proof” than the former. It can be used to achieve significant emissions reductions relatively quickly, while at the same time tackling certain aspects of the energy system that will be necessary for the large-scale application of hydrogen “ahead of schedule”. Later, this can mean that the transition to the endgame of green, sustainable hydrogen will make a flying start.

It is worth noting that there are different perspectives on the use of blue hydrogen as a forerunner to pave the way to green hydrogen. Some stakeholders are confident that it will be possible to have access to large amounts of green hydrogen relatively quickly (prior to 2030) if we rapidly upscale the underlying technology or import large amounts of green hydrogen to make blue hydrogen redundant<sup>10</sup>.

<sup>10</sup> To give an idea: 1 GW of offshore wind generates an amount of electricity that can produce of the order of 10 PJ of hydrogen. Dutch industry uses approximately 100 PJ of hydrogen. Current forecasts indicate that in 2030, there will be 11.5 GW of offshore wind.

Others see CCS technology as an excessively expensive “lock-in” of fossil resources in the energy transition. It is not our intention to adjudicate this discussion here, but only to identify the innovation needs<sup>11</sup>. The innovations needed for the capture, transport and storage of CO<sub>2</sub> are not discussed in the MPAH; for these, see the innovation agenda for CCS<sup>12</sup> (under MMIP 6 of the industry sector table). The prioritisation of the innovation activities in the coming years must actively take into account the discussions between the relevant actors and society as a whole about this blue route and the innovation needs that this calls for, as well as the willingness of stakeholders to innovate and invest in this area.

### **Production of grey, blue and green hydrogen**

The production of hydrogen on the basis of natural gas for industrial, non-energy occasions is a standard, large-scale and largely optimised process. For this application, the challenge lies in decarbonising current production and replacing current production with green hydrogen. Decarbonisation can take the form of capture of CO<sub>2</sub>, which is then stored underground (CCS). CO<sub>2</sub> capture (without storage) is also a standard process that is already used on an industrial scale for applications with a need for a supply of concentrated CO<sub>2</sub>, such as the production of urea and carbon dioxide for carbonated drinks. The costs involved are passed on in the costs of the products. However, the use of CO<sub>2</sub> capture pushes up the costs of natural gas for energy as compared to the situation without CO<sub>2</sub> capture. Minimising these costs will require both optimisation of existing and development of new, more efficient and more economical CO<sub>2</sub> capture processes.

Research into CO<sub>2</sub> capture is treated as a CCS subject. This comprises attention into post-combustion, oxy-fuel and pre-combustion capture concepts. Capture during the production of hydrogen is in essence a pre-combustion process in which natural gas is first stripped of carbon and then used as hydrogen. This use may be non-energy (as industrial gas) and for chemical conversions (as in the current situation), or energy use (for combustion<sup>13</sup>, in which case this hydrogen is referred to as blue hydrogen).

There are a number of alternatives for the production of sustainable hydrogen, the primary one being electrolysis of water using sustainable electricity. Other options include reforming of biogas or green gas, gasification of sustainable biomass and waste, and supercritical water gasification of biomass waste flows. In all of these examples, carbon plays a role (in some cases sustainable) alongside hydrogen. Due to the expected future demand for sustainable carbon for chemical products and materials and for sustainable synthetic liquid fuels, biomass is most likely more relevant for the production of sustainable syngas than for production of hydrogen alone. This is why the MPAH places a focus (at present) on electrolysis.

11 See the “CSS Fact-Finding Study” drafted by a separate working group for discussion in the context of the Climate Agreement. The memorandum can be found at [www.klimaataakkoord.nl](http://www.klimaataakkoord.nl).

12 This programme also devotes attention to Direct Air Capture, which is the direct extraction of CO<sub>2</sub> from the air (i.e., not by means of release through a chemical process).

13 Here, there is a distinction between thermochemical conversion of hydrogen with oxygen using burners for production of high-temperature or low-temperature heat, electricity, or a combination thereof (CHP) and electrochemical conversion of hydrogen with oxygen in fuel cells, with electricity being the primary product.





# Chapter 3

## 3 | Consideration of the hydrogen innovation system

Hydrogen technology is an area that has been in and out of the spotlight over the years, but recently has been enjoying a new Renaissance. A significant difference with previous periods in which hydrogen has been a focus of attention is that now people are looking at more than just the use of hydrogen as a fuel for electric vehicles powered by fuel cells. The focus now is on the much broader systemic role that hydrogen can play in the energy system as a flexible storage and transport medium for a flexible supply of electricity from renewable energy sources (solar and wind in particular), with a wide range of energy and non-energy applications (see Figure 1) that cannot be electrified or are difficult to electrify.

The innovation system for hydrogen is moving rapidly, and due to the several different roles for hydrogen, the developments in it are happening in a much broader realm than in the past. There are multiple consortia currently building organisations and developing plans for introducing hydrogen and mobility and transport, industry and the built environment. These plans are currently in varying states of maturity, from first idea to very concrete<sup>14</sup>. A recent inventory performed for the Netherlands Enterprise Agency (RVO), the Ministry of Economic Affairs and Climate Policy, and FME (the trade association for the technological-industrial sector) revealed that over 250 companies and organisations are currently pursuing hydrogen-related initiatives and that there are good economic opportunities for these parties<sup>15</sup>. There have also been a large number of regional plans developed (e.g. for the Northern Netherlands, the provinces of Zuid-Holland, Limburg and Gelderland, the North Sea Channel zone and the Zeeland Delta (SDR)), each of which describes a potential role of hydrogen for the future. The innovation calls-for-tender performed by RVO at the request of the Top Sector Energy have brought a wide range of parties together, and these are currently working jointly towards new innovations. It is striking to see the broad spectrum of actors coalescing around the hydrogen ecosystem: large companies, SMEs, network managers, knowledge institutions, regional organisations, municipalities and provinces, ministries and civil society organisations are all showing an interest in hydrogen technology and a willingness to participate both actively and financially. The fact that a broad group of stakeholders, all with an eagerness to take an active role, have come together in such a short time is not in itself a guarantee for success, but it does put this potentially broad development in a very good starting position: it is clear that building successful hydrogen chains will depend on players like these.

All consortia are encountering challenges in innovation and other areas that will have to be surmounted to make hydrogen successful. To make sure that these challenges are defined properly,

14 An inventory of hydrogen initiatives (as of December 2017; now somewhat outdated) can be found at: [www.topsectorenergie.nl](http://www.topsectorenergie.nl), TKI Nieuw Gas, search term: "routekaart waterstof".

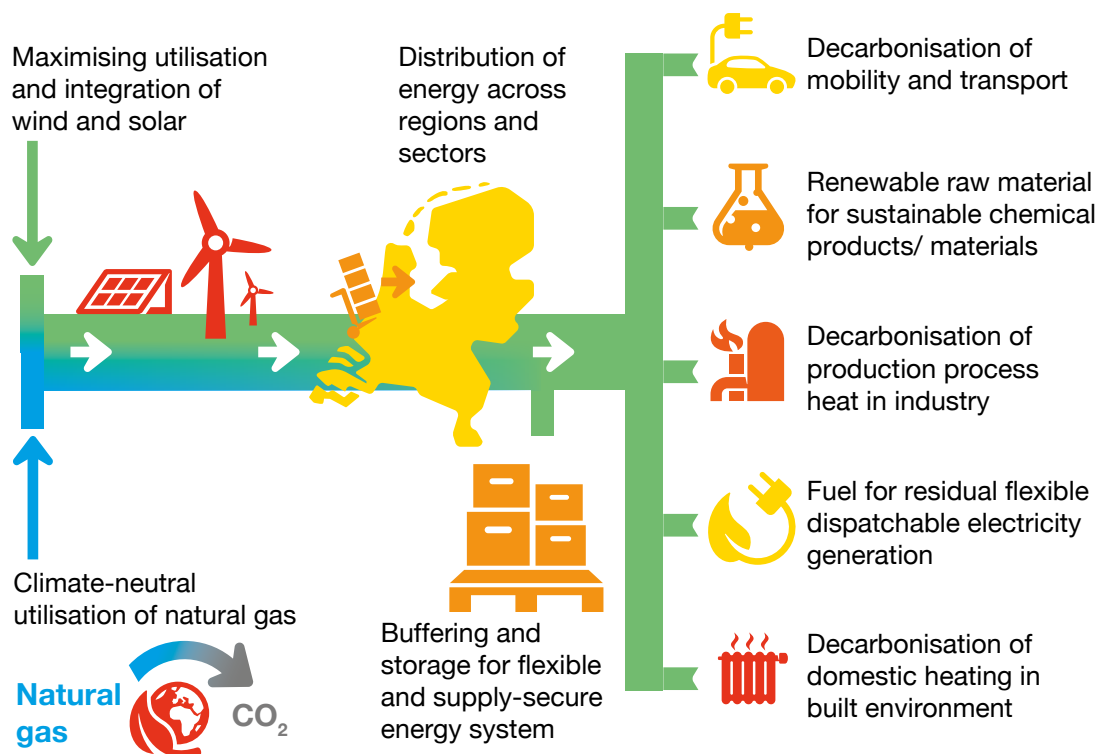
15 "Hydrogen: opportunities for Dutch industry (Perspective on sustainable growth through hydrogen)" (Original title: Waterstof: kansen voor de Nederlandse industrie (Perspectief voor duurzame groei door waterstof).) Report by Ekinetix and Stratelligence, commissioned by RVO/EZK. Published Autumn 2019.

the choice was made in the MPAH to take the chain of production from initial development to end application as the framework. Figure 2 is a schematic of these challenges including the intended objectives for hydrogen applications.

We identify the following components in the hydrogen chain:

- Production of hydrogen: this includes the production of green and blue hydrogen through various processes such as electrolysis of water and reforming (SMR, ATR, pyrolysis of natural gas, etc.) and gasification of fossil and biomass-based hydrocarbons.
- Storage, transport and distribution of hydrogen, including large-scale underground storage in gas fields, caverns and aquifers, as well as small-scale storage in tanks and cylinders, for example at hydrogen filling stations, and the transport of hydrogen through pipelines (including retrofitted natural gas pipelines), on ships, by rail and by road, as compressed gaseous hydrogen, as liquid hydrogen, or as hydrogen bonded to a carrier.
- Applications: This refers to applications using hydrogen as an energy carrier (fuel) for the production of process heat in industry, domestic heating in the built environment, generation of electricity onboard fuel cell-powered electric vehicles in mobility and transport, and for the production of electricity in flexible, dispatchable gas power stations or in stationary or mobile production units based on fuel cells or dedicated hydrogen combustion engines. Hydrogen can also be used as raw material for the production of fuels and chemicals; the processes involved, such as methanol synthesis and Fisher-Tropsch synthesis, do not fall under the scope of the hydrogen programme and are an element of MMIPs 6 (Closing of industrial chains) and 8 (Electrification and radically innovative processes).

**Figure 2 | Schematic of the hydrogen chain(s) from production, via transport and distribution, to application for various purposes** (source: Hydrogen Roadmap, 2018).





These chains also relate to overarching themes that must be addressed, such as safety, hydrogen quality, import, etc. These themes are covered in the programmatic approach.

**Table 2 | Relationships between the hydrogen innovation chain and the IKIA MMIPs.**

Subject in the innovation chain	Relationship with MMIP
Production of blue and green hydrogen	MMIP 1 Sustainable electricity generation at sea MMIP 6 Circularity, incl. CCS MMIP 8 Electrification and radically innovative processes
Buffering, transport, distribution and (seasonal/long-term) storage for a flexible and supply-secure energy system	MMIP 1 Sustainable electricity generation at sea MMIP 2 Sustainable electricity generation on land MMIP 5 Balanced energy system for the built environment MMIP 13 Robust and integrated energy system
Decarbonisation of mobility and transport	MMIP 9 Propulsion and energy sources in mobility
Renewable raw material for chemistry	MMIP 6 Circularity MMIP 8 Electrification and radically innovative processes
Sustainable heat production in industry	MMIP 7 CO <sub>2</sub> -free industrial heating system
Dispatchable flexible electricity production	MMIP 13 Robust and integrated energy system
Sustainable heating in the built environment	MMIP 4 Sustainable heating/cooling in the built environment MMIP 5 Balanced energy system for the built environment

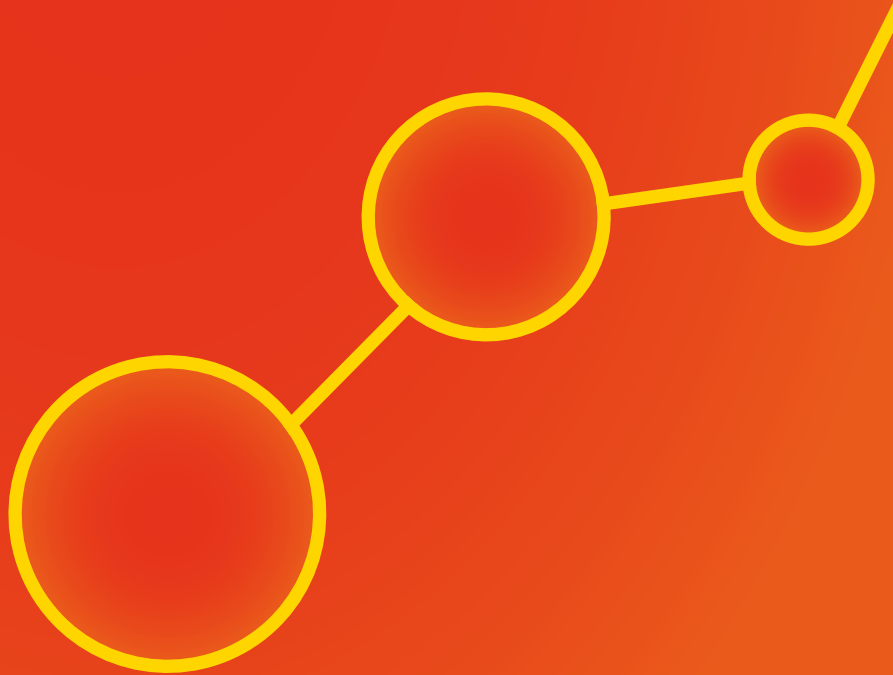
The programmatic approach for hydrogen endeavours to act as a link between the IKIA MMIPs with relevance to hydrogen in order to drive shared, targeted and efficient innovation. It serves the role of recurring thread for hydrogen, running through all MMIPs and connecting them into an integrated, programmatic approach. The relationship between the hydrogen chains of Figure 2 and the individual MMIPs is broadly described in Table 2. The Table shows the subjects that the hydrogen programme will need to address in order to effectively respond to the needs within the individual MMIPs.

In addition to the connections within the IKIA, there are also a number of different interfaces with other top sectors, including Chemistry, Water and HTSM. These connections are identified briefly in Table 3; more detailed descriptions can be found in the full explanations of the individual MMIPs.

**Table 3 | Indicative overview of interfaces between the MPAH and other top sectors.**

<b>Hydrogen theme:</b>	<b>Collaboration with:</b>	<b>Subjects:</b>
In the chemical industry (MMIPs 6-8)	TS Chemistry TS Agro & Food TS HTSM	Hydrogen's role in circularity Hydrogen's role in circularity, organic production Materials research in relation to hydrogen
In the built environment (MMIP 4)	TS Creative Industry	Social embedding, consumer behaviour, etc.
In mobility and transport (MMIPs 9-10)	TS Logistics TS Water TS HTSM	Application in mobility and transport, location of filling stations, materials research
In the manufacturing industry	TS HTSM	New materials for production (electrolysis) and application (fuel cells)

The governance with respect to the implementation of the IKIA and the coordination of the MPAH is set out at the mission level, i.e. by sector of the Climate Agreement. In the structure, hydrogen is designated as a “shared theme” in which essentially all missions are involved. In the governance, this will be expressed in a strong connection with each of the missions. This is in keeping with the integrated nature of the programmatic approach. The details of the governance of the MPAH will be further specified in the coming months.





# Chapter 4

# 4 | Innovation needs for hydrogen

## 4.1 Goal and contribution of the programme

This chapter describes the innovation tasks for hydrogen across the entire chain of production, storage, transport and distribution up to and including end use, including the system functions of hydrogen:

- Green hydrogen (electrolysis, etc.) and blue hydrogen are discussed under production.
- Storage, transport and distribution comprise a wide variety of subjects related to all elements that make up part of a storage and pipeline infrastructure for hydrogen, as well as an infrastructure for distribution or supply of hydrogen to mobility and transport applications. This takes into account the various forms in which hydrogen can be transported, distributed and stored.
- Fuel cells, burners and gas turbines are the primary technologies for end use applications, and it is in these technologies where the innovation tasks for the development, implementation and testing of systems lie. For fuel cell systems, these pertain primarily to concrete applications such as in buses, trucks and ships.

For each of these elements, a broad picture is presented: an outline of where the needs are, with the object of obtaining a reasonably complete picture of the areas in which activities are needed (longlist). Next, Chapter 6 identifies the priorities defined in consultation with stakeholders (shortlist).

The MPAH is primarily dictated by the societal challenge “Energy transition and sustainability” as defined in the top sector policy. This societal challenge is directly linked to the Climate Agreement. Consequently, the MPAH also addresses the targets and ambitions formulated for 2030 (-49%) and 2050 (fully climate-neutral and circular).

The focus of the MPAH is to contribute, over the coming five to ten years, to the achievement of the Climate Agreement by:

- demonstrating in upscalable practical projects (pilots, demonstration and implementation projects, upscaling) how in 2030 hydrogen can make practical contributions to the achievement of the objectives and, on the way to doing so, can be scaled up in specific applications.
- thus show society what hydrogen is, to introduce the theme of hydrogen to society and get society behind hydrogen as a movement (seeing is believing), and to discover the needs and requirements that actors in society have for these innovations.
- create beneficial circumstances for implementation and upscaling of hydrogen by removing technical, economic, societal and institutional obstacles.

- developing the knowledge, products and services that will be necessary in the future (2030 and 2050) to have hydrogen make a robust contribution.
- addressing and tackling the interdisciplinary/overarching topics on which a collective approach will produce advantages of synergy, such as: infrastructure, import, storage and safety; including vision-building for the energy transition and the questions surrounding it.
- ensuring that innovations are joint innovations produced as effectively and efficiently as possible (cooperation, informing, achieving, facilitating) in consideration of the scarcity of the resources available and the need to actually achieve the energy transition.

The programmatic approach is intended to produce an integrated innovation agenda that supports and supplements the innovation tasks under the various MMIPs. Table 4 shows the relationship between the various innovation tasks broken down broadly by MMIP. This Table lists only a brief explanation of the function; a more detailed explanation and indication of the underlying themes is provided in the breakdown of the innovation chains for hydrogen.

**Table 4 | Relationship between the MPAH and the challenges in the IKIA MMIPs.**

<b>MMIP</b>	<b>Interaction between MPAH and MMIPs</b>
1. Sustainable electricity production offshore	<ul style="list-style-type: none"> <li>• Flexibility to match supply and demand through the use of electrolyzers</li> <li>• Offer alternative infrastructure (pipelines instead of cables)</li> <li>• Creation of new markets (from electrons to molecules)</li> <li>• Buffering and storage in order to enable continuous matching of supply and demand and to bridge periods without sustainable production (long-term towards 2040-2050)</li> </ul>
2. Sustainable electricity production on land	<ul style="list-style-type: none"> <li>• Flexibility to match supply and demand through the use of electrolyzers</li> <li>• Buffering and storage in order to enable continuous matching of supply and demand and to bridge periods without variable production</li> </ul>
3. Energy renovations in the built environment	<ul style="list-style-type: none"> <li>• None</li> </ul>
4. Heating/cooling in the built environment	<ul style="list-style-type: none"> <li>• Production of sustainable heating/cooling in the built environment</li> <li>• Options for mixing (possible well before 2030) and pure hydrogen (primarily after 2030)</li> </ul>
5. Balanced energy system for the built environment	<ul style="list-style-type: none"> <li>• Support of introduction of local sustainable energy by taking pressure off bottlenecks in the electricity network in combination with local/regional hydrogen applications (for example mixing into the gas network and dispensers at service stations)</li> </ul>
6. Circularity in industry	<ul style="list-style-type: none"> <li>• Raw material for the production of renewable/sustainable chemical products and materials</li> </ul>
7. Heating in industry	<ul style="list-style-type: none"> <li>• Production of high-temperature heat</li> </ul>
8. Electrification of industry	<ul style="list-style-type: none"> <li>• Raw material for a wide range of chemical products</li> <li>• Raw material for transport fuels</li> </ul>
9. Propulsion and energy sources	<ul style="list-style-type: none"> <li>• Use as a transport fuel (directly in fuel cells and as a base component for the production of synthetic fuels)</li> </ul>
10. Effective transport	<ul style="list-style-type: none"> <li>• None</li> </ul>

**Table 4 | Relationship between the MPAH and the challenges in the IKIA MMIPs.**

MMIP	Interaction between MPAH and MMIPs
11. Food/non-food production	• None
12. Land and water	• None
13. System integration	• Infrastructure needs, including large-scale storage of energy • Market mechanisms, models and data

To be able to use the available innovation funds as efficiently as possible, and to take maximum advantage of the potential advantages of synergy, it will be important to make good choices about where to focus the programmatic approach in the coming years. In making these choices (Chapter 6), it is important to consider the following elements:

- A. *Upscaling perspective*: does the option or the development fit into the vision on the future role of hydrogen, and can it be upscaled and play a meaningful role in the achievement of the energy transition? An aspect of this is the options to make innovations available relatively quickly (what TRL levels can be successfully completed, can costs be reduced fast enough). See box.
- B. *Timing*: in what time frame can the option be expected to make a meaningful contribution to the development of hydrogen and the energy transition?
- C. *Innovation ecosystem*: is there a broad group of stakeholders involved or with an interest in the development and willing to take an active part in it?
- D. *Current activity*: are there/have there been activities in this area already, or are there activities to be expected, desired or necessary in the short term in order to make progress in this area?
- E. *Economic position*: can the Netherlands acquire an economic position with this development, for example on the basis of the current knowledge position or with current products and services? This can be done by activating and supporting the Dutch manufacturing industry in building capacity around the theme of hydrogen or by incentivising international companies to establish themselves in the Netherlands with hydrogen-related activities.
- F. *International development and cooperation*: are the developments also stimulated in international programmes like FCH JU with budgets that the Netherlands can use, and are comparable activities happening elsewhere that can be used or joined with for the purposes of learning enough for application in the Netherlands?

For these elements, there has been no indicator included for the degree of CO<sub>2</sub>, nitrogen and other emission reductions. This is because the assumption is that the use of hydrogen as an alternative for fossil hydrocarbons as an energy source will ultimately lead to a completely emissions-free energy system; otherwise, there would be little reason to pursue the development of hydrogen technology<sup>16</sup>. Obviously, the end goal is the use of green hydrogen.

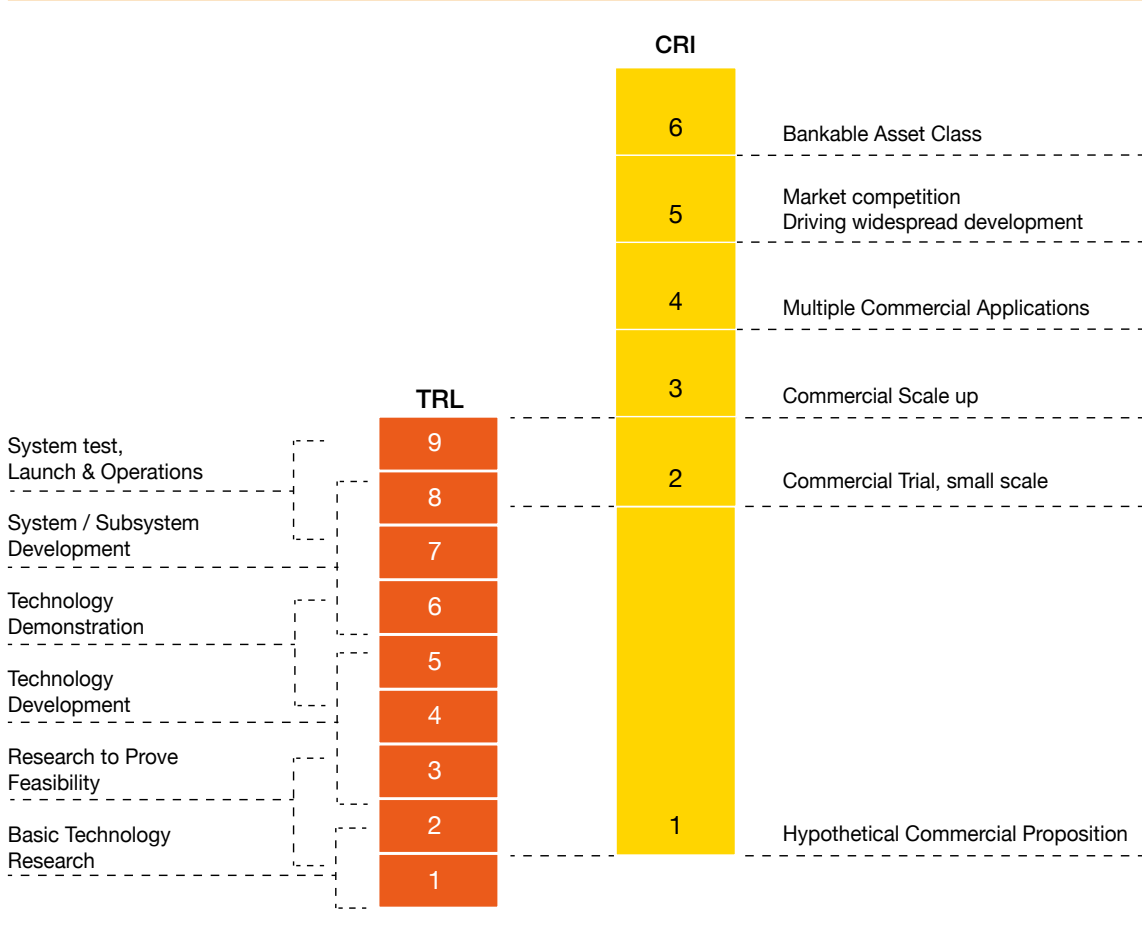
<sup>16</sup> Looking at the complete picture from source to end use, the application of hydrogen does not in all cases reduce CO<sub>2</sub> and other emissions from the very first moment, because the emission factor of the electricity that is necessary for electrolysis goes down only gradually as more electricity generation from renewable sources becomes available.

In essence, there are no activities involving fossil hydrogen production that are supported. This would, however, be possible for hydrogen applications based on the perspective for green hydrogen outlined here.

**Technological Readiness Levels and Commercial Readiness Index**

The degree of development of a technology is often quantified using a parameter known as the “Technological Readiness Level” (TRL). On the TRL scale, a rating of TRL 1 indicates a technology that is at the starting stage of development (fundamental research), and TRL 9 indicates a technology that is technologically and commercially ready. It should be noted that TRL 9 does not automatically entail that commercialisation of the technology is a given. There is also a “Commercial Readiness Index” (CRI), which indicates the degree to which the market is receptive to large-scale application of the technology. Looking at hydrogen technology, environmental factors in the energy system will play an important role here, as the figure below shows. The implication for the MPAH is that innovation is not “ready” at the moment that TRL 9 is reached. When proceeding through the CRI phases on the way to a fully commercial product, investment decisions in the market will be based on developments in policy and legislation & regulations.

**Figure 3 | Relationship between TRL and CRI** (source: Australian Renewable Energy Agency 2014).

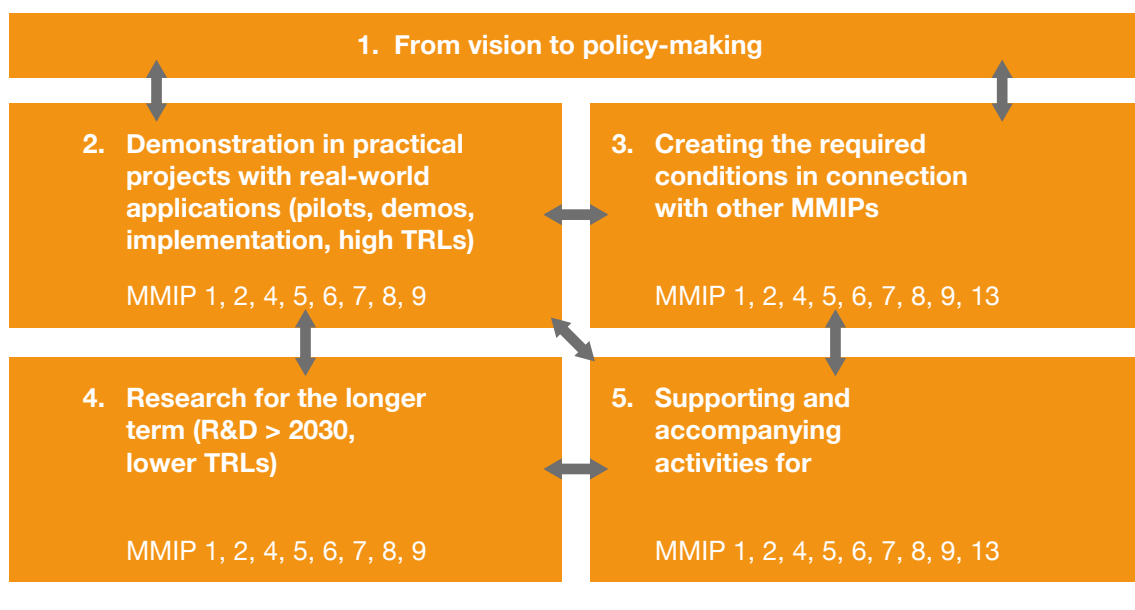




## 4.2 Substantive approach and details of the programme

The programmatic approach of the MPAH is based on five interrelated components. Figure 4 shows these components and their interconnection and also indicates the connections with relevant MMIPs. These five components are shown in more detail below.

**Figure 4 | Schematic of the structure and interconnection of the MPAH and its connections with the MMIPs of the IKIA.**



### 1. From vision to policy-making

This overarching section focuses on vision-making with the object of identifying the various options for the energy transition and the functions that hydrogen can play in it, in terms of nature and scope. It is important to position the theme of hydrogen in relation to other sustainability options in a way that makes clear where the biggest added value is, in part from the perspective that a certain scarcity applies to all possible alternatives. Model-based analyses of the energy and raw materials system can reveal what functions hydrogen can fulfil, what time frame will be required (in relation to what is feasible), and the best/fastest way to achieve this. This may, for example, include integrated energy system analyses, well-to-wheel and energy chain analyses, life cycle analyses, supply security analyses, and levelised and marginal cost calculations to compare all technologies and options based on a standard methodology with uniform financial parameters (as in the methodology for SDE+(+)).

These activities should produce sound analyses to substantiate the choices made on the contribution that the various sustainability options can make, and where the development of hydrogen (production and applications) will be desired and feasible. This way, this information will contribute to the vision-making around hydrogen. Interfacing with MMIP 13 (Robust, integrated energy system), which on the model-based side is intended to generate correct and reliable data, will be important to gain insight into promising solutions for the many systemic questions. Further, within the vision-making, there is room for “programme-specific” analyses, for example exploring new hydrogen options that emerge, analyses of specific transition and infrastructure scenarios for hydrogen, and monitoring the progress of the programme and international developments in the field of hydrogen and hydrogen technologies. All analyses and insights will also be useful in making necessary adjustments to the programme at regular intervals. Below, Table 5 describes a number of important issues.

**Table 5 | Issues for vision-making on hydrogen.**

<b>Business and market models</b>	<ul style="list-style-type: none"> <li>• Which business models and market models will work in the future and what does this mean for the production and application of hydrogen? What policy is needed for optimal support? What market models facilitate individual choices of residents (in the built environment)? Consider adjustment of allocation and billing of sustainable gases on the basis of gas composition (individual supply; what is the situation with respect to physical and contractual separation?).</li> <li>• How can the benefits of individual services be paid for and billed? For example: hydrogen storage, demand-side response and imbalance optimisation. What sales opportunities are there for byproducts of electrolysis, such as oxygen, heat and (in some cases) CO<sub>2</sub>?</li> <li>• How can a trading hub or marketplace for hydrogen be structured at the national/international level?</li> </ul>
<b>Role in energy system</b>	<ul style="list-style-type: none"> <li>• What role can hydrogen play in the supply of system flexibility, transport and storage capacity for energy; what competes with it, and what is the added value of hydrogen (and its derivatives) as compared to the alternatives?<sup>17</sup></li> </ul>
<b>Technology analyses</b>	<ul style="list-style-type: none"> <li>• What technologies are favoured according to a techno-economic and societal cost-benefit analysis? This should pertain to all links in the chain.</li> <li>• Where is the improvement potential in each technology, including cost reductions (CAPEX decrease, OPEX decrease, efficiency gains) particularly the most expensive links of the hydrogen chain?</li> <li>• What cost methodology (target costs, CO<sub>2</sub> price, SCBA/intrinsic costs) must be applied in view of the higher price of green hydrogen?</li> </ul>
<b>Transition management</b>	<ul style="list-style-type: none"> <li>• How can the transition to the large-scale application of hydrogen be organised in the most effective and cost-efficient way, with phased and balanced conversion and construction of infrastructure, production and applications on the one hand and phaseout of the current (natural gas) system on the other?</li> <li>• How can this transition be stimulated? What distribution of roles will there be between the various parties that will prevent “competition” and accelerate the development to the maximum possible extent (who can have/wants/needs something)?</li> </ul>

<sup>17</sup> Example: for flexible regulatable zero-emissions electricity power stations, there are multiple conceivable options: conversion of coal-driven power stations into power stations running on biomass/wood chips, new nuclear power stations, natural gas power stations equipped with CSS or gas-powered power stations running on hydrogen.

**Table 5 | Issues for vision-making on hydrogen.**

<b>Institutional impediments</b>	<ul style="list-style-type: none"> <li>• What institutional aspects with short-term relevance must be resolved in order to make implementation possible (legislation/regulations, roles and tasks of network managers, certification of green hydrogen, Gas Act and market regulation)?</li> </ul>
<b>Choice of production and storage location</b>	<ul style="list-style-type: none"> <li>• Where are the best locations for large-scale hydrogen production? What is the optimal scale? What are the advantages and disadvantages of onshore and offshore production? Can seaports fulfil the role of hubs for hydrogen?</li> <li>• Can the functions large-scale production, large-scale storage (strategic supply) and large-scale use of hydrogen for synthetic fuels (e-fuels) be combined?</li> </ul>
<b>Role of import</b>	<ul style="list-style-type: none"> <li>• What role can import of green hydrogen play in the future? What is the timing for development of this important chain, taking into account transshipment to neighbouring countries? In what form or forms can hydrogen best be transported, stored and used?</li> <li>• What opportunities are there for green hydrogen production in emerging economies with export to the Netherlands/Europe? What implications does this have?</li> </ul>
<b>Role of blue hydrogen</b>	<ul style="list-style-type: none"> <li>• What is the role that blue hydrogen can play in relation to green hydrogen, including aspects of timing/phasing, capacity, available stocks and cost perspective/relationship between green and blue? What does a transition with and without “blue” look like? What role does grey hydrogen play in this transition? Can a review framework for projects be developed based on this?</li> <li>• How can regional “green” hydrogen visions (North-Holland, South-Holland, Northern Netherlands, etc.) and “blue” hydrogen initiatives such as H-vision, H2Magnum and hydrogen backbone be integrated (system study)?</li> </ul>
<b>Role of infrastructure</b>	<ul style="list-style-type: none"> <li>• What role can/must the existing gas and other infrastructure play in the distribution of hydrogen, such as mixing of hydrogen into natural gas or the development of onshore and offshore infrastructure for transport of hydrogen?</li> <li>• What is the result of the cost comparison between greenfield offshore electricity cables vs. hydrogen pipelines to transport offshore wind power?</li> <li>• What is the optimal storage infrastructure for the Netherlands from a perspective of costs, energy efficiency and local availability (meta-study of completed and ongoing research)?</li> </ul>
<b>Long-term tasks</b>	<ul style="list-style-type: none"> <li>• What other long-term tasks are there for hydrogen apart from the R&amp;D needs?</li> </ul>

Further survey of these subjects will lead to better understanding of the themes, a better assessment of the risks, and a clearer picture of the desired direction for the development of hydrogen. This, in turn, will help us make well-founded choices in the coming years and achieve the desired acceleration. Here, there will be interaction with the practical projects (see elsewhere in this document): in order to refine the visions, we have now, we must learn from the practical projects currently conducted. Is the application of hydrogen really going to work like we think it is? Might it turn out to be more difficult, or perhaps even easier than we anticipate? The visions must be refined on the basis of the practical results.

Some of the activities proposed have already started, such as the import studies in the context of the Hychain project series by a large IPST consortium, or studies of large-scale hydrogen use for the built environment in the United Kingdom. This is why, for reasons of efficiency, it is recommended to follow existing work closely (including international cooperation and exchange), use the results of this work and make informed decisions about the utility and necessity of new studies, research and projects.

## 2. Demonstration in practical projects with real-world applications

In this section, the focus is on practical projects, consisting of pilot studies and demonstration and implementation projects<sup>18</sup> in hydrogen technology that must be complete and ready for broad implementation for the 2025-2030 period. These projects serve multiple purposes, of which the following are the most relevant:

- Accelerating the testing, demonstration and introduction of hydrogen technology solutions (technology acceleration and implementation). This must also create space for accompanying research (in the higher TRLs; for lower TRLs, see part 4) in support of advancements to optimise the technology into real-world products and services for broader implementation in the 2025-2030 period.
- In concrete projects, organising the chain into a functioning whole to increase the chance of successful upscaling, both regionally and nationally.
- Working towards embedding in society by showing practical examples of hydrogen projects that can serve as good examples for future upscaling. This means that these projects must devote attention to involvement of societal actors, including carefully crafted information packages and knowledge-sharing to create maximum support for projects.

These practical projects have an important connection with the MMIPs where application of hydrogen is a possible and feasible solution, for example MMIP 4 (Heating/cooling in the built environment), MMIP 7 (CO<sub>2</sub>-free industrial heating system) and MMIP 9 (Innovative propulsion and use of sustainable energy sources for mobility and transport). Relevant requirements are the following:

- Solutions that can be implemented in 5-10 years must be demonstrated now and, where possible and feasible, implemented at scale in order to build up experience, actively introduce these solutions to society, and identify and eliminate the barriers to the solution (including institutional obstacles and legislative barriers). This demands a properly substantiated selection of projects and a strong focus on these developments.
- The focus must be on robust subjects that are both relevant to the achievement of the objectives (making a potentially significant contribution) and a good “fit” with the Netherlands (building up a strong position).
- Where there is a need for additional R&D, this must be taken up quickly, linked to existing practical projects and built into new projects.
- Solutions need to contribute to the development of the position of Dutch companies and knowledge institutions (“make” or else “buy”).
- We need an ongoing search for options to accelerate the introduction of hydrogen and the developments necessary to achieve it.

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<sup>18</sup> There are a number of different terms in use to denote the activities to be performed in practice following the experimental development: pilot projects, demonstration projects, practical projects, implementation projects, rollout projects, living labs, etc. What all of these refer to is projects that are for the most part past the R&D phase and which are ready to be demonstrated (on some scale), or which may even be ready for implementation (implementable at large scale and funding-ready).

The following sections present some good examples of practical projects. Many of these initiatives are in development, and the level of specifics given here may vary; some are ready to be implemented in the real world, while others have only just passed a feasibility study or are still in the middle of one. The common denominator is that these projects have the potential to meet the goals described above to accelerate the innovations of the energy transition and to achieve the embedding in society. By and large, these practical projects are complex and expensive initiatives, which is why it is a good idea to implement a coherent mix of practical projects selected because they can best learn and benefit from each other and to maximise the collective chances of success of further upscaling. Here, “practical projects” also refers to their implementation.

## 2a. Practical projects in Industry

Ultimately, industry is expected to be the biggest market (in terms of demand) for hydrogen technology applications. This refers in particular to the use of hydrogen as raw material or auxiliary material for a range of chemical products, such as methanol and ammonia, and for use in oil and biomass refining processes<sup>19</sup>. Hydrogen can also play a role in the generation of high-temperature heat/steam for industrial applications. For some of these possible applications for hydrogen, there is a strong R&D need that is defined in the industry mission (MMIP 6-8). It is already technically possible to produce green or blue hydrogen, but the limiting factor for industrial application remains the pricing, as well as (to some extent) the availability of large quantities of sustainable electricity and, where applicable, biomass for the production of green hydrogen and the availability of the technology (e.g. electrolyzers) in the quantities required.

From a cost perspective, hydrogen production by means of electrolysis can currently only compete with conventional hydrogen production from natural gas under certain specific conditions. There are systems available on the MW scale, but the technology needs to become cheaper and the systems have to be scaled up towards the GW scale in the form of serial, automated production. Because for larger systems, the peripherals scale less proportionally than the electrolysis cells and stacks, upscaling will in itself have the effect of decreasing the cost. In addition to this, the systems need to be optimised and the more expensive materials need to be replaced by cheaper substitutes while improving efficiency and lifetime of the systems. Cost reductions also need to be achieved in the form of economies of scale (larger numbers), industrialisation/automation of the production, and more competition in the chain of suppliers of components.

In the Netherlands, over the past 12 months, there have been announcements of a large number of projects in the industry with electrolysis capacities ranging from 10 to 250 MW. This includes, at a minimum, eight projects that are included in this report, representing a total estimated investment volume on the order of (at least) €1 billion.

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<sup>19</sup> The greatest demand for hydrogen currently comes from ammonia production and oil refining, but a much greater demand will emerge when petroleum and natural gas are replaced by hydrogen and CO<sub>2</sub> or CO as a basis for the production of synthetic fuels (diesel and kerosene), as well as for the production of sustainable bulk chemicals (methanol, alkenes and aromatics) that in the chemical industry are processed into every known chemical product and material.

Essentially, all projects are currently in the feasibility and engineering phase, and consequently must first undergo their own dynamics and business-internal processes. This is why for most of these projects, it is uncertain whether they will ultimately be implemented or not.

It is, however, important to ensure that promising projects can actually go into implementation after a careful consideration, by supporting demonstration and implementation (for example by making funding available from DEI+ en SDE++). Additionally, the options of European grant funding, such as H2020/Europe, the Innovation Fund and IPCEI (Important Projects of Common European Interest) should also be used to the maximum possible extent.

The recommendation is to monitor the projects that are in preparation in terms of progress, innovation need and financing requirements. Each of these projects is, most likely, too large to be fully funded from Dutch sources, but funding from the MPAH can support drafting plans for learning the maximum possible across a selection of projects. The MPAH can also support the application for and combination of Dutch and European funding.

**Table 6 | List of innovation needs and current/potential practical projects in industry. In some cases, projects for industry and the energy sector are developed jointly; this explains the overlap with Table 7**

Subject	What is the innovation need?	Who is involved?	What previous/current projects?	Programmes/funding
Central production of green hydrogen via electrolysis with renewable electricity in industry	<ul style="list-style-type: none"> <li>Gaining experience with implementation of electrolysis plants to arrive at efficient project development (preliminary process currently takes a great deal of time because it is new to everyone)</li> <li>Make connections with Netherlands manufacturing industry in supply of components for electrolysis systems and plants</li> <li>Development of a suitable policy framework with institutional adoption and support</li> </ul>	Nouryon, Gasunie, TATA, Dow, BP, Engie, TenneT, Green Coalition, SkyNRG, KLM, Port of Amsterdam	<ul style="list-style-type: none"> <li>1 MW electrolyser Gasunie</li> <li>10-20 MW Nouryon and Gasunie</li> </ul>	Due to size, aim for European funding (Innovation fund, H2020/Europe, IPCEI)
	<p><i>Practical projects:</i></p> <ul style="list-style-type: none"> <li>20 MW Nouryon, Gasunie</li> <li>100 MW Nouryon, TATA, Port of Amsterdam (H2ERMES)</li> <li>100 MW Engie, Gasunie</li> <li>250 MW Nouryon, BP</li> <li>40 MW SkyNRG, KLM, Nouryon (Delfzijl)</li> <li>Ambition for construction of GW-scale water electrolysis in 2030 (Gasunie, TenneT, Green Hydrogen Coalition)</li> </ul>			

**Table 6 | List of innovation needs and current/potential practical projects in industry. In some cases, projects for industry and the energy sector are developed jointly; this explains the overlap with Table 7**

Subject	What is the innovation need?	Who is involved?	What previous/current projects?	Programmes/funding
<p>Central decarbonisation of natural gas and exhaust gases by CCS with use of low-carbon (blue) hydrogen for electricity generation and provision of heat for industry</p>	<ul style="list-style-type: none"> <li>• Development of large-scale blue hydrogen projects that can kickstart the hydrogen infrastructure (GW-scale)</li> <li>• Modifications in gas turbines to make them suitable for being supplied with hydrogen</li> <li>• Modified burners for hydrogen</li> <li>• New hydrogen/oxygen (oxyfuel) burners for high temperature in the industry, such as glass production</li> <li>• New generation of ovens for hydrogen (glass, steel and ceramic industry)</li> <li>• Optimisation of product quality for direct heating processes upon transfer to hydrogen combustion</li> <li>• Solutions for large-scale storage on-site</li> </ul> <p><i>Practical projects:</i></p> <ul style="list-style-type: none"> <li>• Conversion of Magnum electric power station to hydrogen with modified burners and gas turbines (2025)</li> <li>• Conversion of Maasvlakte coal power stations to hydrogen (2025)</li> <li>• Large-scale demonstration of hydrogen for high-temperature heat in industry</li> <li>• For example, hydrogen as replacement for natural gas at FrieslandCampina facility in Bedum</li> </ul>	<p>Vattenfall, Equinor, Gasunie, H-Vision consortium, burner and turbine suppliers (Ansaldo Thomassen etc.), Port of Amsterdam</p>	<ul style="list-style-type: none"> <li>• Hydrogen-to-Magnum</li> <li>• H-Vision</li> </ul>	<p>Due to size, aim for European funding (Innovation fund, H2020/Europe)</p>

## 2b. Practical projects in the Energy Sector

As the generation of electricity from solar and wind does not run in parallel with the demand profiles, hydrogen can meet the need for a dispatchable, decarbonised generation capacity. The need for this capacity will grow as solar and wind increase their share of the renewable energy generated. There are several large projects in development for the conversion of existing power stations to hydrogen. As with the projects in industry, these are largely in the feasibility and engineering phase and have yet to go through their own dynamics and internal processes; consequently, it is not certain that these will actually be completed. Also, as with the industry projects, it will be advisable to monitor the project in preparation with respect to progress, innovation need and financing requirements, and to support them where possible in seeking and combining funding sources.

One approach already applicable is the use of electrolyzers by having them take more or less electricity (variable capacity), for net stabilisation or balancing, and combined with wind turbines (in some cases the electrolyser may be integrated into a “hydrogen turbine”) or with PV solar parks. The first such project was already tested in the TSO2020 project and can be an extra functionality for this type of industrial project with large-scale electrolysis. The feasibility of the direct combination with wind turbines and PV solar parks has yet to be demonstrated.

A driving force for local and regional hydrogen projects can be the congestion on the electricity network. Electrolysis (for example) can be used to maximise the utilisation of locally generated electricity in order to ease bottlenecks in the infrastructure in this way. Due to the scale of production, an attractive option is combining this with the use for regional mobility projects and projects in the built environment (such as mixing hydrogen in the natural gas network). It would be advisable to carefully consider the number of combined innovations in order to keep the risk manageable and increase the chances of success.



**Table 7 | List of innovation needs and current/potential practical projects in the energy sector. In some cases, projects for industry and the energy sector are developed jointly; this explains the overlap with Table 6.**

Subject	What is the innovation need?	Who is involved?	What previous/current projects?	Programmes/funding
<p>Central conversion of electricity from wind and solar to green hydrogen in and by the energy sector</p>	<ul style="list-style-type: none"> <li>• Engagement and use of electrolysers, by varying the capacity, for network stabilisation or balancing.</li> <li>• The project QualyGrids sets standardised test protocols for electrolysers in order to perform electricity grid services.</li> </ul>	<p>TENNET, Gasunie / Energystock, Energy Storage NL, RWE Innogy</p>	<ul style="list-style-type: none"> <li>• HYSTOCK/ TSO2020</li> <li>• Qualygrids</li> </ul>	<p>FCH JU, Ministry of Economic Affairs innovation funds</p>
	<p><i>Practical project:</i></p> <ul style="list-style-type: none"> <li>• Trials with 1 MW electrolyser and simulation for 300 MW upscaling in HYSTOCK</li> <li>• 100 MW RWE Innogy (Eemshaven)</li> <li>• Ambition for construction of GW-scale water electrolysis in 2030 (Gasunie, TenneT, Green Hydrogen Coalition)</li> </ul>			

**Table 7 | List of innovation needs and current/potential practical projects in the energy sector. In some cases, projects for industry and the energy sector are developed jointly; this explains the overlap with Table 6.**

Subject	What is the innovation need?	Who is involved?	What previous/current projects?	Programmes/funding
Local production of or conversion to green hydrogen via electrolysis for application in transport and/or the built environment and industrial sites	<ul style="list-style-type: none"> <li>• Hydrogen turbine: Develop and demonstrate a wind turbine that generates hydrogen directly. Equip a 4.5 MW wind turbine with 2 MW electrolyser in the province of Noord-Holland</li> <li>• Local incorporation of wind and solar energy via hydrogen from electrolysis for heating in the built environment, potentially in combination with hydrogen for a filling station (community power station idea)</li> <li>• Makes small-scale systems affordable (generation, conversion, application) for locations with a surplus of local generation, congestion on the network and local energy needs such as farms</li> </ul>	HYGRO, Lagerweij, Stedin, Hygear, Lectorenplatform Urban Energy (LPUE), HAN, HyMatters	<ul style="list-style-type: none"> <li>• Duwaal/W2H2</li> <li>• Power-to-Gas Rozenburg</li> <li>• NEFUSTA</li> </ul>	DKTI, Ministry of Economic Affairs and Climate Policy innovation funds
Demonstration (MW scale) of a Power-to-Power system: local storage of green energy in hydrogen for electricity production in low production hours, mobility and heating	<ul style="list-style-type: none"> <li>• Integration of electrolyser, H<sub>2</sub> compression, storage and fuel cell technology</li> <li>• Grid stabilisation at local level where wind and solar power are used</li> <li>• Development of Power Management System</li> <li>• Make optimal use of existing infrastructure/avoid network expansion</li> <li>• Conversion of industrial park IPKW in Arnhem to energy-neutral</li> </ul>	MTSA Technopower, Dekra, Alliander, Nedstack, HAN, Hygear, Hyet, IPKW, Veolia, Kiemt	• Demcopem	Province of Gelderland, Municipality of Arnhem

## 2c. Practical projects in Mobility and Transport

Mobility and transport are a major area of application for fuel cells and hydrogen. The Netherlands has an opportunity to play a significant role in the development of buses for public transport and freight trucks running on hydrogen, as well as “special vehicles” (garbage trucks, livestock carriers, etc.). In addition, there is a huge variety of mobile equipment in ports and at airports that could be suitable for hydrogen applications. There are also opportunities for application in the maritime sector, such as sightseeing cruise boats, river ferries, car ferries, inland waterway vessels and the various types of ship used for port services (inspection, tugboats, etc.). The degree of market readiness for these applications can be described as variable, as is the commitment in the Dutch industrial sector to the development and production of these applications. This must therefore be taken into account in the priority-setting.

- Passenger cars are commercially available to a limited extent and are implementation-ready. Development and production is taking place in other countries. Upscaling requires tax advantages, with the caveat that overstimulation (as was the case with battery electric vehicles) should be avoided.
- *Light duty vehicles* (minibuses, delivery vehicles):, there are companies in the Netherlands that focusing their activities on the conversion/modification of regular vehicles for hydrogen. The car industry has not yet produced a broad range of models but is working towards this.
- *Heavy-duty vehicles* (freight trucks, garbage trucks, livestock transports, etc.): this is a promising segment because the Netherlands has a strong position with a number of manufacturers and conversion companies and a large logistics sector.
- Buses are already available in series-based manufacture. Costs can be reduced by acquisitions of larger numbers, which is the objective of a number of large European projects in which the Netherlands is among the participants. The Netherlands’ biggest bus manufacturer is involved.
- Trains are in development and manufactured abroad and can already be purchased. The market in the Netherlands is relatively small because there are few non-electrified lines.
- Ships: it is with regard to inland waterway vessels in particular that the Netherlands has a position of the leading shipper within the Rhine area. This is, in part, why hydrogen applications are particularly promising, especially in implementations involving mobile hydrogen-based energy containers and/or batteries. For this, international regulations must be adjusted; exemptions for pilot studies can be granted. For the time being, ocean shipping is more inclined to focus on liquid fuels (with regard to synthetic fuels, hydrogen can play a role in production).
- Mobile equipment: here, the application of fuel cells and hydrogen gets a boost from the development of heavy-duty vehicles and mobile energy containers for inland waterway vessels. Where at present diesel generators are used for relatively expensive onboard power generation, potentially profitable business cases based on hydrogen can be developed.
- Aviation: Like the shipping industry, the aviation industry will for the time being depend on liquid fuels. We are, however, already seeing commercially available small fuel cell systems becoming available for powering drones of up to approximately 25 kg. Further development of these will presumably make these systems suitable for light aircraft applications. This can be seen in Table 11 (research for the longer term).

A limiting factor for scaling up mobility and transport solutions is the lack of a network with national coverage of hydrogen filling station with affordable hydrogen. It is also important that these filling stations become cheaper and more robust (in terms of less maintenance). In the Netherlands, there are a number of companies that are producing complete filling stations or components thereof and at the same time have to compete with international providers. Here, a careful balance needs to be sought between space for innovation and opting for security with respect to the market introduction and upscaling of hydrogen, and likewise the “make or buy decision” needs to be made with care.

Innovations are important on components that as of now can still lead to problems, such as more precise flow measurement and equipment and procedures for calibrating and periodic approval of flow meters. There is also a great need for reliable and cost-effective methods and equipment for calculating (preferably online) impurities at the ppm and ppb level in order to guarantee the required hydrogen quality. There is also a need for innovations that can contribute to substantially reducing the investment and operational costs. There is still room for improvement on a number of components such as compressors, filling hoses, filling nozzles, high-pressure tanks and methods for filling tanks as fast as possible within the defined safety parameters. These subjects are described in the section on synergy themes (see hereinafter).

The limited resources available for a number of the larger demonstration projects for heavy transport by road and water should be bundled, with filling stations a “necessary” component of the project. Ports are particularly interesting locations because here the use of hydrogen for ships, road transport and mobile equipment can be combined. Ideally, these efforts should join up with European programmes and cooperative relationships in the Benelux region, the Northrhine-Westfalia region of Germany and the regions of northern France. Projects with a focus on road transport are driven by policy on emission-free zones for urban logistics in the 30-40 biggest municipalities in the Netherlands as of 2025. The projects for shipping draw their motivation from the Green Deal on sea shipping, inland waterways and ports. The emission-free zones and the Green Deal are products of the Climate Agreement. There are also synergies to be gained from the pilot studies for clean river ports as proposed in the National Clean Air Agreement.

Hydrogen also offers prospects for sustainability (decarbonising) in aviation, including larger aircraft. While energy storage in batteries remains insufficient for this sector, hydrogen can be a substantial improvement, both by direct use of hydrogen as hydrogen-based production of synthetic fuels. Further development of small fuel cell systems is expected to ultimately make them suitable for use in small aircraft, where we already see a few examples of fully electric aircraft using battery storage, with this technology soon to be implemented in larger aircraft. Because these are not yet practical projects for the short term, hydrogen for aviation is included in Table 11 (research for the longer term).

**Table 8 | list of innovation needs and current/potential practical projects for hydrogen-powered mobility.**

Subject	What is the innovation need?	Who is involved?	What previous/current projects?	Programmes/Funding
Zero-emissions public transport with hydrogen	<ul style="list-style-type: none"> <li>Expansion of demonstrations in daily services and achieve cost savings through upscaling and volume purchasing</li> </ul> <p><i>Practical projects:</i></p> <ul style="list-style-type: none"> <li>At present, 10 buses in use, within two years 60 via EU project JIVE2 (Groningen-Drenthe, South-Holland)</li> <li>Hydrogen-powered train in Groningen</li> </ul>	VDL, Qbuzz, Connexion, Hymove, Zuid-Holland, Groningen-Drenthe, Gelderland, Hymove, Keolis, Nedstack, HAN	<ul style="list-style-type: none"> <li>High VLO City</li> <li>3Emotion</li> <li>JIVE2 (50 buses)</li> <li>Hydrogen buses Arnhem/Apeldoorn</li> </ul>	FCH JU, plus additional DKTI
Zero-emissions logistics	<ul style="list-style-type: none"> <li>Trial projects are needed, in part to test the technology under a variety of conditions (including weather). Cost of construction/conversion of the trucks and hydrogen must come down, and more filling stations are needed.</li> </ul> <p><i>Practical projects:</i></p> <ul style="list-style-type: none"> <li>Development and demonstration of 27-ton and 40-ton distribution trucks</li> <li>Hydrogen-powered forklifts are ready for rollout, but hydrogen distribution logistics and costs remain an issue.</li> </ul>	VDL, DAF, Scania, Toyota Materials Handling, Mobihy, Still, Linde, Hymove	H2SHARE	FCH JU, Interreg, DKTI
Zero-emissions urban cleaning	<ul style="list-style-type: none"> <li>Within the logistics applications, there is a focus on garbage trucks and streetsweepers because battery-electric proves to be generally inadequate due to radius of action and charging time.</li> </ul> <p><i>Practical projects:</i></p> <ul style="list-style-type: none"> <li>Demonstration of hydrogen-powered garbage trucks in Groningen</li> </ul>	E-trucks Europe, Holthausen, various municipalities, Roteb Lease, HYGRO, GP Groot, E-trucks Europe, HVC, Nedstack, Hymove	<ul style="list-style-type: none"> <li>Life'n Hy Grab</li> <li>REVIVE</li> <li>Power to Flex</li> <li>Duwaal/W2H2</li> </ul>	Interreg, DKTI

**Table 8 | list of innovation needs and current/potential practical projects for hydrogen-powered mobility.**

Subject	What is the innovation need?	Who is involved?	What previous/current projects?	Programmes/Funding
Zero-emissions shipping	<ul style="list-style-type: none"> <li>• Need for energy source hydrogen as alternative to batteries, for reasons of energy density and speed of bunkering</li> </ul> <p><i>Practical projects:</i></p> <ul style="list-style-type: none"> <li>• Modular fuel cell-electric drive for coastal ships and inland waterway vessels in FELMAR</li> <li>• Mobile energy containers (20-foot) based on hydrogen with competitive LCOE (levelised cost of energy)</li> <li>• Onboard electricity supply with fuel cell as alternative to diesel generator</li> <li>• Mobile onshore power generation in seaports as alternative for heavy network connections</li> <li>• H2SHIP: development of a hydrogen supply chain for shipping sector (TU Delft, Port of Amsterdam, Tata Steel, others)</li> </ul>	<p>Damen Shipyards, Nedstack, MARIN, H2SHIP, PTC, TATA, BCTN, Heineken, ENGIE, ENECO, ING, Future Proof Shipping, Havenbedrijf Rotterdam, Hymove, Koedood, NPRC, Port of Amsterdam, TU Delft</p>	<ul style="list-style-type: none"> <li>• MariGreen</li> <li>• H2SHIP</li> <li>• FELMAR</li> <li>• MECs consortium</li> <li>• Lovers Amsterdam canal tours</li> </ul>	<p>Interreg</p> <p>Ministry of Economic Affairs and Climate Policy innovation funds</p>
Filling stations for mobility and transport applications	<ul style="list-style-type: none"> <li>• Expansion of refuelling facilities to demonstrate and upscale previous applications</li> </ul> <p><i>Practical projects:</i></p> <ul style="list-style-type: none"> <li>• At present, there are 4 large filling stations and several smaller ones in the Netherlands, with a number of initiatives for expansion.</li> <li>• Development of refuelling infrastructure along waterways</li> <li>• Hydrogen fuel cell for work ships that maintain the channels and canals in cities.</li> </ul>	<p>Pitpoint, Shell, WaterstofNet, Hygear, I&amp;W, ENGIE, Bovag, Beta (sector), HyET Hydrogen</p>	<ul style="list-style-type: none"> <li>• Rhoon, Helmond, Arnhem, Delfzijl, Den Haag, Alkmaar, others</li> <li>• Clean Energy Hubs (MIRT)</li> <li>• Green H2UBs</li> </ul>	<p>DKTI, European funds, tax facilities, Ministry of Economic Affairs innovation funds</p>

## 2d. Practical projects in the Built Environment

Hydrogen applications in the built environment are a realistic option. There are still many questions to be answered because as of now, it is not yet clear whether these applications will come and what form they may take. We can envision, for example, hydrogen being delivered to individual homes, or perhaps only to a community power station in combination with local heat networks at relatively low temperature levels. Another option could be a transition scenario in the form of the mixing of hydrogen into the gas distribution grid instead of moving straight to pure hydrogen because mixing can be implemented faster. With the right safety precautions mixing of up to 20-30% is already technically possible (see the text box “Hydrogen in existing gas networks”) but the current Gas Act prescribes that the hydrogen content of natural gas may not exceed 0.5%. Although hydrogen in its pure form is more valuable, until the end use applications are adequately available the decarbonised energy value can already be used by mixing. This is addressed in more detail under the synergy themes.

For the time being, there is room for research activities oriented towards the suitability of the local gas distribution network, safety aspects and the costs of the modifications needed. The results may dictate an innovation need relating to the use of hydrogen in central heating boilers, peak boilers for heat network and hybrid heat pumps, and the development of small-scale fuel cell/CHP systems.

There are a number of different projects in development that are oriented around the application of 100% hydrogen in the built environment, including Rozenburg, Stad aan 't Haringvliet and Hoogeveen. This is a challenging segment due to the direct involvement of residents/members of the public. Important considerations for residents are affordability, safety and security of supply. The government has a task in the creation of the necessary conditions: ensuring affordability by allowing costs to be socialised across all gas network users; monitoring safety and market effects; offering network managers the freedom to make targeted investments in hydrogen. If these conditions are not met, practical projects will not get off the ground and upscaling will be impossible.

The widespread application of natural gas in the Netherlands has brought a great deal of knowledge and capacity for production and installation of gas equipment that can also be used for hydrogen. The Netherlands has a number of leading companies in this area that are capable of developing and producing the equipment that will be needed. This means that the Netherlands has a strong economic position and interest here.

**Table 9 | List of innovation needs and current/potential practical projects for hydrogen for heating in the built environment.**

Subject	What is the innovation need?	Who is involved?	What previous/current projects?	Programmes/funding
Low-carbon gas for urban heating	<ul style="list-style-type: none"> <li>• Testing and demonstration of replacement of natural gas with hydrogen in existing, disconnected networks at the residential block or community level. New natural gas equipment is officially rated suitable for max. 10% hydrogen (K-band equipment 2017). For higher percentages of hydrogen, new equipment must be developed<sup>20</sup>.</li> <li>• Smart grid aspects: study synergy and interaction between electricity, hydrogen, natural gas/green gas and heat, energy storage</li> </ul> <p><i>Practical projects:</i></p> <ul style="list-style-type: none"> <li>• Convert community in Groningen to low-CO<sub>2</sub> urban heating, investigate options for hydrogen in this area</li> <li>• Hydrogreenn: hydrogen for new residential community in Hoogeveen (large-scale demonstration of central heating boilers)</li> <li>• Hydrogen in Rozenburg</li> <li>• Goeree Overflakkee: convert Stad aan 't Haringvliet to hydrogen</li> </ul>	Stedin, Remeha, Bekaert, GasTerra, Netbeheer Nederland, KIWA, ATAG, Hygear	<ul style="list-style-type: none"> <li>• Stedin “Opening offer”</li> <li>• Power-to-gas Rozenburg</li> <li>• Stedin case Goeree Overflakkee</li> <li>• Hydrogreenn</li> <li>• Foreign source of inspiration: H21 Leeds City Gate (UK); HyDeploy and HyNet</li> </ul>	<p>Hydrogen Innovation Agenda for Network Managers Ministry of Economic Affairs and Climate Policy innovation funds, Ministry of the Interior and Kingdom Relations funds</p> <p>Follow UK lead?</p>

20 H-gas equipment is tested with 23% hydrogen, but this does not mean that this equipment can handle 23% hydrogen in practice for a number of reasons, for example variations in the Wobbe index and wear-and-tear over time. In the Netherlands, G-gas equipment (L-band) is generally used; this has not been tested with 23% hydrogen.



### 3. Creating the required conditions

In order to make implementation of the practical projects described above possible and/or to test the proposed solution directions, a number of overarching themes for hydrogen are going to be of crucial importance for multiple MMIPs and missions in the short to medium term. The most effective approach will be to take these up together, to get the maximum advantages of synergy and to set up the conditions to carry out the activities as quickly and efficiently as possible. The focus is on the themes that are urgent in the short to medium term and which will be necessary for the successful performance of the practical project and/or for testing the proposed solution directions. As this suggests, parts 2 (Practical projects) and 3 (Required Conditions) cannot be seen independently of each other.

Policy, legislation and regulations, safety and infrastructure issues are good examples, as are infrastructure-related themes such as the distribution infrastructure in the built environment and hydrogen filling stations for mobility and transport. Another theme pertains to the quality requirements to be set on hydrogen. One important requirement is that stakeholders must tackle these subjects jointly and/or in proper coordination, so they get the right priority and support, that the knowledge gained is shared and innovation funds and other financial resources are used efficiently and effectively.

The highest priority goes to infrastructure issues and related themes in combination with application in end use sectors, such as gas quality, durability of components, infrastructure for industrial projects and hydrogen filling stations for mobility and transport. Other themes have, for the time being, lower priority, because the volumes of hydrogen in the energy system are not yet particularly large (underground storage), the demand is not yet leading to scarcity of supply (import chain), and the volume of offshore wind does not yet necessitate transporting the energy generated in the form of hydrogen (offshore hydrogen). It is, however, important to begin launching preparatory studies and in some cases small-scale pilot studies so that the system elements will be ready for rollout at the moment that this becomes necessary (heading into 2025-2030). A list of good example projects and subjects is given in Table 10.

**Table 10 | List of examples of the necessary conditions including innovation needs. Subjects for the short term (meaningful <2030) in black, and for the long term (meaningful > 2030) in blue.**

Subject	What is the innovation need?	Who is involved?	What previous/current projects?	Programmas / funding
Safety (risk management)	<ul style="list-style-type: none"> <li>Gaining a clear picture of the safety risks in the entire chain and the interpretation of these risks. This image is needed to arrive at nationally coordinated measures and instruments for safety aspects and risks; legislation and regulations; uniform permitting; and uniform incident response and control.</li> <li>Education and training on aspects including safe maintenance, incident response and human capital needs (education and training)</li> <li>Specific point of attention is tunnel security when blowing off hydrogen from stranded cars: there is a lack of knowledge on fluid dynamics of hydrogen in tunnels.</li> </ul>	<p>H<sub>2</sub> Platform</p> <p>IFV, Netherlands fire brigades</p>	<ul style="list-style-type: none"> <li>Hydrogen Safety Innovation Programme</li> <li>Safe Energy Transition Knowledge Platform</li> <li>Hytunnel</li> <li>QRA model for tunnels (Department of Public Works &amp; Water Management)</li> </ul>	Application pending with TKI Nieuw Gas
Legislation and regulations	<ul style="list-style-type: none"> <li>Removing impediments for hydrogen in existing legal frameworks and administrative processes, such as permitting in areas like planning, safety, installation and operation, which in many cases only allow for the use of existing technologies</li> <li>Removing impediments in REDII to effectively produce green hydrogen with grid-connected electrolysers (issue of additionality and delegated acts)</li> </ul>	NEN, WaterstofNet, NWBA, RVO	<ul style="list-style-type: none"> <li>HYLAW</li> </ul>	FCH JU
Standardisation	<ul style="list-style-type: none"> <li>Acceleration of the process for the rollout of the hydrogen economy, in part with respect to the development of new technology, of innovative systems, of the management and safety/security, as well as acceleration of market and public acceptance</li> </ul>	Dutch hydrogen standards commission	<ul style="list-style-type: none"> <li>CEN-CLC TC6 Hydrogen in energy systems</li> <li>Hazardous Materials publication series</li> </ul>	<p>Technical commissions of CEN and ISO</p> <p>PGS</p>
Gas quality	<ul style="list-style-type: none"> <li>Establishing what gas quality is needed/desired in order to coordinate end user equipment (fuel cells, turbines, gas engines and burners) and fuel quality; determination of optimal techno-economic specifications</li> <li>Consequences for the chain if different qualities are required depending on area of application, such as how and where to purify?</li> </ul>	DNV GL, KIWA, network managers	<ul style="list-style-type: none"> <li>Hy4Heat (UK)</li> </ul>	Ministry of Economic Affairs and Climate Policy innovation funds, SBIR, funding via network managers

**Table 10 | List of examples of the necessary conditions including innovation needs. Subjects for the short term (meaningful <2030) in black, and for the long term (meaningful > 2030) in blue.**

Subject	What is the innovation need?	Who is involved?	What previous/ current projects?	Programmas / funding
Use and repurposing of the natural gas infrastructure for hydrogen (including blends)	<ul style="list-style-type: none"> <li>Inventory of what natural gas lines, receiving stations, etc. are suitable for use in a hydrogen transport network, what modifications are necessary (technical, organisational, legal), what large-scale conversion would look like, and what the costs will be.</li> <li>Research into embrittlement of material (pipes, etc.) by hydrogen</li> <li>How fast is the current odourisation from the former natural gas network gone before a fuel cell can be supplied from this network (contamination)?</li> </ul> <p><i>Case studies:</i></p> <ul style="list-style-type: none"> <li>Research into reuse of gas production locations for generation and distribution of renewable electricity (e.g. Emmen)</li> <li>Development of a hydrogen network in the Delta region (Zeeland)</li> <li>Backbone: research into a hydrogen infrastructure of 10-15 GW to connect the five big industrial clusters, including storage</li> <li>Hoogeveen: reuse of distribution network of Rendo, GasTerra and Gasunie as component of Hydrogreenn (hydrogen in the built environment)</li> <li>Stad aan 't Haringvliet: similar to Hoogeveen, with Stedin</li> </ul>	Gasunie Transport Services, KVGn, EBN, TNO, Stedin, Port of Amsterdam	<ul style="list-style-type: none"> <li>Hydrogen symbiosis (Dow, Yara)</li> <li>Nexstep</li> <li>Offshore Reuse Potential for Existing Gas Infrastructure in a Hydrogen Supply Chain</li> <li>The effects of hydrogen injection in natural gas networks for the Dutch underground storages</li> </ul>	Application pending with TKI Nieuw Gas
Mixing hydrogen into natural gas grid at low percentages	<ul style="list-style-type: none"> <li>As long as precautions are taken, existing gas infrastructure can technically handle low percentages of hydrogen. Issues of concern are, for example, whether the current gas applications can handle hydrogen, and the extent to which specific non-steel components in the gas networks are resistant to hydrogen in the gas.</li> <li>Demonstration projects under controlled conditions to establish what the long-term effects on existing Dutch domestic appliances are when hydrogen is added to natural gas.</li> </ul>	DNV GL, HyET Hydrogen	<ul style="list-style-type: none"> <li>Ameland project</li> <li>JIP Industry Project HYREADY</li> <li>Energiepark Mainz (mixing up to 20%) (DE)</li> <li>Hydeploy (mixing up to 20%) (UK)</li> <li>GRHYD demo project Dunkirk, (mixing up to 20%) (FR)</li> </ul>	Follow lead of DE, UK, FR?
Purification of hydrogen from natural gas flow (demixing after mixing)	<ul style="list-style-type: none"> <li>Development of electrochemical hydrogen purification that will make it possible to purify hydrogen selectively from a gas flow</li> <li>Technology has been proven on a small scale. Goal is upscaling with cost reduction and less sensitivity to contamination by choice of different membranes.</li> </ul>	HyET Hydrogen, Hygear, TU/e	<ul style="list-style-type: none"> <li>PurifHy</li> <li>HyGrid</li> <li>Memphis</li> <li>Bio-Mates</li> </ul>	FCH JU
			HyET also active in United States DOE programme	

**Table 10 | List of examples of the necessary conditions including innovation needs. Subjects for the short term (meaningful <2030) in black, and for the long term (meaningful > 2030) in blue.**

Subject	What is the innovation need?	Who is involved?	What previous/ current projects?	Programmas / funding
Mixing hydrogen in natural gas at higher percentages (up to 100%)	<ul style="list-style-type: none"> <li>When mixing hydrogen at higher percentages or running pure hydrogen through the gas lines, the question becomes whether the seals and connectors are at this point suitable and whether noise effects may arise due to the higher volume flow with the energy supplied remaining the same.</li> <li>In the UK, research is done into the risks (including ignition risks) of and in the event of leakage in homes and distribution networks when pure hydrogen is used. The goal is to gain insight into how safety aspects and risks in homes and during distribution compare to those of natural gas.</li> <li>Because the Dutch and British distribution networks and the infrastructure in homes differ, such tests must also be carried out for the homes and gas distribution networks in the Dutch situation. Next step is to gain practical experience with pilots and large-scale demonstrations.</li> </ul>	DNV GL	<ul style="list-style-type: none"> <li>H21: Hydrogen Distribution, FBM: Measuring and billing new gases,</li> <li>H100: Hydrogen Distribution (DNV GL)</li> </ul> HYPOS:H <sub>2</sub> -NETZ, MITNETZ Gas, Wasserstoff Dorf	
Filling stations for hydrogen	<ul style="list-style-type: none"> <li>Flow meters for hydrogen with the right range and precision for use at filling stations</li> <li>Optimise the layout of hydrogen filling stations, taking into account the hydrogen phase (gas vs. liquid), dimensions and pressure and compression table</li> <li>Specific properties of the locally generated hydrogen</li> <li>Standardisation of the filling pressure and shape of nozzle</li> <li>Options for modular or mobile hydrogen filling stations to counteract understaffing during the introduction phase of FCEV</li> <li>Lowering of investment costs for a hydrogen filling station</li> <li>High-speed filling for trucks (10 kg/min)</li> <li>Due to the lack of space at filling stations, particularly in the built environment, underground storage and hydrogen tanks must be evaluated Various projects performed in the recent past</li> <li>Connection of hydrogen in cylinders so equipment does not need to go on the road to a refuelling station, must be assessed and evaluated in more detail.</li> </ul>	Pitpoint, Shell, WaterstofNet, Hygear, I&W, ENGIE, Bovag, Beta (sector), HyET Hydrogen, Holthausen	Various projects performed in the recent past must be assessed and evaluated in more detail.	

**Table 10 | List of examples of the necessary conditions including innovation needs. Subjects for the short term (meaningful <2030) in black, and for the long term (meaningful > 2030) in blue.**

Subject	What is the innovation need?	Who is involved?	What previous/current projects?	Programmas / funding
Hydrogen from offshore wind	<ul style="list-style-type: none"> <li>Research into synergy between offshore energy infrastructures, incorporation of offshore wind energy into the energy system, reuse of platforms for hydrogen production, storage and distribution</li> <li>Research into the feasibility of combined tenders for offshore wind and electrolysis capacity</li> </ul> <p><i>Case studies:</i></p> <ul style="list-style-type: none"> <li>IJmuiden Ver and subsequent parks: Research into the best way to bring energy from IJmuiden Ver and subsequent areas to land</li> <li>North Sea Wind Power Hub: research into the options for energy islands at Doggersbank</li> <li>Preparatory pilot for testing offshore hydrogen production.</li> </ul>	KVGN, Gasunie, EBN, TNO, various universities of applied sciences, HAN	<ul style="list-style-type: none"> <li>Power-to-Hydrogen IJmuiden Ver</li> <li>North Sea Energy Programme</li> <li>Hydrogen on offshore platforms</li> <li>Offshore reuse potential for existing gas infrastructure in hydrogen supply chain</li> <li>3P2GO</li> </ul>	
Development of import chain for hydrogen	<ul style="list-style-type: none"> <li>Detailed feasibility study, potentially followed up with a design study for import chain for hydrogen with attention to source, method of transport (i.e. liquid hydrogen tanker ships, ammonia, MCH/ LOHC), transport means needed, receiving and storage installations, gasification to pipelines or breakbulk, trading platforms, etc.</li> </ul>	VOPAK, others	<ul style="list-style-type: none"> <li>Analogy with LNG import chain, including the GATE import terminal at the Maasvlakte</li> <li>HYCHAIN: projects by broad ISPT consortium</li> </ul>	
Underground storage of hydrogen in salt caverns	<ul style="list-style-type: none"> <li>Inventory of suitable salt caverns in northern and eastern regions of the Netherlands, including infrastructure, such as salt industry, water, natural gas pipelines and high-voltage network</li> </ul> <p><i>Case study:</i></p> <ul style="list-style-type: none"> <li>Energystock Zuidwending. A follow-up project may be making a salt cavern physically suitable for hydrogen storage</li> </ul>	Gasunie/ Energystock, EBN, Nouryon / AkzoNobel, ECN part of TNO, Shell	<ul style="list-style-type: none"> <li>HYUNDER</li> <li>HYSTOCK</li> <li>OPVIS 1 &amp; 2</li> <li>Large-Scale Energy Storage in Salt Caverns and Depleted Gas Fields</li> </ul> <p>Initiative in framework of German HYPOS consortium</p>	Ministry of Economic Affairs and Climate Policy innovation funds

**Table 10 | List of examples of the necessary conditions including innovation needs. Subjects for the short term (meaningful <2030) in black, and for the long term (meaningful > 2030) in blue.**

Subject	What is the innovation need?	Who is involved?	What previous/current projects?	Programmas / funding
Underground storage of hydrogen in gas fields	<ul style="list-style-type: none"> <li>Overriding question is the extent to which large-scale storage of hydrogen and gas fields will be necessary and desired.</li> <li>Research into the options requires answering questions such as: could chemical reactions occur between hydrogen and the reservoir? How much hydrogen loss would the reactions cause? What is the microbial activity in each gas field in the Netherlands? What is the sealing effectiveness and corrosion resistance to hydrogen of the materials used in the gas fields? How much cushion gas would be needed?</li> </ul>	Gasunie, EBN, NOGEP, TNO	<ul style="list-style-type: none"> <li>The effects of hydrogen injection in natural gas networks for the Dutch underground storages (DBI)</li> </ul>	Ministry of Economic Affairs and Climate Policy/RVO  Follow lead of project in Austria?
Integration of mobility and built environment	<ul style="list-style-type: none"> <li>Options to use fuel-cell vehicles and applications in the built environment to create flexibility, storage and peak capacity (e.g. smart grid projects)</li> </ul>	Nissan, TU Delft, Lectorenplatform, HAN	<ul style="list-style-type: none"> <li>Analogy with Vehicle-to-Grid battery-electric car projects</li> </ul>	Ministry of Economic Affairs and Climate Policy innovation funds

#### 4. Research for the longer term

This section is devoted to the research and development for solutions for the longer-term solutions that may be important going into 2030 and beyond, and/or the robust elements for achieving the energy transition approaching 2050. This pertains primarily to research and development in the lower TRLs and topics that may be relevant in the future (towards 2050) as sustainability options. The most important conditions and questions are:

- Solutions must make a significant contribution to the energy transition in the Netherlands in the future, such as sustainable synthetic fuels and chemistry (sustainable hydrocarbons).
- Knowledge institutions and companies active in this area must have a strong starting position (demonstrable, from international perspective) in the area in question in order to be able to make an impact and qualify for financing (particularly applicable for NWO).

For these themes, attention must be given at an early stage to industrialisation, that is the upscaling of the production of components and systems to an industrial scale. In this development and the process of industrialisation, the principles of circularity (reuse and recycling) must be taken into account. The subjects under this aspect of the approach are related to a broad spectrum of various MMIPs. In many cases this refers to long-term research.

The ECCM (Electro-Chemical Conversion & Materials) Commission (see text box) brings the medium and long-term research needed under this aspect as well as the communities behind them together into a single broad programme.

### **ECCM**

The advisory commission for Electro-Chemical Conversion & Materials (ECCM) advises the Dutch government on making the transition to a CO<sub>2</sub>-neutral industrial sector based on intermittent sustainable energy generation, storage and conversion. The commission is supported in its mission by the top sectors HTSM, Energy and Chemistry, the Ministry of Economic Affairs and Climate Policy, the Ministry of Education, Culture and Science, NWO and TNO. ECCM integrates the short and medium-term opportunities in the field of hydrogen (oriented towards system integration and cost price reduction) and longer-term opportunities in the field of electrochemistry. The commission is convinced that hydrogen can only be advanced through an integrated approach with system integration in cooperation with the electricity sector. Electrochemical conversion and storage (in industry) and the materials science knowledge these will require are seen by the commission as key technology.

ECCM is the cross-sector theme for achieving this transition goal. The commission coordinates efforts in the area of ECCM at the national level by initiating new cooperation initiatives and by adapting initiatives that fit within the advisory report the commission has published<sup>21</sup>. From a national perspective, the Commission advises the government on the efforts that will be needed for cooperation across the entire innovation chain. In addition, the commission is building an ECCM community of knowledge institutions, companies, governmental institutions and NGOs, in part by organising ECCM conferences. In 2019, an ECCM graduate school was launched to further expand the ECCM community in the Netherlands. The ECCM community brings together existing communities and sectors (HTSM, Energy, Chemistry): industry, TKI's, e-Refinery-TUD, MCEC-UU, Solar Fuels-DIFFER, ARC CBBC, IRES-TU/e, ISPT, VoltaChem, etc.<sup>22</sup>

Table 11 presents a number of examples of themes, programmes and projects in this area. There is also a need for fundamental research on various hydrogen themes. The Netherlands has a great deal of expertise in these areas available, as well as research facilities for them. Annex 1 provides a list of relevant research institutions.

Electrolysis is the key technology for sustainable hydrogen production. The innovation needs in this area are elaborated in more detail in Annex 2.

<sup>21</sup> <https://www.co2neutraalin2050.nl/docs/reports/advies-elektrochemische-conversie-materialen-eccm-september-2017.pdf>

<sup>22</sup> More information: [www.co2neutraalin2050.nl](http://www.co2neutraalin2050.nl).

**Table 11 | List of innovation needs, programmes and projects in the chain, from production to end use of hydrogen. R&D for the short term (meaningful <2030) in black, R&D for the long term (meaningful > 2030) in blue.**

Subject	What is the innovation need?	Who is involved?	What previous/current projects?	Programmes/funding
<b>Hydrogen production – electrochemical</b>				
Low-temperature electrolysis: alkaline, Proton Exchange (PEM) and Anion Exchange Membrane (AEM)	<ul style="list-style-type: none"> <li>Alkaline and PEM electrolysis are already at TRL 7-9 and are moving towards demonstration, but there is a need to further investigate and develop new better components starting from low TRL, such as more stable, more active and cheaper membranes, electrodes and catalysts.</li> <li>Development of more knowledge of and insight into the degradation behaviour and lifetime of proton exchange membranes and their associated maintenance costs.</li> <li>Development of a scalable version of the AEM electrolyser that produces hydrogen with a much lower capital-intensity and higher efficiency than currently existing electrolysers.</li> </ul>	Hydron, ECN part of TNO, Siemens, ITM, Hydrogenics, Hygear, Dutch Electrolyser 2.0 consortium, MTSA Technopower	<ul style="list-style-type: none"> <li>NextGenH<sub>2</sub></li> <li>ELECTRE (test infrastructure and test protocols)</li> <li>Dutch Electrolyser 2.0</li> </ul>	Ministry of Economic Affairs and Climate Policy innovation funds, Voltachem, NWO
Electrotechnical issues and BOP	<ul style="list-style-type: none"> <li>E.g. performance and costs of transformers and rectifiers</li> <li>Cost reduction and technical optimisation of BOP (Balance of Plant).</li> <li>Can we intensify processes, for example, with pressure, temperature?</li> </ul>	TU/e, MTSA Technopower		
High-temperature electrolysis: Solid Oxide Electrolysis (SOE) for applications such as: co-electrolyse of CO <sub>2</sub> and water	<ul style="list-style-type: none"> <li>Development of more stable electrodes with suppression of aging effects (TRL 5)</li> <li>Demonstration of adequate lifetime of electrolysis in general (and high-temperature electrolysis specifically)</li> <li>How can we select complex oxide materials for specific properties and applications?</li> </ul>	Hygear, ECN part of TNO, DIFFER		



**Table 11 | List of innovation needs, programmes and projects in the chain, from production to end use of hydrogen. R&D for the short term (meaningful <2030) in black, R&D for the long term (meaningful > 2030) in blue.**

Subject	What is the innovation need?	Who is involved?	What previous/current projects?	Programmes/funding
Materials and scaling issues for electrolysers	<ul style="list-style-type: none"> <li>How do we make high-quality, pinhole-free thin films and (free-standing) membranes on a large scale and in large sizes?</li> <li>How do we transfer experiments at the lab scale to large-scale and mass production? Scale for size or quantity?</li> <li>How can electrolysis be performed on a large scale? What would a demonstrator look like? How to deal with intermittent electricity production?</li> <li>How do we lower costs through research of material use and the production process of the electrolysis components and systems?</li> </ul>	DIFFER et al.		
Plasma water splitting	<ul style="list-style-type: none"> <li>Proof-of-concept is proven (TRL <math>\leq 3</math>), the plasma reactor and the gas separation linked to it must be further developed in order to arrive at a practically applicable system. Goals are increasing energy yield from 50% to 80%, and cost reductions.</li> <li>Use of semiconductor technology is investigated as a replacement for current microwaves</li> <li>Also option to split water and CO<sub>2</sub> into syngas as a step towards synthesis of hydrocarbons</li> </ul>	DIFFER, TU/e, UT, Ampleon, Alliander, Gasunie, Hygear	<ul style="list-style-type: none"> <li>HyPlasma</li> <li>Plasma Power-to-Gas</li> <li>Solid State Plasma</li> <li>SynPlasma</li> </ul>	NWO, STW, TKI HTSM
Photocatalytic water splitting (solar fuels)	<ul style="list-style-type: none"> <li>Photocatalytic water splitting with sunlight (TRL4/5)</li> <li>Development of a photo-electrochemical demonstrator with high yield and low degradation based on earth-abundant materials</li> </ul>	WUR, TU/e, RU Leiden, University of Amsterdam, Solliance, DIFFER, Hygear	<ul style="list-style-type: none"> <li>Vloeibaar Zonlicht</li> <li>FotoH<sub>2</sub></li> <li>Alliantie Energie Opslag (formerly Fuelliance)</li> <li>Sunrise</li> </ul>	
Combined electricity storage and water electrolysis (Battolyser)	<ul style="list-style-type: none"> <li>Development of a combination of battery and electrolyser that first charges the battery section and then switches to hydrogen production. After a proof of concept at the lab scale, the goal is to demonstrate a module of 20 kW, after which will follow a test at the industrial scale of several MW at an industrial company.</li> </ul>	TU Delft, Vattenfall, BASF, Ørsted, Allego, Proton Ventures	<ul style="list-style-type: none"> <li>Battolyser</li> </ul>	STW

**Table 11 | List of innovation needs, programmes and projects in the chain, from production to end use of hydrogen. R&D for the short term (meaningful <2030) in black, R&D for the long term (meaningful > 2030) in blue.**

Subject	What is the innovation need?	Who is involved?	What previous/current projects?	Programmes/funding
Combination of electrolysis with other processes/products	<ul style="list-style-type: none"> <li>How do we combine H<sub>2</sub> with CO<sub>2</sub> or N<sub>2</sub> in a single device for products with a higher added value?</li> <li>How do we integrate electrochemical, plasmonic or plasma processes with thermal processes?</li> <li>Adjustment of electrolysis processes for the production of ozone (O<sub>3</sub>) that can be used as a raw material or as a heat source.</li> </ul>	DIFFER  O3 Systems Technology	• KEROGREEN	NWO, STW
<b>Hydrogen production – thermochemical</b>				
Selectively splitting natural gas into hydrogen and a valuable solid carbon production (pyrolysis or new type of reforming with focus on natural gas; possible transition option)	<ul style="list-style-type: none"> <li>Screening, selection and possible piloting and demonstrating of electrically driven pyrolysis processes (e.g. plasma-chemical and molten metal reforming) for splitting small hydrocarbons such as methane into natural gas and exhaust gases from refineries and hydrocarbon cracking units into hydrogen and solid carbon.</li> <li>What materials can be designed and used to separate gas flows in CO<sub>2</sub>-neutral hydrogen production processes?</li> </ul>	Brightlands / Chemelot ECN part of TNO	Interest in demonstrating technology from Monolith (VS)  Knowledge project, molten-metal reforming ECN part of TNO	
Supercritical water gasification (wet waste and biomass residual flows)	<ul style="list-style-type: none"> <li>This option may be of greater value for production of syngas than for hydrogen alone.</li> <li>Upscaling to larger units is needed (towards 10-100 MW in 2030) on the basis of wet organic residual flows from industry. Additionally, demonstration with sewer sludge and biogenic flows with high ash and salt content such as manure, roadside grass and seaweed (challenges relating to charring and scaling).</li> </ul>	SCW Systems, Gasunie		Private equity, Gasunie, PFZW, RVO

**Table 11 | List of innovation needs, programmes and projects in the chain, from production to end use of hydrogen. R&D for the short term (meaningful <2030) in black, R&D for the long term (meaningful > 2030) in blue.**

Subject	What is the innovation need?	Who is involved?	What previous/ current projects?	Programmes/ funding
<b>Infrastructure for hydrogen</b>				
Post-treatment and odorisation	<ul style="list-style-type: none"> <li>• New technology and/or improvement of existing technology for purification of hydrogen to the desired quality for various applications (PSA, cryogenics, membranes, etc.) at the lowest possible costs.</li> <li>• Methods and equipment/sensors for monitoring hydrogen quality and the level of critical contaminations (CO, sulphur compounds) in hydrogen in relation to fuel cell applications.</li> <li>• Possible odorants (odorisation) that could be added to hydrogen to help detect leaks without having a negative impact on end use applications with fuel cells.</li> <li>• Determine where odorisation is necessary: only in built environment or also industrial and mobility applications?</li> </ul>	Kiwa, DNV GL		
Storage systems (underground storage in Table 10)	<ul style="list-style-type: none"> <li>• Research into the necessary scope of storage with a view to seasonal effects, and the impact of dynamic operations from these storages (short-term balancing of supply and demand).</li> <li>• Systems for large-scale storage of hydrogen both above ground and underground (tanks for storage of compressed or liquid hydrogen).</li> <li>• New materials and production processes for lighter and cheaper high-pressure tanks (&gt;800 bar) for vehicles, by which tanks should be manufacturable in various shapes for effective and safe application in vehicles.</li> <li>• Optimisation of the tank geometry, reduction of components and integration of valves and pressure regulators in the tanks used in vehicles.</li> <li>• Small-scale storage other than at high pressure, e.g. liquid and cryo-compressed (super critical), powder, formic acid, liquid organic hydrogen carriers (LOHC).</li> </ul>	ALE/low8, H2Fuel Systems, Hygear, Hydrogenious /JP-Energiesystemen, DENS, Bam Groep, TU/e		

**Table 11 | List of innovation needs, programmes and projects in the chain, from production to end use of hydrogen. R&D for the short term (meaningful <2030) in black, R&D for the long term (meaningful > 2030) in blue.**

Subject	What is the innovation need?	Who is involved?	What previous/current projects?	Programmes/funding
Transmission/transport and distribution per pipeline	<ul style="list-style-type: none"> <li>• Increasing the pressure during transport to reduce the amount of labour needed for compression at filling stations.</li> <li>• Suitability of pipeline materials and components in natural gas transport and distribution networks for mixtures of natural gas/biomethane and hydrogen, or for pure hydrogen.</li> <li>• Flow meters for variable gas composition and/or pure hydrogen in the built environment.</li> <li>• <b>Research into the effects of higher transport speeds of hydrogen gas in pipelines with regard to potential noise nuisance and noise effects.</b></li> <li>• <b>Improvement of the efficiency and reliability of compressors, both conventional compressors and new types such as ionic liquid compressors and electrochemical compressors.</b></li> </ul>	Resato, Shell, HyET	KIWA has produced an inventory for Netbeheer Nederland of what will be necessary to adjust/upgrade the gas network to be a fully sustainable gas network, with an emphasis on hydrogen (alongside biogas/green gas).	
Other transport and distribution	<ul style="list-style-type: none"> <li>• Increase of the capacity of tube trailers for transport of hydrogen over 900kg</li> <li>• Continued development and upscaling of technologies and concepts for production (reduction of energy consumption by half), storage and transport of liquid hydrogen.</li> <li>• <b>Development of new materials for transport, distribution and storage of liquid hydrogen (below -253 °C).</b></li> </ul>			
<b>Use/application – fuel cells</b>				
Fuel cells	<ul style="list-style-type: none"> <li>• Gain better insight into degradation mechanisms to further improve the lifetime of fuel cells, for example, through focused development of new membranes.</li> <li>• Better and different catalysts in order to further reduce the use of Platinum Group Metals (PGM).</li> </ul>	Nedstack		FCH JU

**Table 11 | List of innovation needs, programmes and projects in the chain, from production to end use of hydrogen. R&D for the short term (meaningful <2030) in black, R&D for the long term (meaningful > 2030) in blue.**

Subject	What is the innovation need?	Who is involved?	What previous/current projects?	Programmes/funding
Fuel cell systems	<ul style="list-style-type: none"> <li>Fuel cell systems for specific applications such as buses, trucks, specialty vehicles, mobile vehicles and generators.</li> <li>Fuel cell systems for the production of electricity in Power-to-Power and other renewable energy applications.</li> <li>Development of specific “balance of plant” components coordinated to the requirements dictated by fuel cell systems in order to improve efficiency and reliability of systems.</li> <li>Industrialisation of the production of fuel cell components, stacks and systems; automation of large-scale and reproducible production within narrow product tolerances.</li> </ul>	Nedstack, HAN, MTSA Technopower, Hymove	<ul style="list-style-type: none"> <li>Demcopem</li> <li>Hydrova</li> <li>Hymove bus</li> </ul>	FCH JU
<b>Use/application – thermal systems for high percentages of hydrogen in natural gas (up to 100%)</b>				
Industrial burners for various processes	<ul style="list-style-type: none"> <li>Development and demonstration of flexible burner technology that functions from 100% natural gas to 100% hydrogen. This must be usable for direct heating processes such as steam and hot water boilers (~100 °C), drying, chemical conversion and distillation (100-600 °C), as well as ovens and stoves (&gt; 600 °C). The objective is optimal combustion with minimum NO<sub>x</sub> emissions.</li> <li>In the case of direct heating, the need is to maintain or improve the product quality (glass, stone) when using hydrogen as fuel.</li> <li>Development of combustion systems for burning H<sub>2</sub>/O<sub>2</sub> (oxyfuel) mixtures so the oxygen from electrolysis can be utilised and NO<sub>x</sub> emissions can be avoided.</li> </ul>	DNV GL, Zantingh, Stork Thermeq	<ul style="list-style-type: none"> <li>Varigas</li> <li>Follow-up project in preparation</li> </ul>	SBIR TKI Nieuw Gas
Burners for central heating boilers, H <sub>2</sub> peak boilers for sustainable heat networks and hybrid water pumps		Follow-up project with 25 market parties		
Burners for gas turbines	<ul style="list-style-type: none"> <li>Development of retrofit packages to make gas turbines suitable for high percentages of hydrogen (up to 100%)</li> </ul>	Ansaldo Thomassen, TUD, others	<ul style="list-style-type: none"> <li>High Hydrogen Gas Turbine Retrofit</li> </ul>	TKI Nieuw Gas

**Table 11 | List of innovation needs, programmes and projects in the chain, from production to end use of hydrogen. R&D for the short term (meaningful <2030) in black, R&D for the long term (meaningful > 2030) in blue.**

Subject	What is the innovation need?	Who is involved?	What previous/ current projects?	Programmes/ funding
Gas engines	<ul style="list-style-type: none"> <li>Development of retrofit packages to make gas engines robust for higher percentages of hydrogen in natural gas without the hydrogen mixing resulting in knocking engines and exceeding statutory NO<sub>x</sub> emissions requirements</li> <li>Development of gas engines for pure hydrogen.</li> </ul>	DNV-GL	<ul style="list-style-type: none"> <li>Hydeploy (mixing up to 20%) (UK)</li> </ul>	
Hydrogen for regeneration of metal powder as energy source	<ul style="list-style-type: none"> <li>Development of industrial burner for metal powder that combusts into metal oxide and is regenerated with hydrogen. This allows metal powder to be used as a medium for energy storage. It can be used as a replacement for gas, mineral oil or coal in combustion processes.</li> </ul> <p><i>Practical project:</i></p> <ul style="list-style-type: none"> <li>Construction of a 100 kW demonstration system to be used to supply steam in an industrial environment.</li> </ul>	EM Group, Romico, HeatPower, Swinkels Family Brewers, Nyrstar, Uniper, TU/e, Enpuls	<ul style="list-style-type: none"> <li>Metal Power 20 kW</li> </ul>	Province of Noord-Brabant
<b>Use/application – aviation</b>				
Application of hydrogen for decarbonisation of aviation	<ul style="list-style-type: none"> <li>Hydrogen storage under high pressure and cryogenically, risk/safety analysis for onboard storage, analysis of materials science consequences (e.g. metal embrittlement, effects on composites).</li> <li>Continued development of lightweight fuel cell systems (cooling systems/ concepts, higher voltages and outputs).</li> <li>Regulations (e.g. certification requirements) and guidelines for the use of hydrogen, starting with drones.</li> <li>Analysis of infrastructure required for application of hydrogen in aviation; drafting roadmaps.</li> </ul>	NLR, Drone Hub, GAE, Vliegend.nl, Nouryon, AirLiquide, GKN/ Fokker, TU Delft	<ul style="list-style-type: none"> <li>Hydrogen drones</li> <li>Phoenix motorglider with liquid hydrogen</li> <li>E-volution project</li> <li>Novel Aircraft Configurations and Scaled Flight Testing Instrumentation (NOVAIR)</li> </ul>	EU Clean Sky 2 programme

**Table 11 | List of innovation needs, programmes and projects in the chain, from production to end use of hydrogen. R&D for the short term (meaningful <2030) in black, R&D for the long term (meaningful > 2030) in blue.**

Subject	What is the innovation need?	Who is involved?	What previous/current projects?	Programmes/funding
<b>Fundamental research</b>				
<b>Mechanisms &amp; Processes</b> <ul style="list-style-type: none"> <li>• Chemistry</li> <li>• Physics</li> <li>• Materials</li> <li>• Bioengineering</li> </ul>	<ul style="list-style-type: none"> <li>• What are the processes taking place on surfaces, interfaces and bulk? What are the intermediate products? How to measure intermediate products? How to measure operandi? How to identify reaction mechanisms?</li> <li>• What plentiful, non-toxic, cheap materials are the best for specific applications (high performance, efficiency, yield, etc.)?</li> <li>• What are the most efficient means for getting the best performance out of chemical/electrochemical processes? Light? Plasmons? Plasmas? Other stimulations? Can we drive processes using these stimulations? Can we selectively control processes?</li> <li>• Can we apply tools from other fields, such as nanophotonic tools, to hydrogen production, conversion or storage?</li> <li>• How stable are the processes? Are industrial lifetimes possible in theory? What is the strategy for achieving long-term stability?</li> </ul>	Universities, scientific institutions, TNO, ECN part of TNO, other research institutions	<ul style="list-style-type: none"> <li>• NWO/FOM programme CO<sub>2</sub> neutral fuel</li> <li>• NWO programme Solar to products</li> </ul>	NWO, STW
<b>Materials &amp; Components</b> <ul style="list-style-type: none"> <li>• Synthesis and Manufacture</li> <li>• Characterisation: structural and functional</li> </ul>	<ul style="list-style-type: none"> <li>• What are the best materials for the production, conversion and storage of hydrogen? What classes of materials and stoichiometry are the most promising? Is nanostructuring the solution? How stable are the materials in the long term?</li> <li>• How do we manufacture these materials? Can we use tools from other fields, such as the semiconductor industry?</li> <li>• How can we scale the material selection by component? Scale for size or quantity? What are the limitations of the component? How do we integrate it into a system?</li> </ul>	Universities, scientific institutions, TNO, ECN part of TNO, other research institutions	<ul style="list-style-type: none"> <li>• KEROGREEN</li> <li>• Programma Materials for sustainability</li> </ul>	NWO, STW

In many areas, especially electrolysis, fuel cells and high-pressure tanks, it should be kept in mind that at the early stage of any development, “manufacturability” and standardisation of the technology and system must be principal considerations so that ultimately large quantities of standardised products of high quality can be produced at sufficiently low cost. The industrialisation of the production of electrolysis components, stacks and systems and the automation of large-scale serial production within narrow product tolerances are areas in which the Netherlands is internationally strong (as attested to by ASML, VDL and others).

One question is what the preferred size of electrolysis units would be to meet the demand for hydrogen for specific applications. There must also be attention to efficient raw material use, reuse and recycling in the development of new technology and the design of new product (thematic approach in the context of the Mission Circular Economy). One example is the development of a technical and economic model oriented towards the reuse of PEM electrolysis and fuel cell stacks, which will also have a positive impact on the total cost price of hydrogen.

## 5. Supporting and accompanying activities

Under this component are the activities that can create the right context for the capacity to develop and upscale hydrogen technologies. These subjects are located at the interface between innovation and implementation; some, in fact, do not involve innovation at all. Themes that may play a role here are information campaigns, communication, education and training, etc. To take one example, a major target group in the built environment is the technicians, whose advice the consumer generally trusts. This means that it is essential to make them familiar with hydrogen technology and ensure that they understand it. Chapter 5 covers a number of other themes relating to this.

Relevant activities and questions are:

- Activities must focus on broad, solvable problems in which the relevant stakeholders are involved and willing to find solutions, such as standardisation, stimulating policy instruments, and the discussion on security of supply (and self-sufficiency of supply).
- Alongside techno-economic aspects, it is important to ensure that overarching aspects across projects (as identified below) are integrated as fully as possible within projects. This means that embedding through the practical projects under 2 is desirable, because this creates the optimal opportunities for developing and testing solutions in practice. A good approach to this embedding is to consolidate, analyse and evaluate all practical and research projects and to redistribute the information for successful implementation. This also means monitoring of developments abroad and facilitating knowledge exchange and cooperation.
- There must be a consensus that these themes are urgent, so steps forward can be taken actively and jointly.

Table 12 highlights a number of themes. These are themes that generally require ongoing attention, and so there is no obvious prioritisation for them.

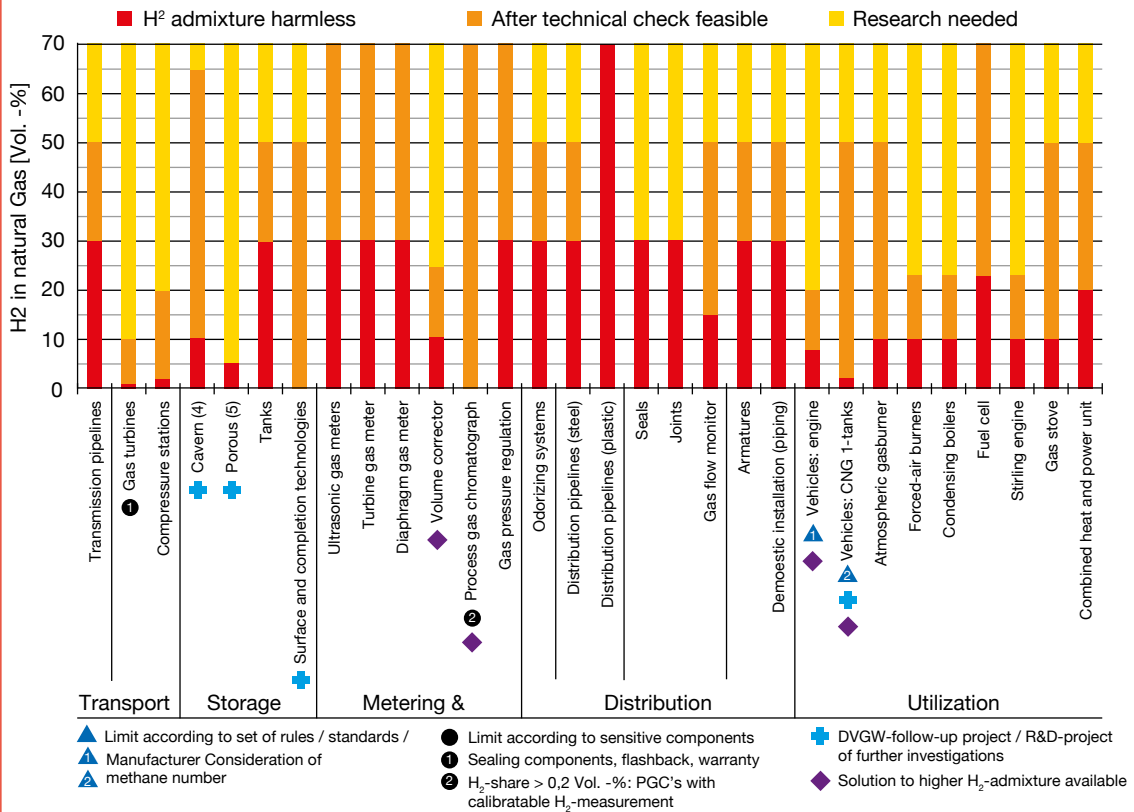


The programmatic approach must devote attention to these themes in order to establish a collective knowledge level in the developing sector. The recommendation is to reserve a portion of the available innovation budget (5-10%) for joint projects on these themes. Having norms and standards ready in time is a requirement for effective functioning of the integrated hydrogen system at the international level. NPH2IGO (the standardisation platform for hydrogen in industry and the built environment) is conducting a broad inventory of the subjects for standardisation and pre-standardisation research needs relating to hydrogen (see Annex D).

### Hydrogen in existing gas networks

The KIWA report “Future-proof gas distribution networks” (2018) describes how hydrogen could be transported in existing gas networks. This does set certain requirements on the maximum value of certain gas components. This would also involve certain other modifications, such as to gas meters, because the volume difference and flow rate of hydrogen and hydrogen-natural gas mixtures differs from that of natural gas. This flow rate can also have repercussions in terms of noise in the network. DVGW/DBI conducted research (2018) into the options for mixing hydrogen into the existing gas networks, and the percentages to which this could be possible. Their results are outlined below.

**Figure 5 | Suitability of and research needs for hydrogen/natural gas mixtures in relation to various options.**



**Table 12 | List of supporting and accompanying activities oriented towards removing the impediments and creating required conditions.**

Subject	What is the innovation need?	Who is involved?	What previous/current projects?	Programmes/funding
Safety (risk management)	<ul style="list-style-type: none"> <li>• Gaining a clear picture of the safety risks in the entire chain and the interpretation of these risks. This image is needed to arrive at nationally coordinated measures and instruments for safety aspects and risks; legislation and regulations; uniform permitting; and uniform incident response and control.</li> <li>• Education and training on aspects including safe maintenance, incident response and human capital needs (education and training)</li> <li>• Specific point of attention is tunnel security when blowing off hydrogen from stranded cars: there is a lack of knowledge on fluid dynamics of hydrogen in tunnels.</li> </ul>	<p>H<sub>2</sub>Platform</p> <p>IFV, Netherlands fire brigades</p>	<ul style="list-style-type: none"> <li>• Hydrogen Safety Innovation Programme</li> <li>• Safe Energy Transition Knowledge Platform</li> <li>• Hytunnel</li> <li>• QRA model for tunnels (Department of Public Works and Water Management)</li> </ul>	Application pending with TKI Nieuw Gas
Legislation and regulations	<ul style="list-style-type: none"> <li>• Removing impediments for hydrogen in existing legal frameworks and administrative processes, such as permitting in areas like planning, safety, installation and operation, which in many cases only allow for the use of existing technologies</li> <li>• Removing impediments in REDII to effectively produce green hydrogen with grid-connected electrolysers (issue of additionality and delegated acts)</li> </ul>	NEN, WaterstofNet, NWBA, RVO	• HYLAW	FCH JU
Standardisation	<ul style="list-style-type: none"> <li>• Acceleration of the process for the rollout of the hydrogen economy, in part with respect to the development of new technology, of innovative systems, of the management and the safety/security, as well as acceleration of market and public acceptance</li> </ul>	Dutch hydrogen standards commission	<ul style="list-style-type: none"> <li>• CEN-CLC TC6 Hydrogen in energy systems</li> <li>• Hazardous Materials publication series (PGS)</li> </ul>	<p>Technical commissions of CEN and ISO</p> <p>PGS</p>

**Table 12 | List of supporting and accompanying activities oriented towards removing the impediments and creating required conditions.**

Subject	What is the innovation need?	Who is involved?	What previous/current projects?	Programmes/funding
Measurement methods	<ul style="list-style-type: none"> <li>Development and establishment of standards for the measurement of quantity and quality of hydrogen, e.g. at dispensing by filling stations</li> </ul>	VSL, Shell, NEN	<ul style="list-style-type: none"> <li>MetroHyVe</li> </ul>	FCH JU
Education and training	<ul style="list-style-type: none"> <li>Incorporation of hydrogen into education and training</li> <li>Upon the transition to sustainable gases, taking adequate education of technical and other personnel into account, and launching a campaign for public awareness of the different ways that sustainable gases behave</li> </ul>	KIWA	<ul style="list-style-type: none"> <li>Gas 2.0 Energy college hydrogen programme for students and professionals</li> </ul>	
Certification of sustainable hydrogen	<ul style="list-style-type: none"> <li>Development and testing of EU-wide Guarantee of Origin system for green and low-carbon hydrogen</li> <li>Transposition RED II: influence detailing of delegated acts that must regulate the loose ends and offer opportunities for improving the required conditions for green hydrogen</li> </ul>	ECN part of TNO, industry	<ul style="list-style-type: none"> <li>CertifHy</li> </ul>	FCH JU
Information provision and campaigns	<ul style="list-style-type: none"> <li>Information provision and information campaigns for awareness-raising, and creation of understanding, base of support and societal acceptance</li> <li>Can we predict the societal acceptance of specific solutions?</li> <li>Development of tools that enable parties to easily compare hydrogen against other sustainability options</li> </ul>	H <sub>2</sub> Platform, NWBA (Netherlands Hydrogen and Fuel Cell Association), RVO, Milieucentraal	<ul style="list-style-type: none"> <li>The world of hydrogen</li> <li>The Hydrogen Challenge</li> </ul>	



# Chapter 5

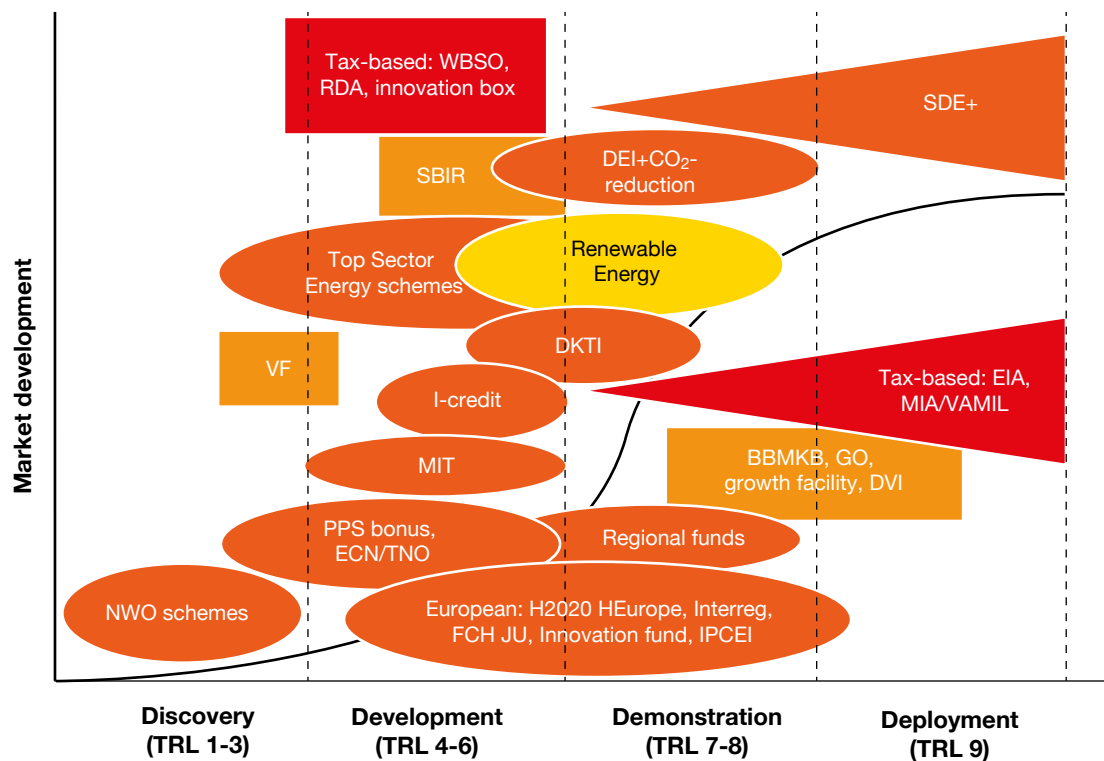
# 5 | Non-technological themes in the programmatic approach for hydrogen

This chapter deals with a number of non-technological themes that will be relevant and determinant for the successful development and upscaling of hydrogen technologies.

## Policy-based support for hydrogen

One of the most crucial factors for the development and upscaling of hydrogen is facilitative and stimulating policy. At present, there are a number of different sources of funding for hydrogen (Figure 6).

Figure 6 | Schematic of funding sources for innovations (RVO, 2019).



Specific to hydrogen and directly related themes, the following schemes are important (this list is not exhaustive):

- TRL 1-3: NWO schemes, available predominantly to universities and TO2 institutions. The PPS bonus can also be applied towards low TRLs.
- TRL 4-6: In the middle segment of the innovation chain, there are schemes such as TSE, MIT (for SMEs) and the PPS bonus. With the TSE resources, funding can go directly towards hydrogen, as was the case in 2017-2019. Likewise, the DKTI scheme is suitable for hydrogen (and other technologies) specifically for mobility themes. The PPS bonus can also be applied in this segment. Additionally, there are regional and European resources available, such as H2020/Europe, Interreg and Innovation Fund.
- TRL7-9: in the higher segment of the innovation chain, there are a number of instruments, such as the DEI+, HER, DKTI and instruments that cover a larger portion of the innovation chain, such as regional and European funds. There are also a number of financing programmes for businesses. The PPS bonus can also be applied for TRL 7/ 8. There is no support available for TRL 9.

The demand for grant funding dramatically outstrips the supply. In light of the enormous challenge in developing hydrogen technology in both the short and long term, current resources are clearly insufficient. The fact that a certain degree of selection is needed does not necessarily have to be a negative but developing hydrogen to full maturity and implementing it on a wide scale will take more. In fact, this applies for all TRL phases (fundamental and industrial research, experiments, pilot studies, demonstrations, and implementation/upscaling).

One of the most significant problem areas lies in the demonstration and implementation phase. Alongside innovation funding for new subjects and combinations of subjects, and funding that supports the often significant investments, both of which is available to a certain degree, support during the operational phase is very much needed. In fact, it is in the demonstration phase and, absolutely, the implementation and upscaling phase, that operational costs come out much higher than the “traditional” (often fossil or fossil-based) alternatives. Due to the desired upscaling of the production and application, the costs increase very rapidly. This is unquestionably true for hydrogen. And this means that funding that only supports investment is no longer sufficient. Here, one can see the analogy with the development of offshore wind, in which the costs of sustainable electricity were subsidised via SDE+ to allow it to compete with conventional alternatives. Such support, for example per produced kg of sustainable (green) or climate-neutral (blue) hydrogen, or subsidy on the CO<sub>2</sub> emissions avoided, would be necessary because otherwise the implementation and upscaling would not be possible due to the high costs (still too high at present). Here, the public interest in achieving the climate objectives justifies support in the form of operating subsidies. The hydrogen policy vision, to be published in early 2020, must address these issues to clear the way for hydrogen and its contribution to the energy transition. Alongside resources for research, development and innovation, hydrogen applications and the energy transition also need a long-term financing structure. An important part of creating this is providing insight into the financial markets and financial instruments based on sound knowledge of the market and the technology. As an example, consider guarantees and mezzanine (blending) loans in the early phases of market introduction.

It is important to include financial institutions in the development of hydrogen technologies, so that institutions like banks, Invest-NL, EIB, venture-capital providers and pension funds can develop the knowledge and motivation needed to finance the move towards hydrogen and the energy transition in the various phases.

Special attention to financing options for SMEs is needed, because these tend to be major drivers of innovation. The study surveying and describing the manufacturing industry (both small and large companies) active in hydrogen in the Netherlands, published in autumn 2019, lists over 250 SMEs<sup>23</sup>. Hydrogen projects are often capital-intensive projects, which means that the high interest rate that borrowing entails makes the threshold high for SMEs. This is why it is important to make financial instruments for hydrogen activities available.

### Regional embedding and societal innovations

Cooperation on the energy transition is best focused at the “landing pads” for the transition. These are, generally, physical locations, varying from municipalities and regions to industrial sites and logistics centres. The locations offer excellent opportunities for showcasing the energy transition to a broad range of actors in society and testing whether the innovations work effectively from the perspective of all stakeholders: the investor, the operator, the user and the local community. This produces a wide range of experiences, all of which have to go into producing the next, improved version of the product, concept or service. For the MPAH, the regional embedding is of critical importance because practical projects (in this case pilots, demos and implementation projects) are a crucial element of the programme. In many cases, the technology is far enough advanced to be able to be tested and used in practice; in some cases, it is even ready for implementation. Because these products are new to the society (like fuel cell cars or hydrogen applications in homes), this “introduction” of hydrogen to society will have a number of benefits, all helping to achieve the goal of incorporating the needs and desires of these actors, ideally in the early stages and otherwise upon each subsequent generation of the product. Without this “test phase”, there is a risk that the actors in society will not feel involved, will not be informed, and will reject the innovation.

For each hydrogen application, there are specific regions that can be identified as ideal for playing a role in the regional embedding:

- *Applications in Industry*: When the draft Climate Agreement was written, there was a great deal of contact within the industry sector table with the relevant industry clusters in the Netherlands, including the Northern Region (Chemiepark Delfzijl, Eemshaven, Emmen), the North Sea Channel zone (Amsterdam and environs), the Rotterdam port area including the chemistry clusters, the Zeeland chemistry cluster and the chemistry cluster in South Limburg (Geleen). These regions are hotbeds for industrial practical projects. These activities are prepared in consultation with MMIPs 6-8. Here, the rate of development will be determined primarily by the industry’s interest in making significant investments in these expensive projects versus continuing “business as usual” in the industry.

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23 Report: Waterstof: kansen voor de Nederlandse industrie (“Hydrogen: opportunities for Dutch industry”), October 2019.

- *Electricity Production applications:* For the projects oriented towards large-scale production of blue hydrogen, like H-Vision (Rotterdam) and H2Magnum (Northern Region), a link with these regions would seem the best approach.
- *Mobility and Transport applications:* In mobility and transport, a number of demonstration and implementation projects have been launched or are soon to be launched in the Netherlands, including projects with hydrogen-powered buses and garbage trucks in certain regions and municipalities, and projects on hydrogen filling stations and passenger vehicles. Partnerships between these regions and municipalities would again seem ideal, in part due to the presence of multiple filling stations. The use of hydrogen in mobility and transport will benefit from fast development of infrastructure with more or less national coverage. Solutions are also needed for the delivery of hydrogen to the customer for hydrogen-powered mobile equipment on construction sites and industrial sites. MMIP 9 provides for partnership in this area. Mobility and transport is typically a very visible segment, and as such lends itself well to introducing hydrogen to the public.
- *Built Environment applications:* There are a number of projects oriented around hydrogen applications for the built environment in preparation in various municipalities (examples include Rozenburg, Hoogeveen, Rotterdam and Stad aan 't Haringvliet). Due to the complexity of the projects and the direct link with local residents/the public, it would appear to be advisable to limit the number of practical projects of this type for the time being in favour of building a body of solid knowledge and expertise over the coming years to facilitate rapid implementation of future projects in a safe and controllable environment. Additionally, the fact that municipalities are currently concentrating on developing Regional Energy Strategies (RES) that are scheduled to be completed in 2021 means that there is some time to gain initial experience in a limited number of projects. Organised information provision on projects, and knowledge exchange with other projects in this area elsewhere in Europe can build greater confidence and accelerate developments here. Because the use of hydrogen applications in the built environment has a direct impact on the public, this theme is also ideal for innovating in partnership with society.
- *Other applications:* Alongside the application of hydrogen in the sectors described above, there are also practical projects in preparation that focus on the system function of hydrogen, i.e., creating storage, flexibility and transport capacity for electricity in the form of hydrogen or an energy source derived from hydrogen. These projects are often linked to specific situations, such as the North Sea (electrolysers in combination with wind parks, with for example electrolysers being installed on available gas and oil production platforms). In the field of storage, projects may be linked to salt caverns in the Northern Netherlands as is the case with the HyStock project.

Most of these projects are suited to being test objects for questions relating to the societal embedding of hydrogen as one major element of achieving the energy transition. This is why the goal is to explicitly include the societal aspects in practical projects and to maximise lessons learned, so that future projects can benefit from the experiences gained and the needs and requirements. Every practical project should be required (for example as a condition for receiving government funding) to address this in a separate section on society, describing the way in which society has been involved in the initiative.



This will also depend on the regions and interested municipalities drafting plans and defining the areas in which there are opportunities for setting up practical projects. This will allow the right parties and resources to come together for the implementation at the local/regional level. There may also be opportunities for clustering of activities in specific areas/regions and focusing on specific activities and themes that offer the potential for cost benefits and advantages of synergy. For optimal development of these projects, it is also important for local and regional governments to gain experience with the policy frameworks applicable to hydrogen projects. Finally, it is important for the regions to cooperate and exchange inter-regional knowledge and experiences. For more on this, see the points identified in the next section with regard to cooperation with our neighbouring countries. While this multi-year approach was drafted, it was announced that the North Netherlands region had been awarded a major European funding package for the development of the region as “Hydrogen Valley”, as an example for how other European regions could begin working with hydrogen for the energy transition. This underscores the value of a cohesive regional approach to hydrogen applications.

Another area that requires attention is the potential social and ecological impact of the large-scale international development of hydrogen. If hydrogen continues to grow as expected and large-scale production begins happening elsewhere in the world in areas with high solar potential and/or wind areas, there will also need to be a survey of the socio-societal and ecological implications. Preservation of local and regional diversity, attention to working conditions, the ecological footprint of sustainable hydrogen production and related activities, and the consequences of large import flows of hydrogen that this may set off are all aspects to consider here.

### International coordination and cooperation

The spectrum of hydrogen initiatives underway in Europe and around the world is broad. The task of the energy transition is, however, tremendous, and so calls for work on hydrogen and hydrogen projects in many countries, each from their own perspective and vision. Additionally, in recent years, a number of different international bodies have emerged around the development of the hydrogen option, and the IEA has expressed optimism about the role that hydrogen can play in a sustainable energy system. It is not only in the scientific world; in the industrial sector too, there are voices at the international level, such as Hydrogen Europe and the Hydrogen Council, that are heralding a future in which hydrogen has a major role to play.

Speaking generally, there are still only very few projects where we see hydrogen applications that can compete with conventional alternatives, and most of these involve hydrogen of fossil origin (with their associated CO<sub>2</sub> emissions). Hydrogen projects tend to be relatively expensive, in part because they involve new technology that is still in development (or has yet to be developed), that is not yet producing at an industrial scale (mass production), and because institutional frameworks (policy and regulations) have not yet been updated to accommodate them, all of which mean increased costs. As an additional factor, there is generally no infrastructure available to be used for the project (at least not without modification).

The lack of sufficient scale makes the production or construction of infrastructure very expensive in the short term. This can be partially compensated for by combining applications, but ultimately demands a longer-term perspective taking into account the “growing pains” scenario with the prospect of a business case in the (near) future. For the areas of research, development, demonstration and implementation of hydrogen technology international cooperation is indispensable. Due to the enormous task of developing hydrogen at the breadth called for, there is virtually no individual country that is up to the task of the major investments this will require, and the knowledge and expertise needed. Various countries have selected individual key focus areas, mostly on the basis of their specific local circumstances, availability of resources or presence of particular companies and/or knowledge institutions.

A number of international bodies have been set up to facilitate cooperation, examples being the hydrogen activities within the IEA, Hydrogen Europe, the Hydrogen Council and, within the European Commission, via the Fuel Cell and Hydrogen Joint Undertaking (FCH JU). Examples of cooperation specifically oriented towards the government level are Mission Innovation (MI) and the Clean Energy Ministerial (CEM). There are also a number of international projects involving Dutch organisations. All these initiatives are helping to create a shared vision of the role of hydrogen in the energy transition through surveys, research, continued development and implementation.

The goal is to continue this cooperation into the future and, where possible, to intensify it. This is why the Netherlands is striving for good representation in Europe and on international bodies, programmes and projects in order to get the most out of cooperation and learn from the knowledge and experiences gained elsewhere. This can also take the form of bilateral cooperation, with examples in the United Kingdom (hydrogen in the built environment), Germany or Belgium (hydrogen in mobility and transport and industrial applications). Likewise, there are potential bilateral cooperation initiatives being investigated with partners in Japan, South Korea, China and the United States. The experiences with next-door neighbours Flanders and Northrhine-Westfalia, where good relationships have been built, show that strong physical connections lend themselves to intensive cooperation.

Additionally, there are areas where the Netherlands has a good starting position and could serve as an example for other countries, as an incubator for new developments or because others have expressed an interest in Dutch products and services. Our strong basis includes the presence of an extensive gas infrastructure, a strong chemical sector, a large transport sector for transport by road and water, and activities on the North Sea (blue hydrogen, the combination of offshore wind farms and green hydrogen production). The presence of a high-level knowledge infrastructure (particularly in gas) is also a contributing factor.

To sum up, the recommendation is made to focus on a four-pronged international strategy:

- Good representation on international bodies, such as Hydrogen Europe, FCH JU, Synergy calls of CEF (TEN-T, TEN-E), MI and CEM, in order to have an input in the hydrogen agenda at the highest level and to profile the Netherlands on the themes we have the strongest position in, while additionally taking on an active role and influencing international programmes in favour of Dutch interests where possible. This will call for a unified lobbying/influencing strategy.

- Active participation in international research and demonstration projects in order to contribute knowledge and expertise, build experience and knowledge and to jointly innovate towards making hydrogen an early leading solution of the energy transition.
- Intensification of the cooperation with our next-door neighbours Flanders (Belgium) and Northrhine-Westfalia (Germany) in order to make optimal use of the opportunities and synergies that are already in front of us, for example in industry, mobility, etc. Additionally, creating collaborations with interested countries, such as Japan and the United States, where one significant challenge is finding good cooperation opportunities for both countries.
- “Opening up” the Netherlands for innovations in areas where we have a strong starting position and which make it interesting for other countries to perform their research and practical projects here.

This strategy demands customized approaches and further development together with parties that have experience and contacts in this area.

## HCA – Human Capital Agenda

Hydrogen technology is a relatively new area. Although hydrogen has been used on a large scale in industry for decades, it is a new technology in many other applications such as mobility and transport, the built environment, energy storage and transport and flexible energy applications, and the pool of hydrogen expertise in the industrial world is by no means developed enough to carry these new applications forward into the future. In fact, the industrial sector is itself already struggling with dramatic shortages of professional personnel with the right expertise. This is why it is high time to pursue activities that are oriented towards the specific knowledge and expertise to make hydrogen a major factor in the energy transition in the coming years. This means that knowledge and expertise will have to be developed at all levels. And that expertise must be found in a broad spectrum of areas, such as working with gases, high pressure, extreme cold, stationary and mobile applications, and a variety of environments (industry, built environment, mobility and transport, on and offshore), covers many areas (infrastructure, storage, technology applications) and draws on and combines many different disciplines, from technology to economy to institutional affairs and social sectors.

This movement is ambitious, certainly against the background of the huge demand for qualified personnel in all the many areas involved in the energy transition. This is why there is also a need for a strong human capital agenda. Within the sphere of influence, the scope and impact of the Top Sector Energy on the crop of new technical and other personnel is limited, but there are opportunities to contribute to the HCA with a range of activities. In industry, for example, there are already various efforts being made, such as ISPT, TKI Energy & Industry and Gasunie (“The world of hydrogen”) in learning communities. TKI Nieuw Gas has good connections with the speakers platform LEVE and hydrogen-related activities clustered around intermediate vocational education, such as the Gas 2.0 programme. And these activities must be expanded: more learning packages about hydrogen in secondary schools and automotive technical schools, to generate interest in the subject among young people.

The goal is to take up these activities in cooperation with the other MMIPs, and preferably to connect them with the activities being conducted from within the overarching mission teams (for the various use sectors), because it is there that the strongest connections with the relevant companies, knowledge institutions and sectors lie. Together we will be searching for new opportunities for the MPAH to pursue additional activities.

## Digitalisation

The importance of digitalisation for the MPAH cannot be understated. One of hydrogen's biggest strengths is the functions that it can fulfil within the system, such as providing flexibility, transport of large quantities of energy (electricity in the form of hydrogen), and storage. These are high-tech functions that will demand high-tech controls, which means that the digital tech sector is an indispensable link. Tech applications like dynamic pressure regulation and better modelling of gas distribution networks will be critical to introducing hydrogen in the built environment and for mobility through a hydrogen network or an existing gas network.

But hydrogen is also strongly interconnected with the various applications that are driving a digital tech agenda within the current MMIPs. Tech applications are also expected to become an embedded aspect of the specific sectors; for example, industrial hydrogen applications are expected to “piggyback” on other activities surrounding the digitalisation agenda in industry (MMIPs 6-8). And in mobility and transport, hydrogen applications are expected to piggyback on the tech agenda of MMIPs 9 and 10 (for example optimisation of traffic flows and autonomous vehicles). For the system function, there will be an intersection of tech applications with MMIP 13. And for the built environment, that intersection is expected to be found in MMIP 5.

Because of all this, there are no separate digitalisation initiatives being launched within MPAH, but we are looking out for potential advantages of synergy and themes where there is a need for an extra impulse in this area in close collaboration with the other MMIPs. These can then also be addressed within the context of the MPAH.





# Chapter 6

# 6 | Setting the priorities of the Multi-year Programmatic Approach for Hydrogen

This chapter presents a proposal how the theme of hydrogen can be developed in the coming years and the priorities that can be identified in it. This proposal is based on multiple sources: discussions in recent months with many different stakeholders, the internal expertise of the core team, active participation in national and international projects and bodies working in this area, and input obtained during a broad consultation workshop and consultation online and via email. This gives us a robust picture.

As a basis for setting the priorities for the MPAH in the coming years, we used the issues and activities catalogued in chapter 4, which we then compared against the ambitions for hydrogen set out in the Climate Agreement. These ambitions are summarised in Table 13 (which is identical to Table 1 but given here again for ease of reference).

**Table 13 | References to the theme of hydrogen in the Climate Agreement**

Sector	Goal (What?)	Approach (How?)
Industry	<ul style="list-style-type: none"> <li>Installation of 3-4 GW electrolysis in 2030 (500 MW in 2025)</li> <li>Reduction in investment costs for electrolysis by 65% between now and 2030</li> </ul>	<ul style="list-style-type: none"> <li>Hydrogen programme with €30-40 million/year for pilots and demos within national funding</li> <li>Research for inclusion of hydrogen in SDE+(+), use of EU funds, involving financial sector institutions like InvestNL</li> </ul>
Electricity Generation	<ul style="list-style-type: none"> <li>For flexibility of electricity system, development of CO<sub>2</sub>-free dispatchable production, potentially up to 17 TWh in 2030, for which CO<sub>2</sub>-free hydrogen is an option</li> <li>Development of Green Powerhouse North Sea (up to 60 GW in 2050) with partial conversion to hydrogen</li> </ul>	<ul style="list-style-type: none"> <li>Timely modification of existing infrastructure for hydrogen and construction of new infrastructure to link industry clusters</li> <li>Establishment of a national government vision of market regulation and energy transition, with updating of legal frameworks by 2021</li> <li>Development of green hydrogen certificates (EU)</li> </ul>
Mobility and Transport	<ul style="list-style-type: none"> <li>In 2025 50 filling stations, 15,000 fuel cell cars and 3,000 heavy vehicles; in 2030 300,000 fuel cell cars</li> <li>Reduction in investment costs for filling stations by average 10% per year</li> <li>Hydrogen contributing to at least 150 emissions-free inland waterway vessels in 2030</li> </ul>	<ul style="list-style-type: none"> <li>Covenant with stakeholders to promote hydrogen-powered mobility</li> <li>Tax incentives and use of EU funding</li> <li>Government as launching customer (sustainable procurement by national government and local authorities)</li> <li>Zero-emissions zones for city logistics in 30-40 largest municipalities</li> <li>National Agreement on Zero-Emissions Bus Transport</li> <li>Green Deal on sea shipping, inland waterways and ports</li> </ul>
Built Environment	<ul style="list-style-type: none"> <li>By 2030, clear picture of how hydrogen can contribute to achievement of 2050 goal, including for buildings and communities that are difficult to make sustainable otherwise</li> </ul>	<ul style="list-style-type: none"> <li>Lay foundation in legislation &amp; regulations and community-focused approaches for pilots and demos in the coming years</li> </ul>

The ambitions of the Climate Agreement are (in part) determinant for the prioritisation presented here. The priorities will be essential for rapid development and upscaling of hydrogen in the period up to 2030. The breakdown of the priorities does not entirely map to the thematic breakdown into 5 components as presented in chapter 4, but the relationship with these components is as follows:

- In order to achieve the ambition for 2030, the priority must be with implementation and upscaling through large-scale practical projects in the four areas of application (component 2),
- with sufficient scale to (for example) justify serious infrastructure development (component 3),
- and gain insight into impediments that must be removed and the conditions required for upscaling (component 5),
- just as the required innovations at all TRL levels that (where possible) could be integrated into the practical projects (component 4).
- In parallel with this, there is a need for more detailed vision-making on and further development of the role that hydrogen can play in the future energy and raw materials system, the scope of that role, and the way in which and speed at which this can be achieved (components 1 and 3)<sup>24</sup>.

## Programmatic approach

The multi-year programmatic approach for hydrogen is elaborated in five separate but interrelated components:

### 1. From vision to policy-making

The focus here is on vision-building and programme development, with the goal of surveying the options for achievement of the energy transition, the roles that hydrogen can play in this transition and the policy support and market regulation that success will require.

### 2. Practice: demonstration projects (pilots, demonstrations and implementation)

This component is about the practical projects that must be ready for broad implementation in the 2025-2030 period. These projects serve multiple purposes, such as: accelerating the introduction of hydrogen-based solutions, organising integral hydrogen chains, testing and developing business cases, and working towards embedding in society through practical examples suitable for future upscaling. Short-term R&D projects will also be a part of this.

### 3. Creating the conditions

Various overarching themes must be addressed collectively, and tackled with a cohesive approach, to get the most out of existing synergies and to ensure that the activities proceed expeditiously. The focus is the areas that are urgent in the short to medium-term, like legislation and regulations, safety and risk management, standardisation and infrastructure.

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24 This numbering of the components follows the breakdown given in chapter 4.



#### 4. Research for the longer term

This is research and development activities (lower TRLs) for the longer-term solutions that may be important going into 2030 and beyond, and/or the robust elements for achieving the energy transition approaching 2050. A good example is the co-electrolysis of water and carbon dioxide into a syngas that can serve as a basis for the production of climate-neutral chemical products and materials (plastics) and synthetic fuels.

#### 5. Supporting and accompanying activities

This refers to activities oriented towards removing impediments and creating the right conditions for the development and upscaling of hydrogen technology. Themes that can play a role include information campaign, the human capital agenda, tech applications, embedding in the regions, and international partnerships.

For these elements, priority activities have been identified that will be necessary to successfully achieve the ambitions of the Climate Agreement in the coming years and to make hydrogen a mature technology. These are described below.

##### 1. From vision to policy-making

There is a great need for a clear vision on the role hydrogen can play in the future energy and raw materials system and the way in which this can be achieved. For this vision, stakeholders point primarily to the government because most are seeking clarity on the direction of future development on the way in which this can be supported through policy and regulations. What they are actually looking for is insight into the robustness of certain developments and the incentives that the government will be using to support this movement. Of course, this is not a task of the government or governmental institutions alone; parties in industry, the public (users) and other stakeholders must all come together on this and express their commitment and ambitions.

In the Climate Agreement of 28 June 2019, the cabinet outlined the major role it foresees for hydrogen. Separately, in a letter to Parliament (DGBI-DR/19145732), the cabinet announced that in the autumn it would be presenting a policy vision addressing the details of the programmatic approach for hydrogen, the choices to be made with respect to certification and RED II, issues relating to market regulation and infrastructure, the economic opportunities and the international context. By this, the government was in fact expressing the desired clarity on these issues, at least on those with regard to which the government has direct influence. With respect to the support of hydrogen via SDE++, talks are currently underway; initially, PBL advised negatively due to the supposed high costs of CO<sub>2</sub> emissions reductions that green hydrogen could produce in the short term.

The priorities in the “vision-making” component are as follows:

### 1A. Hydrogen policy vision

The government draft of a policy vision for hydrogen (autumn 2019). This needs to provide the desired clarity and, by doing so, offer an incentive for broad implementation of hydrogen heading towards 2030. The market wants a stable long-term policy, on issues like excise duty exemptions for hydrogen and support of the operational costs through an SDE++-like construction, over a longer term in order to be able to define business cases for projects with a sufficient degree of certainty.

- *Parties involved:* government (Ministry of Economic Affairs and Climate Policy), all stakeholders
- *Timing:* autumn 2019
- *Required budget:* none
- *Source of budget:* n/a

Alongside this policy vision, from a strategic perspective, there is an interest in gaining insight into the role that hydrogen can play in various future scenarios under the assumption of an ambitious climate policy (in line with the Climate Agreement) and in what role, function, markets and applications hydrogen will be the most robust. An important point to note is that hydrogen was addressed in many of the analyses produced for the Climate Agreement. Cooperation with MMIP 13, which has a significant focus on model development and analyses, will be productive here.

### 1B. Studies and analyses for programme development

It is important to show what technological advances will be meaningful for hydrogen and hydrogen’s position in relation to alternatives at the national and European levels; this can be done with scenario analyses, which will also make clear where hydrogen is most desirable and in what time horizon. See Table 4 for an overview of all innovation tasks:

- *Parties involved:* all stakeholders, cooperation with MMIP 13, planning offices (PBL, CBS), TNO System Studies, consultants
- *Timing:* ongoing, to start in short term
- *Required budget:* none, mainly ensuring that hydrogen is explicitly included
- *Source of budget:* n/a

For a successful implementation and upscaling of hydrogen technologies, a clear policy vision and insight into scenarios and analysis will be indispensable. A government draft of a policy vision for hydrogen must provide the desired clarity on the incentives for hydrogen and broad implementation going into 2030. There is a need for a stable long-term policy, including aspects such as the taxation of hydrogen for mobile and non-mobile applications (excise duties and energy tax) and support of the operational costs of hydrogen production through (for example) a production subsidy. This will make it possible to define business cases for projects. Additionally, certainty is desired in regard to the upscaling process that will be needed to actually bring down the investment cost for the technology.

Other important aspects are the relationship with existing and additional sustainable electricity generation capacity and the position of blue hydrogen (including the CCS option). Insight into the functioning and applicability of new market models will help assess and shape policy.

## **2. Demonstration in large-scale practical projects**

A consideration of the Climate Agreement results in the following prioritisation themes that can count on broad support from stakeholders and which will be robust for the energy transition. The years and scales indicated are ambitious but, in view of the speed of the developments at the international level and the need to reduce CO<sub>2</sub> emissions rapidly, it makes sense to set the bar high. These priorities are given in random order.

For many of these practical projects, combinations may be possible and worthwhile. This is relevant for a number of reasons: cooperation, coordination and clustering (local and regional, and national and international) accelerates knowledge development and increases the base of support, produces shared infrastructure and advantages of scale, and increases the chances of effective policy and adequate financing options.

For these large-scale practical projects, development plans should be detailed in the coming months to define what needs to happen when, what will be needed in terms of R&D, what issues (legislation/regulations, permits, safety, availability of funding, etc.) will need to be dealt with and what the financing plan will look like. Also needed is a perspective on the consortia of specific parties that could be formed to implement the development plans. These plans could be worked out by programme teams, for example in the regions in which the relevant stakeholders are represented. Such teams are (at least in part) already available, for example Hydrogreenn Hoogeveen, H-vision Deltalinqs and WaterstofNet. Additionally, the H<sub>2</sub>Platform fulfils an important role with regard to the aggregation of demand.

The task is to focus on the “big themes” that strong consortia can get behind with a will to achieve this in a term beyond the period of the MPAH. The next step is then to link the MPAH to these, to allow the programme to be a coherent facilitator of the development of the innovations required. This MPAH lays the foundation for this, but there still needs to be a further specification in order to make well-founded choices for concrete innovation projects and processes.

### **2A. Achievement of large-scale production of hydrogen at GW scale in 2030**

Answering the future demand for hydrogen (fully sustainable production of hydrogen and full utilisation of sustainable electricity generation through hydrogen-based storage and flexibility) will, certainly in the long term, require large-scale production of “green” hydrogen through electrolysis (alkaline, PEM) from water using sustainable electricity.

Upscaling through higher numbers and larger capacities of systems will lead to a gradual reduction of costs. This will be necessary to make large-scale use possible and profitable in the foreseeable future and to achieve utilisation and adoption of wind and solar energy as a gaseous fuel to replace natural gas where alternatives fall short, and as a replacement for the current natural gas-based hydrogen consumption in industry.

A number of project instigators have launched plans for an expansion to 3-4 GW in 2030 moving from the initial installations of 20 MW (now in preparation) through projects of 50, 100 and 250 MW up to the gigawatt scale. The Green Hydrogen Coalition endorses these ambitions, as do the partners in the Northern Netherlands region. The intended technology to be used for this is electrolysis. There are major challenges in the future availability of sustainable electricity, the availability of electrolyzers on a larger scale, the development of the demand for hydrogen, and the financing and commercial operation of these projects. Upscaling in industry would appear to be the clear choice (including refineries) due to the size of the potential demand for hydrogen. If the cumulative upscaling moves towards many hundreds of megawatts and the gigawatt scale, this will absolutely have to be considered in relation to the extra efforts required for achievement of sustainable electricity production in order to attain actual CO<sub>2</sub> emissions reductions in the Netherlands. Looking at the wind power sector, for example, it would seem that up to 2030 more than the currently planned upscaling volume would be possible to meet the potentially higher demand for sustainable electricity for the production of hydrogen.

Alongside green hydrogen, “blue” hydrogen remains an option for maintaining availability of large quantities of climate-neutral hydrogen in the relatively short term, for example for industry and flexible electricity generation. The first initiative in this area is the H2Magnum project (project partners: Vattenfall, Gasunie and Equinor; project location: Eemshaven). Elsewhere, various players in the Port of Rotterdam have put out an ambitious plan (H-vision) for the production of blue hydrogen from natural gas. But here, too, financing and commercial operation remain a significant challenge.

Potential projects are summed up in Tables 6 and 7. A few important parameters for upscaling in this area are:

- *Parties involved:* chemical industry, large companies, Netherlands manufacturing industry, electricity sector, ports
- *Timing:* in the coming 3-4 years, various production facilities available at 20-50 MW scale; thereafter upscaling to 100-500 MW or more (2025) towards GW scale in 2030
- *Required budget:* budget needs are very large (on order of €1,000/kW installed); later the budget demand will decline due to lower costs per kW. Every GW installation requires an investment on the order of €1-1.5 billion. In addition, opex support will be necessary, for example through an SDE++
- *Source of budget:* for smaller facilities financing in part with Dutch (HER, DEI++, Invest-NL) and European funding resources (Innovation Fund, FCH JU, Horizon Europe etc.); for larger facilities (>100 MW) financing through companies, Brussels/EC (including EIB) and various national and international investors.

## 2B. Construction of a “hydrogen backbone” to connect the Netherlands’ major industrial clusters by 2030, including large-scale underground hydrogen storage

Once hydrogen is produced on a large scale, the construction of hydrogen infrastructure will be needed to provide the various production and consumption clusters with green and blue hydrogen. This means establishing a “hydrogen backbone” at the national level to which hydrogen storage (such as gas fields and aquifers) is directly connected, plus hydrogen in distribution networks for the built environment. It may be that conversion of some or all of the natural gas infrastructure will be sufficient, possibly supplemented with new infrastructure where the existing infrastructure is not available or suitable. In addition, large-scale underground hydrogen storage in salt caverns will be needed to keep sufficient quantities of hydrogen available and to create a buffer between production and use. Of course, the necessity of infrastructure and storage will depend on the production and demand for hydrogen, but this cannot be allowed to be the limiting factor; consequently, further research is needed in the short term. Commitments on gas quality also play an important role, and the question of what qualities can be supplied through what infrastructures is important here.

Important parameters for upscaling:

- *Parties involved:* Gasunie GTS, regional network managers, Netherlands manufacturing sector
- *Timing:* due to the long turnaround times, growing along with initiatives in the industrial clusters means that planning needs to start now
- *Required budget:* to be determined; amounts are bigger for construction of new pipelines than for refitting existing pipe networks. Estimate is several hundred million euros
- *Source of budget:* socialisation if hydrogen transport is placed under the Gas Act, and via internal budget of Gasunie TS and other network managers, to be supplemented if necessary and possible by Dutch (Invest-NL) and European (EIB) resources and various national and international investors.

## 2C. Dispatchable, flexible hydrogen-based power stations in 2030

Keeping sufficient quantities of climate-neutral electricity available with the requisite flexibility and peak capacity in an electricity system increasingly dominated by variable (wind and solar) capacity will ultimately require converting gas (and potentially coal) power stations to handle hydrogen. A good example is the Magnum power station at Eemshaven, where the potential for conversion for hydrogen is being investigated.

According to the Climate Agreement, by 2030, there may already be demand on the order of 17 TWh of electricity generated by zero-emissions flexible power stations, even if other options for flexibility in the electricity sector are applied. Alongside hydrogen-fired power stations there are other options, but for various reasons, these seem less feasible or promising: nuclear plants, biomass power stations and natural gas power stations with integrated CCS. Ultimately, these dispatchable power stations, or local variants thereof, will be necessary to achieve fully carbon-free electricity generation heading into 2050 (with the capacity to cover shortfalls in

the supply of wind and solar where other flexibility options are inadequate or more expensive). The production of blue hydrogen also plays a role here. Table 7 provides a detailed list of the project instigators and parties involved.

A few significant characteristics:

- *Parties involved:* electricity producers (large and small-scale), network administrators, local/provincial authorities, the Dutch manufacturing sector
- *Timing:* for large-scale, developed options for implementation in the coming years; for small-scale, inventory concrete projects and catalogue possible solutions, implement demo projects (coming 3-4 years)
- *Required budget:* to be determined, estimated on the order of several hundred million euros for 500-1000 MW
- *Source of budget:* HER, DEI++, Invest-NL and European funding resources (Innovation Fund, FCH JU, Horizon Europe).

## 2D. Demonstration of 3-5 pilots with hydrogen in the built environment, by 2025

There are a number of possible options for sustainability in the built environment. Use of green hydrogen is, alongside green gas, an attractive option for homes and communities where other options are not feasible. Making the built environment more sustainable must start in the short term with research, testing and demonstration of how hydrogen can be used for these applications.

It is important to know, for example, what situations and at what scale (block, neighbourhood, district, etc.) hydrogen can best be applied in the built environment (existing buildings), including research into what needs to change in terms of regulations to make this possible.

In addition, the development of a number of representative projects in various configurations (different situations, proportions of hydrogen and end-user applications) will be needed to gain the broad experience needed and to define the conditions under which retrofitting, application and potential further rollout after 2030 can happen effectively, efficiently and safely, such as:

- Mixing into the natural gas grid in an existing community (e.g. inventory situation and what modifications are necessary). Such a project could be combined with local production.
- Pure hydrogen in an existing community (e.g. inventory the situation in advance, learn how to perform the conversion and switchover).
- Application for individual homes.
- Application in collective heat systems (highrise construction and regional nets).

In terms of end applications, options include central heating boilers, hybrid heat pumps and in the case of pure hydrogen, microscale heat transfer. For new construction, hydrogen does not appear to be the desired option because sustainable all-electric alternatives are better suited here. However, it is worth recommending that a good analysis be made of the options for limited application of hydrogen in newbuilds, for example in homes/complexes where alongside heating, cooling is also required, as well as additional electrical power. Table 9 presents a detailed list of initiatives in this area.

Major characteristics for the application of hydrogen in the built environment are:

- *Parties involved:* construction sector, project developers, housing corporations, municipalities, network managers, electrical/mechanical/technical sector, residents
- *Timing:* over the coming 2-4 years, use pilots and demo projects to explore how this works, resolve issues such as safety and legislation & regulations
- *Required budget:* of the order of €10-20 million
- *Source of budget:* HER, DEI++, European funding resources (FCH JU, Horizon Europe etc.), partial financing through programmes of network administrators

## 2E. Rollout of hydrogen-powered mobility, including filling stations needed in 2025

Much of the technology required (such as cars and fuelling stations) is already available, but certain elements need improvement and optimisation. For heavier transport, development is still needed. The following ambitions for 2025 are formulated in the Climate Agreement:

- at least 50 filling stations at public service stations
- at least 15,000 fuel cell cars and vans
- 3,000 heavy fuel cell vehicles on the roads in 2025: buses, trucks, garbage trucks and municipal vehicles/utility vehicles (or another segment of significant size and potential for duplication), including dedicated filling stations as required
- 10-20 demonstrations with hydrogen in inland waterway vessels
- 10-20 demonstrations with hydrogen for mobile machinery in agriculture, roadworks, hydraulic engineering, construction and industry

These ambitions are shared by H<sub>2</sub>Platform. Here, as elsewhere, there needs to be freedom to move to quick upscaling. Major requirements are favourable TCO (Total Cost of Ownership) of vehicles. This should be primarily focused on the following segments:

- Cars: Expansion of first filling stations to a network of filling stations with national coverage in combination with continuation of market activation and introduction (low income tax addition, exemption from motor vehicle taxes and excise duties on hydrogen, residual value guarantee fund, etc.)
- Public bus transport: Support of further expansion of use of fuel cell-electric buses in concessions where battery-electric buses are not sufficient. Incentivising can, for example, be through regular channels (concessions).
- Zero-emissions logistics: Continued development, testing and demonstration of freight trucks and light commercial vehicles. Forklifts are already available.
- Zero-emissions urban cleaning: Continued development, testing and demonstration of garbage trucks and livestock transports.
- Zero-emissions shipping: Develop and demonstrate hydrogen-powered ships, onshore power options.
- Filling stations: The development of hydrogen-powered mobility and transport in various sectors will depend on an infrastructure with national coverage. This is why upscaling will be necessary, from the current 4-5 filling stations to 50 in 2025. Improvement of the filling stations will also be required with a view to the investment costs, efficiency and maintenance.



A detailed picture is presented in Table 8. The key characteristics are as follows:

- *Parties involved:* freight companies, public transport companies, municipalities and provinces, a broad spectrum of vehicle manufacturers, filling station operators, manufacturers of filling stations, hydrogen producers/suppliers
- *Timing:* in the coming 1-2 years, develop and demonstrate, then scale up
- *Required budget:* budget needs of the order of €10-20 million to develop and demonstrate the first vehicles for a segment
- *Source of budget:* DKTI scheme, regional funding, at European level FCH JU and Interreg, others; plus innovation funding for the required improvement of the filling stations

## 2F. Start of pilot and demonstration projects with new industrial applications for hydrogen in the 2025-2030 period

Alongside the present large-scale application of hydrogen in industry, there are a number of options to use green and blue hydrogen as a replacement for the energy needs currently provided by natural gas and liquid fuels, and the production of raw materials and products. These projects are in line with the priority “Achievement of large-scale production of hydrogen at GW scale in 2030”, because the demand for hydrogen for these applications is potentially huge<sup>25</sup>. Because the financial feasibility in industry is a very important point from the perspective of international competition, the main efforts will be towards pilot projects and demonstration projects, with upscaling and transition to large-scale applications to follow later. Examples include:

- Supply of hydrogen from a 20 MW water electrolysis plant in Delfzijl to BioMCN for the production of green methanol.
- Use of hydrogen from a 100 MW electrolysis plant for production of fuels and/or base chemicals with the carbon monoxide (CO) and carbon dioxide (CO<sub>2</sub>) in the exhaust gases from the cokes and steel production at TATA.
- Use of electrolysis hydrogen for refining deep-frying fat into sustainable kerosene and bio-propane in the SkyNRG initiative.
- Production of green methanol from hydrogen and syngas generated from gasification of waste (Enerkem, Nouryon, others)

More examples of projects are provided in Table 6. Key characteristics are:

- *Parties involved:* chemical industry, large companies, airlines, ports, airports, the Dutch manufacturing sector
- *Timing:* in the coming 3-4 years, prepare various pilot and demo installations and where possible implement them in relation to industrial water electrolysis projects with a scale on the order of 20-50 MW
- *Required budget:* for the budget demand for the electrolysis portion, see the priority “Achievement of large-scale production of hydrogen at GW scale in 2030”. The budget need for the new processes for production of synthetic fuels and green chemicals is expected to be on the same order.

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25 The use of hydrogen in new processes for the production of liquid fuels and the synthesis of chemical products and materials is related to the hydrogen programme, because it requires the large-scale production of sustainable hydrogen, but the development of these processes is not a component of the hydrogen programme.



- *Source of budget:* for smaller facilities financing in part with Dutch (HER, DEI++, Invest-NL) and European funding resources (Innovation Fund, FCH JU, Horizon Europe etc.); for larger facilities (>100 MW) financing through companies, Brussels (including EIB) and various national and international investors.

## 2G. Introduction of local sustainable electricity from hydrogen in 2025 with completion of pilot and demonstration projects.

At a number of locations, there are limitations in the power network capacity, as a result of which the introduction of locally generated electricity from solar and wind is not possible or is not always possible. This means that these projects do not get off the ground or move forward only slowly. In the coming years (up to 2025), there is a need to set up pilot projects and demonstration projects to assess the possibilities of water electrolysis in relation to the introduction of local sustainable electricity generation and remove bottlenecks in the electricity network. Concepts include potentially linking hydrogen filling stations or applications of hydrogen in the built environment like mixing hydrogen into the local or regional natural gas network. See Table 7 for a detailed specification.

Relevant key characteristics of projects:

- *Parties involved:* electricity producers (large and small-scale), network administrators, local/provincial authorities, the Dutch manufacturing sector
- *Timing:* for large-scale, develop options for implementation in the coming years; for small-scale, inventory concrete projects and catalogue possible solutions, implement demo projects (coming 3-4 years)
- *Required budget:* to be determined
- *Source of budget:* HER, DEI++, Invest-NL and European funding resources (Innovation Fund, FCH JU, Horizon Europe, etc.)
- *Substantiation:* hydrogen can offer a solution for taking the load off the electricity network and locations with a lot of (or excessive) renewable energy generation.

## 2H. Design and construction of a “test energy island” combined with offshore wind and hydrogen production for 2030

Due to the great interest in offshore wind as a basis for future electricity production (the “Green Powerhouse North Sea”) and the expected challenges and bottlenecks with respect to transport and landfall of this electricity, a test of the complete system for offshore “wind hydrogen”, on a limited scale and under realistic conditions, and including the required infrastructure such as offshore hydrogen pipelines, is desired. This can be a means of gaining experience in how this option can be applied efficiently and reliably in the future. There are plans being developed for multiple large “energy islands” in the North Sea where hydrogen could be produced using wind power.

The following key characteristics play a role:

- *Parties involved:* wind energy producers, network administrators, local/provincial authorities, the Dutch manufacturing sector
- *Timing:* perform a demonstration project or practical project in the coming 3-4 years
- *Required budget:* of the order of €20-30 million
- *Source of budget:* HER, DEI++ and European funding resources (Innovation Fund, FCH JU, Horizon Europe, etc.).

### 3. Creating the conditions

This component covers a range of subjects that are relevant to the large-scale rollout of hydrogen, including development, suitability and modification of hydrogen infrastructure, safety, standardisation, gas quality (including mixing of hydrogen into natural gas), large-scale storage of hydrogen, tank infrastructure for mobility and transport, import of hydrogen and position of ports, and system integration of onshore and offshore electricity production. Some of these issues will be necessarily addressed by the practically oriented projects, while others are still in the “study phase” with the best options, methods of application, costs, and time frame still under consideration. This is presented in more detail in Table 10. Tackling these subjects is important from both a national and an international perspective. Most of these are major, cost-intensive choices that must be made in consideration of the total picture. This is why there are significant interfaces with MMIPs 1, 4, 7, 9 and 13, and these themes must be addressed jointly.

This also goes for the themes Import and System Integration. The Import theme is still firmly in the study phase. More insight is needed into the cost, technical implementation, production locations for hydrogen, most effective form of transport, societal issues, etc. For system integration, there needs to be an investigation of the options hydrogen offers for flexibility at the central and local levels, the infrastructure options (landfall of offshore electricity via hydrogen), and the most optimal configurations. The first pilots in this area are in preparation (for example electrolysis on a production platform on the North Sea). Another example is the construction of a “test energy island” with a complete system for wind hydrogen at sea on a small scale and under realistic conditions. Further development is necessary and should happen in cooperation with MMIP 13.

### 4. Research for the longer term

This theme is oriented on the longer-term research needed to develop the full capacity of hydrogen for a broad spectrum of applications. The separation between research for the long term (after 2030) and the period up to 2030 is not always cut-and-dried. Some results will be needed earlier but demand more fundamental solutions that will take more time. Additionally, this need will also depend on the speed at which developments in hydrogen move in the shorter term. Table 11 presents a list of the research needs. Broadly, we can distinguish between the following areas:

- **Hydrogen production:** There are a number of technological (electrochemical and thermochemical) routes for the production of hydrogen in various stages of development, the main one being water electrolysis: the splitting of water molecules using energy obtained from the plentiful sources of solar and wind energy. Within this method, there are several

technological variants. For these variants, it is important to further identify the principles and assess whether upscaling will be possible in the future to achieve lower costs and higher efficiency.

- Infrastructure and storage: The research need on this topic is generally significantly more concrete than for production; here the options are in the higher TRL phases. The questions that remain must be addressed in the short term, because they will be extremely relevant for upscaling and for linking the production and application of hydrogen.
- Applications: The research needs in hydrogen applications are diverse. Major topics are the development and optimisation of fuel cell systems for a wide range of applications and the modification of equipment, such as burners and engines, for hydrogen. There are also many concrete questions with respect to application in the built environment.

For a further specification of the research need, see the ECCM programme, which contains a detailed description. Drawing a stronger connection between the research themes and the opportunities for industry in the Netherlands (including, in particular, the manufacturing industry) is desired.

#### 4A. Addressing the research needs for the short(er) term

R&D questions with a near-term horizon will have to be handled quickly and effectively to ensure that hydrogen projects can be carried out and scaled up into the longer term. The expectation is that the practical projects will also give rise to new research questions. This interaction should be actively managed when putting out calls for project proposals.

- *Parties involved:* various, including companies/SMEs, government bodies, knowledge institutions
- *Timing:* pick up in the short term
- *Required budget:* of the order of €4-5 million annually
- *Source of budget:* HER, DEI++, DKTI, cooperative research funding of research institutions

#### 4B. Addressing the research needs for the long(er) term

Right now, hydrogen is at a very early stage of development, the expectation is that there are many fundamental improvements ahead in terms of production and application. New developments may also offer solutions for the “segments difficult to make sustainable”.

- *Parties involved:* research and knowledge institutions, companies
- *Timing:* start now in various programmes (e.g. ECCM), to go into implementation in the coming years
- *Required budget:* of the order of €5-10 million annually
- *Source of budget:* NWO, H2020/Europe, cooperative research funding of research institutions

### 5. Supporting and accompanying activities

This refers to the areas that will be necessary to successfully develop hydrogen projects: for example certification of hydrogen, development and application of measurement methods, embedding in society, the role of regions, tech applications, and the human capital agenda.

Many of the activities this covers can be make-or-break for implementation, which is why these activities should ideally be addressed in the practical projects. Future projects, and future funding, should be made contingent on an integral approach to these. Some of the topics, rather than requiring an earmarked budget, simply need sufficient will and ambition on the part of stakeholders to arrive at a joint solution. The most urgent supporting activities are described here.

### 5A. Certification of hydrogen

Development and application of a uniform European system for Guarantees of Origin for hydrogen and green hydrogen, certificates for green hydrogen and hydrogen with a low fossil/carbon footprint. Characteristics:

- *Parties involved:* Ministries, industry, local/regional authorities, advisors, knowledge institutions, Vertogas
- *Timing:* take up when the questions arise, with the ambition of having everything resolved in 4 years' time
- *Required budget:* limited as yet
- *Source of budget:* -

### 5B. International coordination and cooperation

In this area, it is recommended that the Netherlands opt to approach this strategically and place key experts on significant working groups to ensure that the Netherlands is represented and plays an active role on the policy side.

- *Parties involved:* NEN, Ministries, industry, local/regional authorities, advisors, knowledge institutions
- *Timing:* ongoing activity
- *Required budget:* limited as yet
- *Source of budget:* -

### 5C. Miscellaneous: regional cooperation, HCA, tech, SRI, etc.

There are a number of non-technological themes that will be relevant and contributory for the successful development and upscaling of hydrogen technologies. These will require ongoing attention in relation to the other activities. These are themes such as regional cooperation, the human capital agenda, tech applications and socially responsible innovation.

### Summary overview

Table 14 gives a summary overview of the five components of the approach, including timing and a very general indication of the expected budget needs. Some of these components have already been identified, prioritised and budgeted in the relevant MMIPs. There will be coordination with these MMIPs on an ongoing basis to maximally facilitate the development of hydrogen technologies.

**Table 14 | Initial, global assessment of budget required for the development of hydrogen in the 2020-2030 period.**

Subject	Timing (when ready)	Estimated budget (€ x 1,000,000)
<b>1 From vision to policy-making</b>		
1A. Hydrogen policy vision	Early 2020	None
1B. Studies for programme development	Ongoing	Annually, 0.2-0.5
<b>2 Demonstration in large-scale practical projects</b>		
2A. Large-scale hydrogen production on GW scale	2030	1,000+
2B. Construction of hydrogen backbone infrastructure in the Netherlands and hydrogen storage	Around 2030	Partially public
2C. Controllable, flexible hydrogen-based power stations	2030	250+
2D. Demonstration of 3-5 pilot studies with hydrogen in the built environment	2025	10-20
2E. Rollout of hydrogen-powered mobility, including filling stations	2025	10-20
2F. Hydrogen pilot projects and demonstration projects in industry (partly falls under 2A)	2025-2030	50-100
2G. Introduction of local sustainable electricity generation using hydrogen	2025	10-20
2H. Design and construction of test energy island	Before 2030	100+
<b>3 Creating the conditions</b>		
Various subjects, to be worked out in detail in the coming years (safety, legislation/regulations, gas quality, standardisation, etc.)	2020-2021	10-20
<b>4 Research for the longer term</b>		
Implementation of medium to long-term R&D agenda	2020-2030	Annually, 5-10
<b>5 Supporting and accompanying activities</b>		
5A. Certification of hydrogen	2020-2021	Limited
5B. International coordination and cooperation	Ongoing	Limited
5C. Miscellaneous: regional cooperation, HCA, Tech, SRI, etc.	Ongoing	Limited
<b>TOTAL</b> <i>(very rough estimate for 2020-2030 period)</i>		<b>Order of 1,500-2,000</b>









# References

- Bundesministerium für Verkehr und digitale Infrastruktur (BMVI). (2018). *Study IndWEde Industrialisierung der Wasserelektrolyse in Deutschland: Chancen*. Berlin
- DBI GUT. (2017). *The Effects of hydrogen injection in natural gas networks for the Dutch underground storages*. The Hague: RVO
- E4tech with Element Energy Ltd. (2014). *Development of water electrolysis in the EU*. FCH JU
- FCH 2 JU. (2018). *Annual Work Plan and Budget*. EU: FCH 2 JU
- FCH JU. (2014). *Multi-Annual Work Plan 2014-2020*. FCH JU
- IEA. (2015). *Technology Roadmap Hydrogen and Fuel Cells*. Paris: International Energy Agency
- KIWA. (2018). *Toekomstbestendige gasdistributienetten*. Apeldoorn: netbeheer nederland
- Nagashima, M. (2018). *Japan's Hydrogen Strategy and its Economic and Geopolitical Implications*. Paris: IFRI Centre for Energy
- Proost, J. (2018). State-of-the art Capex data for water electrolyzers, and their impact on renewable hydrogen price settings. *Elsevier*, 4406-4413
- Satyapal, D. S. (2019, April 28). Hydrogen and Fuel Cell Program Overview. Crystal City, VA, USA: United States Department of Energy
- World Energy Council. (2018). *International Aspects of a Power-to-X Roadmap*. frontier economics



# Annexes

## Annex A | Expertise and facilities for hydrogen research in the Netherlands

In the Netherlands, there is a large body of expertise and facilities for hydrogen available. In general, research is based on various small-scale installations spread out across the country, rather than large-scale facilities. Along with specific foundational and applied research institutes, university research groups are combining their efforts in the Debye Institute (Utrecht University), the Van 't Hoff Institute (University of Amsterdam), Kavli Institute (TU Delft), Zernicke Institute (University of Groningen) and the Institute Renewable Energy Storage (IRES, Eindhoven University of Technology).

The Table below presents a non-exhaustive overview of the available knowledge and expertise in the Netherlands and the relevant actors. Note that this is by no means all the academic and research activities going on in the field.

Table A1	Available knowledge and expertise on the basis of selected resources and facilities	Relevant actors in the Netherlands
<b>Mechanisms &amp; Processes</b> <ul style="list-style-type: none"> <li>• Chemical</li> <li>• Physics</li> <li>• Materials</li> <li>• Bioengineering</li> </ul>	<p>Analysis techniques for eliminating the foundations of physical, chemical and biological processes and reactions that occur in the bulk and at interfaces, including microscopy, surface sciences, functional characterisation:</p> <ul style="list-style-type: none"> <li>• in-situ and ex-situ techniques for studying the effects of processes and reactions</li> <li>• Real-time and operando probing during reactions and processes</li> </ul> <p>Computational modelling of processes and mechanisms at multi-scales of time and dimensions</p>	<p>Academic universities TUD, TU/e, UT, RUG, UvA, UL, UU, RUN, WUR</p> <p>Universities of applied sciences Fontys, Avans, Hanze, HAN</p> <p>Academic Institutes DIFFER, AMOLF, NIOZ, CWI</p>
<b>Materials &amp; Components</b> <ul style="list-style-type: none"> <li>• Synthesis and Manufacture</li> <li>• Characterisation: structural and functional</li> </ul>	<p><i>Synthesis and manufacture</i> State-of-the-art synthesis, deposition and micro/nanostructuring techniques for advanced materials</p> <p><i>Structural and chemical characterisation</i> Extensive and highly sensitive microscopic, diffracted and spectroscopic methods for investigating the structure, morphology and chemistry of advanced materials; methods based on: X-ray, light (UV/IR), electrons...</p> <p><i>Functional characterisation</i> Advanced measurement techniques to characterise the functional qualities of materials, such as electrochemical, catalytic, electric, magnetic properties</p>	<p>Applied research organisations TNO, ECN part of TNO,</p> <p>Unique (larger) research institutions</p> <ul style="list-style-type: none"> <li>• NanoLabNL facilities <i>Eindhoven, Delft, Twente, Amsterdam, Groningen</i></li> <li>• Ion Beam Facility <i>DIFFER</i></li> <li>• SURFSARA HPC facility <i>Amsterdam</i></li> <li>• EnTranCe <i>Groningen</i></li> <li>• AlgaeParc <i>Wageningen</i></li> </ul>
<b>Equipment</b> <ul style="list-style-type: none"> <li>• Proof-of-Concept</li> <li>• Demonstrator</li> <li>• Prototyping</li> </ul>	<p>Development of new concepts and equipment for electrochemical/ photoelectrochemical applications <i>e.g. artificial leaves, plasma-driven chemistry, spinning disk electrolysis, AEM electrolysis, engineering of algae and microorganisms</i></p> <p>Cost reduction of state-of-the-art electrolysis systems (alkaline and PEM electrolysis) by incremental improvements</p> <p>Long-term stability of materials and components during functioning of equipment <i>e.g. lifetime studies, bubble formation</i></p> <p>System integration and techno-economic considerations</p>	

## Annex B | Key technology: electrolysis

### *Current status*

Electrolysis is the key technology for the production of hydrogen from water using electricity (ideally sustainably generated). There are multiple variants of water electrolysis technology, the primary ones being alkaline electrolysis (AEL), proton exchange membrane electrolysis (PEM electrolysis or PEMEL) and high-temperature electrolysis (HTEL), also known as solid oxide electrolysis cell (SOEC or SOE). Additionally, there is increasing attention given to anion exchange membrane electrolysis (AEM). AEL is the most mature technology and is currently at TRL 8/9. PEMEL is slightly less mature, currently at TRL 7/8. HTEL and AEM are still at an early stage of development, at TRL 5 and TRL 4, respectively.

In the twentieth century, AEL was successfully used at a scale of 100-150 MW for the production of ammonia and artificial fertiliser; this was primarily done in areas with cheap hydroelectric power. However, all these plants closed down with the rise of hydrogen based on cheap and abundant natural gas. By nature of its application, the original process is designed for stationary operation. Early systems worked at atmospheric pressure, but over time, systems were developed that could function at higher pressure (around 30 bar). Continued development has produced systems that are relatively fast and can be regulated, and so can play a role in the absorption of large amounts of variable wind and solar power in future sustainable energy systems.

The development of PEMEL dates from the early 1970s when the PEM technology emerged and, against the backdrop of the oil crisis, interest in renewable energy technologies like hydrogen through water electrolysis grew. These systems have only come onto the market in the last 10 years. In 2015, Siemens in Germany installed the first MW-scale PEMEL system, consisting of three units with a total nominal output of 3.75 MW. Since then, ITM has been pursuing a 10 MW system at a refinery in Germany, and Siemens is now building a 6 MW installation based on the next generation of the technology at a Voestalpine steel plant in Austria. Siemens has developed multiple configurations of systems ranging from 5 to 18 MW.

AEL and PEMEL are both available on the market, and several dozen manufacturers around the world offer them in packages ranging from small systems at the kilowatt scale for niche markets up to a system on the scale of 1-20 MW, which in the case of AEL can be combined from multiple units into a system of the order of 100 MW. Prominent players in AEL and PEMEL are found in Norway (NEL/Proton OnSite), Germany (Siemens and ThyssenKrupp, among others), Canada/Belgium (Hydrogenics), France (Areva and McPhy), China (Tianjin Hydrogen Equipment and others), Japan (Asahi Kasei and others), Switzerland (IHT), the United Kingdom (ITM), and the United States (Giner). There are still no Dutch players marketing systems for water electrolysis, although TNO recently launched a test programme in Petten with a 50 kW PEMEL demo installation built by a Dutch consortium and based on Dutch technology from Hydron.

For SOEC and AEM, there are a handful of suppliers of systems, all of which are still in the pilot phase, with capacities ranging from a few to a few dozen kilowatts. There is only one party, an Italian manufacturer, marketing a small AEM system.

Although there are already a considerable number of prominent players in AEL and PEMEL, the manufacturers are still small and the markets for water electrolysis are still modest and fragmented. The installation of capacity is of the order of 100 MW per year, with sales at present estimated at €100-150 million per year worldwide. Systems are manufactured on a made-to-order or project-to-project basis and are not delivered from inventory, and the degree of automation in their manufacture is very low. The number of direct employees in the industry is estimated at approximately 1,000. At the same time, many parts and components for the systems are sourced from elsewhere, which means that the industry represents many more indirect employees with vendors. The capacity for production of systems is of the order of 20-100 MW/year with the larger manufacturers. Recent positive trends in the market have led to several announcements of expansions. For example, in 2018 NEL in Norway announced it was working towards expanding its capacity from 25-40 MW/year to 360 MW/year.

### *Challenges*

For large-scale industrial and energy applications, water electrolysis is still too expensive to compete with hydrogen produced from natural gas or with the energy sources it is intended to replace, such as natural gas. This means the costs have to come down. The primary avenues for doing this are:

- Lowering the investment costs for an electrolysis system, this meaning the costs for producing and delivering an electrolysis system (stack<sup>26</sup>, transformer, rectifier), including balance of plant (system and gas cooling, gas treatment, demi-water production, metering and regulator systems, etc.).
- Increasing lifetime of stack while keeping yield from hydrogen production constant.
- Increasing yield from hydrogen production while keeping lifetime of stack constant.

### *Increasing yield and improving lifetime*

In electrolysis, the cell voltage is a measure of efficiency and the flow density is a measure of productivity per unit of cell surface area. An increase of the cell voltage leads to an increase of the flow density, and thus of the productivity per unit of cell surface area; in other words, less cell surface is needed for the same production capacity. This results in a decrease of the specific investment costs (€/kW). But an increasing cell voltage means a decrease in efficiency, and as such an increase of electricity consumption and the electricity costs per unit of hydrogen produced. An additional factor is that higher flow density can lead to accelerated degradation of the cell performance and thus a reduced lifetime. The type of operations can also be of influence; more degradation would be expected where operations exhibit strong dynamics as compared to a stationary system. Higher degradation can lead to accelerated replacement of stacks, which will increase investment costs over the lifetime of the system.

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26 Stacking of electrolysis cells that consist of two electrodes (anode and cathode) separated from each other by a microporous layer or membrane (Membrane Electrode Assembly, MEA), fitted with bipolar plates on either side. These cells are separated in the stack by separator plates that provide electrical isolation and sealing of the individual cells.

These trade-offs must be considered in the choice of the work point for the electrolyser, and in this choice the relative importance of fixed and variable costs will depend in part on the specific application. The lifetime of a stack is therefore not so much an absolute technical given but much more the result of an economic consideration.

Raising the yield of an electrolyser means higher productivity or less rapid decrease in productivity per unit of cell surface area at a constant cell voltage (efficiency), or a higher efficiency (lower cell voltage) or less rapid decrease in efficiency at constant productivity per unit of cell surface area. Yields can be increased by:

- Research for better understanding of degradation behaviour of electrodes/catalysts and membranes, under both stationary and strongly dynamic operation, in order to then work towards focused improvements.
- More stable electrodes with better catalysts.
- Better membranes with a higher conductivity and fewer defects.
- Reducing resistance by using thinner membranes without reducing lifetime, by optimising porosity of electrodes and gas diffusion layers for supply and extraction of reactants and products, and by optimising cell design.

Better understanding of degradation behaviour and development of better electrodes and membranes will also improve the lifetime of the cells and the stack.

### *Reducing investment costs*

Investment costs can be reduced in a number of ways:

- Developing cheaper alternatives for the most expensive materials and components without compromising yield, reliability and lifetime of the technology and the system. There is a lot to be gained with PEM in particular by replacing the platinum and iridium catalysts in the current form of the technology with cheaper alternatives.
- Optimisation of the design of an electrolysis system to use less material and fewer components.
- Industrialisation of the production of electrolysis components, stacks and systems; upscaling of production numbers (economy of numbers) and automation of large-scale and reproducible production within narrow product tolerances, which would decrease the production costs per system.
- Upscaling of the capacity of a system (economy of scale), by which relative scale effects could be reached, on balance requiring less material per unit of product.
- Development of industrial chains of vendors to create more competition between suppliers of technology and components to reduce prices.

### *Electrolysis programme*

In view of the state of the art in electrolysis, a programme has been proposed focusing on the one hand on implementation of existing technology in order to test the technology under real-world conditions, gain a better picture of the optimal integration of the technology into industrial production processes in parallel with adoption into the energy supply, and to enable upscaling of the technology and facilitate the creation of industrial chains of vendors.

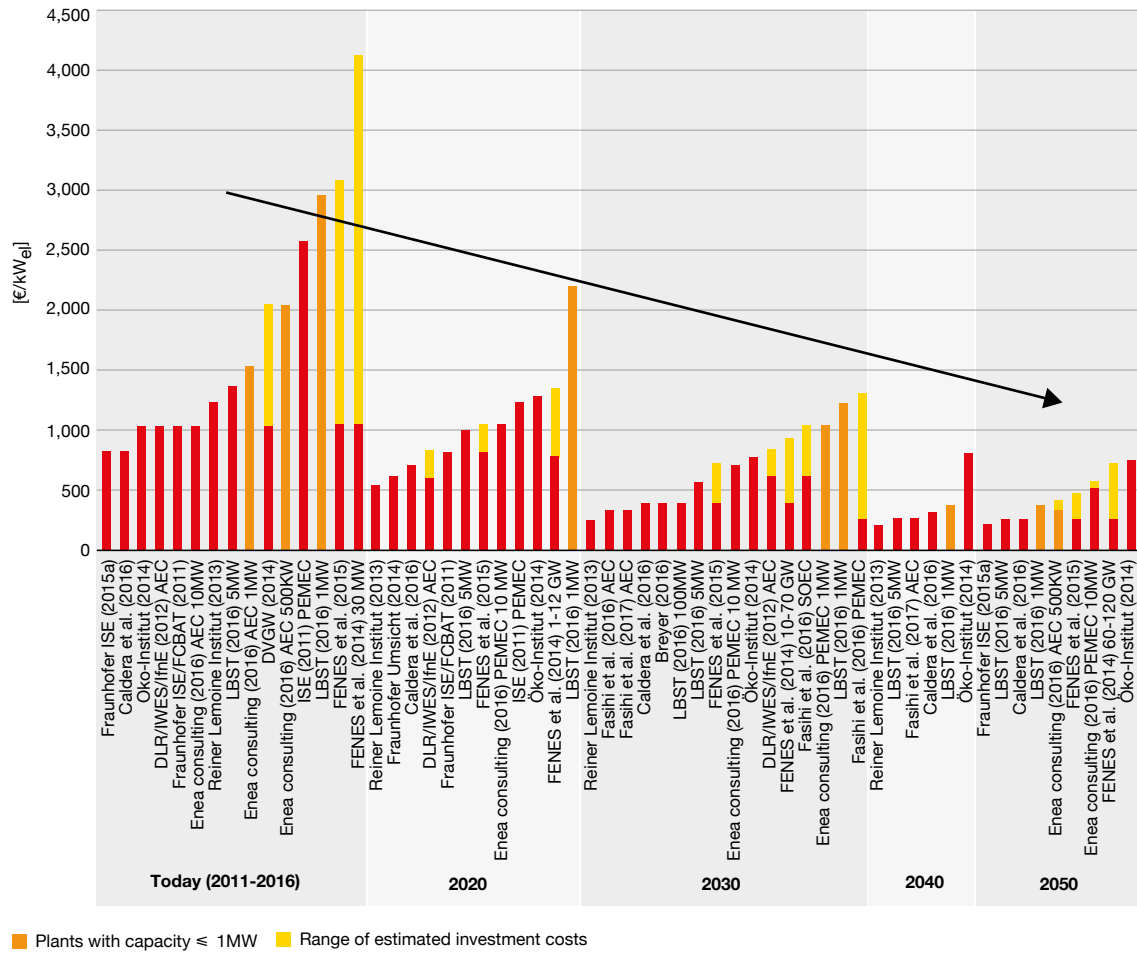
And on the other, to more fundamental improvement of the technology in the long-term through R&D on better membranes, catalysts and electrodes. Broadly speaking, this will lead to the following components for an electrolysis programme:

- Regional rollout of climate-neutral hydrogen at the 10-100 MW scale in industrial clusters, with:
  - Pilot projects of electrolysis at the MW scale, in part to demonstrate duration behaviour
  - Integration and flexibilisation of water electrolysis in the energy system
  - First design of a GW-scale electrolysis plant
- Cost-effective manufacturing technology of electrolysers
- New catalysts and membrane materials for increased lifetime and yield
- More stable, more selective and more efficient electrodes and reactors for hydrogen production

Development goals for the technology can be found in the Multi-Annual Work Programme and Annual Works Programmes of the Fuel Cell and Hydrogen Joint Undertaking (FCH JU) under H2020 (FCH JU 2014) or, for example, the United States Department of Energy's Multi-Year Research, Development and Demonstration Plan.

Figure B2 shows an overview of the expected/estimated cost-price reduction of electrolysis systems identified in 2018, based on various studies. Here, it should be noted that the expectations/estimates are frequently rendered outdated by more recent estimates put forward by manufacturers.

**Figure B2 | Table of decrease in investment costs of electrolysis, on the basis of various sources**  
(World Energy Council, 2018).



MMIP 8 includes a rough estimate of the numbers in terms of projects and budgets that will be necessary to achieve the ambition of 3-4 GW of electrolyser capacity in 2030 (Table B1).

MW output per project	Number up to 2030	Total output (MW)	SCA + SOP (€ x 1,000,000)	Total support (€ x 1,000,000)
20	5	100	70	350
100	4	400	200	800
250	2	500	200	400
500	2	1,000	300	600
1000	2	2,000	550	1,100
		4,000		3,250

**Note:** SCA = Subsidy Capex, SOP = Subsidy Opex



## Annex C | List of hydrogen projects (status: autumn 2019)

Publicly available summaries of funded projects (primarily by the Netherlands), broken down by hydrogen chain. Except where otherwise indicated, amounts given are the funding packages allocated. Where possible, the project names also include hyperlinks to websites with more information. Not included in this list are R&D projects under CSER funding, M-ERANET, NWO CO<sub>2</sub> programme and research talent funding.

### 1. System studies

**Feasibility system integration gas + wind energy island IJmuiden (IJVERGAS)**  
– CE Delft/HAN University of Applied Sciences/ Intecsea B.V./Offshore Service Facilities B.V./ Stichting New Energy Coalition/ TNO Science & Industry – €216,053  
– 15-02-2019/15-02-2020

The goal of this project is to inventory the opportunities, challenges, costs and planning for the production of hydrogen on an artificial island (IJver) using electricity from the windfarms off the coast of IJmuiden, the Vera area. This project is investigating both technical and financial feasibility (including risks) and, additionally, the legal aspects, ecological aspects, stakeholders and required permits. Required conditions and critical milestones are catalogued for recommendations to OSF on how to proceed with the development of the island.

**Feasibility study Power-2-X demonstration Roosendaal**  
– TNO – €25,000 – 01-09-2018/01-04-2019

The ReEnergy plant in Roosendaal is currently supplying electricity generated from waste to the electricity network. This flexible Waste-to-Energy plant can play a new role in facilitating the energy transition, particularly in the Roosendaal region. The ReFuel concept is focused on this transition from renewable waste via sustainable electricity to low-carbon hydrogen, transport fuels and chemical raw materials.

**System design Power to X – KWR Water B.V./ Allied Waters B.V./ Aveco de Bondt B.V./ Pitpoint.H<sub>2</sub> B.V./ Stichting Waternet/ TU Delft – 2017/2018**

The goal of the Urban Energy project “System Design Power to X” (SPX) is to generate knowledge and insight for the development of a blueprint to arrive at a full-scale demonstration of the PtX system.

**HyChain 1 – Stichting TKI-ISPT/ Quintel Intelligence B.V.**

The object is to inventory/predict future demand for hydrogen in industry, as well as the required infrastructure and the implications of H<sub>2</sub> use on other energy sources.

**Hychain 2 – Stichting TKI-ISPT/ Kalavasta B.V.**

Using analyses of various sources and through cooperation with projects conducted through the ISPT programme Energy Sources Value Chain, this project will first make an estimate of the production costs in the Netherlands and the total import costs (production costs, transport costs and storage costs, excluding taxes) of various energy sources – as well as the demand for these sources in the Netherlands and its hinterlands. This data can then be used to make a model with the ability to adjust all relevant input data. The model will calculate how much of each energy source can be imported, produced and consumed on the basis of the lowest total cost. Ultimately, the model will produce an overview of the flows of the prospective energy sources through the Netherlands. Next, on the basis of the model, a number of different scenarios will be worked out and presented in a detailed report. Finally, the primary conclusions will be distilled into a short, non-technical report. Kalavasta is leading the project and research; ECN is providing the material coordination within the ISPT programme and is responsible for validation; other parties are contributing material expertise based on their own domains.

**HyChain 3 – Frames Energy Systems B.V./ Stichting TKI-ISPT**

– €75,000 – 01-09-2018/30-06-2019

The goal is to inventory failure and success factors of production, transport, storage and use of hydrogen based on four different parameters: social, technical, expense, and environment. The knowledge is documented in a database.

**Hydrogreenn** – *(HYDROGen Regional Energy Economy Network Northern Netherlands) – AkzoNobel/ Holthausen/ Gasunie/ ChemPort/ New Energy Coalition/ Vattenfall/ Shell/ Gasterra/ Entrance/ TNO/ Stork/ Province of Groningen/ SBE/ Resato/ Siemens/ Ministry of Infrastructure and Water Management*

HYDROGREENN arose from an initiative by Entrance and STORK following the report “The Green Hydrogen Economy in the Northern Netherlands” by the Northern Innovation Board. HYDROGREENN is an answer to the report’s call for a “strong, steadfast green hydrogen ambassador” Companies and institutions have decided to join forces to embody the ambassadorship of hydrogen as an innovation driver. HYDROGREENN is doing this with the efforts of its partner companies on actual business cases and a study of the feasibility and removal of barriers and future plans. This is done by:

1. Promotion of study, removal of barriers, in part by organising the HYDROGREENN CASE.
2. Identifying existing and potential hydrogen initiatives in the Northern Netherlands and the performance of supply chain analyses.
3. Promotion of network-building between companies and institutions in the Northern Netherlands: organising network meetings and supply chain meetings.
4. Consulting with educational institutions on preparing for work in the hydrogen economy/ hydrogen industry.
5. Organising excursions and visits outside the region (national and international); building national and international networks.
6. Participation in national meetings on hydrogen, renewable energy and gas (TKI Gas, NWWA, others) to promote business development, financial incentives and regulation.
7. Public information campaigns and promotion of pilot and mobility projects; promotion of studies of aspects of safety and public acceptance/opinion.
8. Facilitating the development of testing locations.

**Feasibility of blue H<sub>2</sub> from natural gas** – *Berenschot/ TNO – Completed 2017*

This study considers the feasibility of blue hydrogen, which is produced by splitting natural gas into hydrogen and CO<sub>2</sub> and then storing this CO<sub>2</sub> underground offshore. It also places a main focus on system integration of central generation, underground buffer storage and the use of the existing gas transport network. The use of blue hydrogen must serve as a kickstart to hydrogen, with ultimately a transition to green hydrogen.

**TKI system integration study, offshore wind to hydrogen mobility**

*– Composite Agency/ ECN/ Stichting Energy Expo/ Stichting Energy Valley/ Techmacon – €50,000 – Completed 2017*

The objective was to demonstrate that the conversion of offshore wind energy into hydrogen, applied in the mobility sector, results in lower costs than a higher value (euro/MWh). The study searched for advantages of synergy through integration or use of new technologies, such as: consolidation of output electronics of the wind turbine and electrolysis (lower cost, higher efficiency); maintenance strategies; high gas pressure and use of high-quality composites, temporary storage of hydrogen combined with smaller capacity transport; carrying offshore transport lines through to shore to avoid distribution costs; high-quality hydrogen from electrolysers, meaning longer lifetime and higher efficiency of the fuel cell; etc.

**Conversion of natural gas to hydrogen – Berenschot Groep B.V./ EBN/ N.V. Nederlandse Gasunie/ NOGEP/ TNO – €47,350 – Completed 2017**

This project analysed several system configurations (onshore/offshore, various sales markets for hydrogen and CO<sub>2</sub>). The activities focused on the technical, economic and institutional aspects involved. A supervisory commission made up of various stakeholders and chain partners was formed to develop a broadly supported perspective. Finally, a roadmap was developed to support the further introduction process.

**System study for P2G-routes – ECN/ Alliander/ EBN/ Enexis/ KEMA/ Nederlandse Gasunie/ Rotterdam Climate Initiative/ Stichting Energy Valley/ TenneT TSO/ Vattenfall AB – Completed**

The main question this project addressed is: under what circumstances and in what situations do P2G applications play a role in the transition to a more sustainable energy landscape, in consideration of the complexity of the energy system?

**Archipel – Alliander/HAN University of Applied Sciences/ Hydrogen Efficiency Technologies (HYET) B.V./ Hydron Energy B.V./ MTSA Technopower B.V./ Nedstack Fuel Cell Technology B.V./ Process Design Center B.V./ Stichting TKI-ISPT – €? – Completed 2016**

Generation of sustainable energy from wind and sun demands flexibilising of the demand and storage of energy, because supply and demand will not always match up in terms of volume and time. This project investigated whether small-scale energy storage using hydrogen would be usable and effective in combination with flexibilisation of the demand.

## 2. Production of hydrogen

### Electrolysis

**AMPERE** – *Advanced Materials for PEM Electrolysers Reducing cost and enhancing lifetime.* – ECN/ Fujifilm Europe B.V./ Hydron Energy B.V. Polymer Technology Group Eindhoven B.V. – €249,299 – 01-01-2018/31-12-2019

AMPERE is achieving the objectives by offering a low-threshold platform to component vendors for testing and characterising components, building on earlier projects such as ELECTRE and FlexP2G. In addition, AMPERE is also testing improved electrolyser stack technology based on innovative components that are identified and developed in this project.

#### **Alkaliboost**

– *Nouryon Industrial Chemicals/TUe* – €500,000 – 01-05-2019/01-05-2023

The objective of this project is the development and testing of new alkaline stack designs that can enable operation at a much higher flow density, which can reduce the effective costs of the electrochemical step to below €100/kW. The focus is on minimising the ohmic resistance, which along with the membrane is determined primarily by the structure of the electrodes and the gas bubbles formed.

**Alkaliflex: increase of the flexibility and production capacity of alkaline water electrolysis** – *Nouryon Industrial Chemicals/TUe* – €250,000 – 01-02- 2018/01-08-2019

The object of this study is to make a significant step towards increasing the flexibility and lowering the capital costs of alkaline water electrolysis technology. This is intended to lead to a reduction of the cost price of hydrogen to €2.00/kg in 2025 and €1.50/kg in 2030.

**Development of an advanced MEA production route for PEM electrolysers** – *Hydron Energy B.V/ TNO* – €241,022 – 01-07-2018/01-07-2019

The MEAPRO project has the goal of achieving dramatic cost reductions of PEM electrolysis equipment by developing advanced production technology for the manufacture of the most important component product: the membrane electrode assembly (MEA).

**Cost reduction industrial PEM electrolyzers – ECN/ Frames Energy Systems B.V./ Hydrogen Energy B.V. – €898,129 – 1-11-2017/31-10-2019**

This project combines multiple subprojects pursuing the next generation of PEM electrolyzers with the following objectives:

- A cost, performance and manufacture-optimised 50 kWe PEMWE stack.
- A conceptual design for a 1 MW hydrogen production system. The development of this system will bring Dutch technology to the international state of the art.
- Design of a demonstration product including choice of location and business case.
- Access to knowledge and infrastructure to conduct length of lifetime testing of electrolyser components for Dutch companies to gain insight into and access to the market for electrolyser components.

**Hydrohub – ISPT (coordinator)**

The Hydrohub is an open testing center in which the partners of the consortium, as well as other knowledge institutions and companies, can test innovations from their own labs in 250 kW electrolysis systems (PEM and alkaline). Testing at this scale makes clear whether new problems may arise and how the technology will behave upon upscaling. If the hydrogen technology works in the Hydrohub, then the next step is upgrading it to an electrolysis system at the industrial GW-scale.

**Feasibility of development of mobile windmills with high yield**

– TD Constructies B.V. – €50,000

TD Constructies (TD) is developing a Wind Power Bowl (WPB), a mobile windmill with high yield even at low wind speeds, which avoids most permitting problems due to its low height. TD has recently conducted several tests with this system and is on the point of completing development and starting production/sales. Testing demonstrated that its yield is higher than expected. At the moment that the battery is full and there is no further power draw, the windmill still generates power, but this power is not used. Because this is a waste, TD is investigating whether it is possible to expand the WPB and use the surplus energy for the production of hydrogen and oxygen. Hydrogen is a flexible and environmentally friendly energy source, and can be used as a fuel for cars, a gas for welding, or conversion into electricity. Oxygen can also be stored in cylinders and is suitable for use in welding and cutting metal. Hydrogen is only a sustainable alternative when it is generated from sustainable energy. The value and use of sustainable energy generated with the WPB can be maximised through buffering using hydrogen. The project is investigating whether the residual energy is sufficient to produce hydrogen/oxygen, how to produce hydrogen/oxygen in a relatively small facility, how much hydrogen/oxygen can be produced with the residual energy, and how this can be stored.

**FotoH<sub>2</sub>** – *University of Alicante/ Advanced Technology Solutions/ BroadBit/ CNR-ITAE/ Hygear* – €2,578,971 – 01-01-2018/31-12-2020

FotoH<sub>2</sub> is developing a high-efficiency tandem photo-electrolysis cell for the production of solar H<sub>2</sub> on the basis of sustainable and cost-effective advanced materials and interfaces. FotoH<sub>2</sub>'s most important vision is applying the consortium's experience with innovative solar technologies towards the prototyping and validation of a large-scale deployable solar H<sub>2</sub> production technology in the form of easily integratable flat panels. The input H<sub>2</sub>O and the output H<sub>2</sub> are carried through pipes to the two edges of the panels, consisting of a self-driven throughput system that can be easily connected to a water source. The expectation is that the semiconductor tandem architecture will produce a higher yield and allow a more flexible deployment than external architectures. The validation of the technology is done on a scale of 1 m<sup>2</sup>.

**Flexible energy infrastructure through cost-effective and efficient PEM-electrolysis and Sorption** – *ECN/ Frames Energy Systems B.V./ Hydron Energy B.V./ Stichting Hanzehogeschool Groningen* – €500,000 – Completed 2017

The FLEX-P2G project laid the foundation for the adoption of robust, flexible and cost-effective power-to-gas technology in the energy system.

**Hydrogen production Almere** – *Theo Pouw, Cirwinn, Van den Pol Elektrotechniek*

In Almere, Cirwinn intends to install 3,700 solar panels on its new sorting hall (120 m x 60 m), with the panels to be delivered and installed by Van den Pol Elektrotechniek. This will generate approximately 975,000 kWh per year. With this energy, Cirwinn hopes to produce hydrogen through electrolysis. The production capacity is estimated at 46 kg of hydrogen. The goal is to produce 80 kg of hydrogen per day so that a hydrogen filling station can be installed in Almere and hydrogen trucks will be able to fill up at Cirwinn. The site gets a lot of truck traffic, in part due to the concrete plant. Cirwinn is investigating the options to reduce its CO<sub>2</sub> footprint with this project. Additionally, Cirwinn is contributing to the infrastructure needed for a hydrogen economy. The feasibility study will be completed in early 2020, after which a go/no go decision will be made on the project.

## Offshore electrolysis

**Pre-Pilot Power to Gas Offshore (3P2GO) – EBN/ Engie E&P Nederland B.V. / NAM/ Taqa Offshore B.V. / TNO Science & Industry/ Total E&P Nederland B.V./ Vereniging Nexstep – €160,119 – 20-12-2018/31-08-2019**

The goal of this project is to create the world's first offshore power-to-gas pilot project on an O&G platform. Alongside the P2G pilot project's goal of gaining experience with the production of hydrogen in an offshore environment, the project is also serving as a testing center for other innovative P2G technologies.

In addition, there is practical experience gained with the costs of installation, operation and maintenance of an electrolyser system in an offshore environment. This is reducing the risk of future P2G hydrogen systems on the North Sea for future system integration.

It is also a first step in the upscaling process for this type of system, starting with 1-10 MW, moving up to 20-250 MW and then ultimately to >250 MW systems.

## Hydrogen from biomass

**SCW – SCW systems/ Gasunie**

Super Critical Water gasification (SCW) is an innovative technology that converts wet biomass (generally waste flows such as manure, organic waste and sewer sludge) into sustainable electricity and reusable raw materials. Gasunie New Energy and the company SCW Systems intend to build a demonstration system at the Energy Innovation Park in Alkmaar. New Energy's activities in this are limited to the construction of the infrastructure.

**Green hydrogen production through Continuous Catalytic Re-cracking**  
– CH Energy Zernike B.V./ Solution 2 Nature B.V. – €49,998 – 26-09-2018/31-05-2019

**Hydrogen production from residual biomass**

– Bio Energy Netherlands B.V./ Hygear B.V. – €446,064 – 01-02-2019/31-01-2021

The goal of the project is the development, construction and testing of a gas upgrading system linked to a gasification system for the local production of green hydrogen from biomass.

The applicability is validated at a small scale with a hydrogen production capacity of 10 Nm<sup>3</sup>/hour. A full-scale design is produced. The syngas from the gasification system is first stripped of contaminants to make it suitable for further conversion into hydrogen. The influence of operational parameters of the gasification system on the concentration of contaminants is investigated, and additional scrubbing steps will be introduced. The conversion is a two-step process: first, the CO present is converted into H<sub>2</sub> and CO<sub>2</sub> by steam, and in the second step the gas is upgraded by means of a pressure exchange system into pure hydrogen. The residual flows from the system are used to supply the heat needed for the process.



**Gas cleaning module for High-Quality Utilisation of Biomass**

– TNO/ Albermarle Catalysts Company B.V./ ECN – €? – Completed

Biomass gasification will have its most significant application in the production of products of a higher quality than electricity and heat. These include biofuels, hydrogen, green gas and chemicals.

To do this, the raw product gas must be extensively scrubbed and refined.

Along with removing dust and tar, a number of catalytic process steps are required. There are catalysts available for this, but there is still much room for improvement, for example in terms of tolerance for contaminants, saturation level of absorbents, use of steam to prevent soot formation and flexibility in quality of product gas.

**Hydrogen on-site from natural gas**

**DUOGEN – Carnot Financial Logistics B.V. – €50,000 - 2016**

Process gases in bulk are generally produced centrally and transported by road to the end user. HyGear supplies hydrogen by means of small-scale steam reformers in order to produce the hydrogen locally at the end user. This produces energy savings across the chain and, accordingly, cost savings with the end user.

**MIT Feasibility study – Hygear B.V. – €50,000 - 2015**

HyGear is specialised in small-scale gas generation and purification technology. Its most important product is a hydrogen production system that generates hydrogen on location from natural gas using steam reforming. The advantage of this is that the hydrogen no longer needs to be transported by road, which entails considerable cost savings and improvements in efficiency in the delivery chain. The company has the ambition to be able to deliver and reclaim multiple gases in the process industry. The technological edge in on-site technology should make it possible for HyGear to build up a market position in the process industry.

### 3. Transport, distribution and storage of hydrogen

#### Gas quality

**Hy4heat – Kiwa Gastec/ Progressive Energy/ Embers/ Yo Energy – £25 million - demonstrations in 2020**

Hy4Heat is a programme commissioned by the British Department for Business, Energy & Industrial Strategy to investigate whether the replacement of natural gas by hydrogen for heating and cooking in homes is feasible and could be a component of a plausible potential path for decarbonisation of the heat supply. In the process, the programme will develop and collect knowledge concerning the technology, performance, usability and safety to demonstrate whether hydrogen can be used for heating in buildings. This will, in part, comprise a study of standard, odourisation, colour, gas quality, etc.

#### Hydrogen distribution networks

**H21: Project in UK (100% hydrogen) – Northern Gas Networks/ Cadent/ SGN/ Wales & West Utilities/Health & Safety Laboratories/ DNV GL – £10 million UK Government – since 2016**

The H21 project in Leeds (UK) is a feasibility study under the leadership of gas company Northern Gas Networks (NGN) into the redesign of the gas network to create a high-pressure (17 bar) outer city ring for natural gas transport to SMR systems that produce hydrogen (with CCS) for distribution in the local network (<7 bar). In April 2017, NDN and the city of Leeds opened a project bureau with the object of “delivering innovation projects with a strategic focus on producing solid proof to support the British gas network conversion from natural gas (methane) to carbon-free hydrogen.” Hydrogen will have to be safe for application in the built environment and in distribution networks. This will identify the risks of leakage in homes and distribution networks when using pure hydrogen. It will also look at the risks of ignition and risks of small and large gas leaks. The goal is to demonstrate that hydrogen is no more dangerous than natural gas in homes and during the distribution process.

**H100 – Hydrogen end use (new build)**

Three feasibility studies of the use of 100% hydrogen in the gas distribution network.

## Hydrogen-natural gas mixtures

### **Sensor technology for hydrogen in the gas network.**

– *Bronkhorst High-Tech B.V./ Enexis B.V./ Gasunie Transport Services/ N.V. Continuon Netbeheer/ TNO – €224,877 – 01-03-2019/01-09-2020*

This project is developing technology for a prototype gas sensor, initially developed for the measurement of natural gas composition in the distribution network and to be made suitable for measuring the composition of natural gas/hydrogen mixtures.

### **Hydeploy project (DNV GL involvement)**

In the Hydeploy pilot project (Cadent gas), mixtures of up to 20% hydrogen in natural gas are tested in the built environment. DNV GL has been involved with respect to the impact of hydrogen on the performance of gas engines.

### **Joint Industry Project HYREADY – ENAGAS, GasNatural Fenosa, Gas Networks Ireland, GazSystem, GRDF, GRT-Gaz, SoCalGas (California), TIGF and Enbridge (Canada) – 2017-2018**

Inventory of existing knowledge to create guidelines for introducing hydrogen into transport and distribution networks for natural gas and end user applications.

### **The effects of hydrogen injection in natural gas networks for the Dutch underground storages – DBI – Completed 2017**

The maximum permitted quantity of hydrogen in the gas network varies between 0.02 and 0.5%, depending on the location in the country. This project researches what the effects of hydrogen injection into the natural gas distribution system and underground gas storage are at hydrogen mixtures up to a value of 0.5%. It also looks at the effects of higher hydrogen contents (10% and 100%). The project also surveys the procedures for hydrogen in the gas distribution systems of neighbouring countries.

### **PurifHy – ECN/ Stedin/ KEMA/ HYET – €250,000 – Completed 2015**

This project investigated the possibility of selectively removing hydrogen from a sustainable gas flow such as biogas/green gas for injection into the existing gas line network. HyET is developing a new technology, “electrochemical hydrogen purification”, which makes it possible to selectively pump hydrogen into or out of a gas flow at any pressure differential. This method of purification can have a direct impact on the variation in composition of the sustainably produced gas.

## Compression

### **Development of cost-effective control systems for a hydrogen compressor module – HyET – €22,440**

HyET is developing a hydrogen compressor on the basis of electrochemical technology. For this, the HAN University of Applied Sciences developed the electronic control system in collaboration with Ascos. These electronics are intended to make it possible to produce a relatively inexpensive compressor module on the basis of which the electrochemical hydrogen compressor could be deployed on a large scale.

Electronics developed will offer functionality specific for this application and the CVM (Cell Voltage Measurement) as well as the option to use a relatively inexpensive controller platform. In order to ensure that the control electronics developed can also be produced well and cheaply, a manufacturing party was engaged in the design phase and will later become responsible for the production.

### **High Pressure integrated storage, transport & distribution Solution – Hygro B.V./ Composite Agency/ E-trucks Europe B.V./ GP Groot Brandstoffen en Oliehandel B.V./ NEN/ Schipco Consultancy B.V./ Toyota Material Handling Nederland B.V. – €50,000 – Completed 2018**

Wind turbines can be configured to produce hydrogen at an attractive price. At the same time, mass production in particular will reduce the cost price of fuel cells, which will quickly make the use of hydrogen as a replacement for diesel fuel more attractive. By contrast, it also appears that a large portion of the price for the end user of hydrogen will be in the transport, storage and distribution, “from production to tank”. In the current structure of the chain, hydrogen changes tank, pressure and temperature several times. Integrating and standardising the various links in the chain must make it possible to reduce the cost price of this section of the chain. The study produces an integral vision of how the chain from wind to the various hydrogen applications can be optimally configured and what cost price reductions this can produce in comparison to the current situation.

## Import of hydrogen

### **Development of solar fuel – CE Delft/ N.V. Nederlandse Gasunie/ Vattenfall Power Generation B.V. – €13,185 – Completed 2018**

Alongside the need for short-term flexibility, there is also a need for long-term storage and/or import of renewable energy, due to the imbalance between supply and demand in summer and winter among the various European regions. It seems that there may be a cost advantage to importing renewable fuel generated from solar energy. This suggests that solar fuel could be a medium for both storage and flexibility for bridging the temporal and geographic imbalances.

The project investigates the feasibility of production and import of solar fuel from Southern Europe, North Africa and the Middle East.

Results: a chain model for solar fuel based on cost structures, chain optimisation, structuring of the cost price of solar fuel and feasible returns for the links in the chain; a list of the strengths and weaknesses of the chain model in comparison to domestic alternatives for the production of hydrogen and ammonia; and a roadmap for chain development with the necessary steps, timeline and distribution of roles among actors.

### **Cost implications of Dutch import, export, transport and storage of renewable energy sources – Kalavasta B.V./ Stichting TKI-ISPT – €75,000 – 01-05-2018/31-12-2018**

Using analyses of various sources and through cooperation with projects conducted through the ISPT programme Energy Sources Value Chain, this project will first estimate the production costs in the Netherlands and the total import costs (production costs, transport costs and storage costs, excluding taxes) of various energy sources – as well as the demand for these sources in the Netherlands and its hinterlands. This data can then be used to make a model with the ability to adjust all relevant input data. The model will calculate how much of each energy source can be imported, produced and consumed on the basis of the lowest total cost. The model will produce an overview of the flows of the prospective energy sources through the Netherlands, on the basis of which various scenarios will be developed and presented in a detailed report. The primary conclusions will be distilled into a short, non-technical report. Kalavasta led project and research; ECN provided the material coordination within the ISPT - programme and was responsible for validation; other parties contributed material expertise based on their own domains.

## Storage

### **OPVIS 1 & 2 – TNO/ EBN for the Ministry of Economic Affairs and Climate Policy – Completed 2018**

This study produced an exploratory technical inventory of the various forms of underground storage that could play a significant role in the energy transition (including hydrogen). The results are correlated with expectations with regard to future demand for these forms of storage. Finally, a list of research questions was presented with respect to the development of storage and the conduct of an adequate policy concerning underground storage in general.

### **Large scale energy storage in salt caverns and depleted gas fields – TNO/ Nouryon/ EBN/ Gasunie/ GasTerra/ NAM – TKI Nieuw Gas project – 2019/2020**

TNO with partners EBN, Gasunie, Gasterra, NAM and Nouryon recently started a joint-industry project on large-scale subsurface energy storage: TKI project Large-Scale Energy Storage in Salt Caverns and Depleted Gas Fields. The consortium assesses the value of hydrogen and compressed air storage technologies in the current and future energy system and will address key technical and non-technical hurdles that affect the market implementation of the technologies. The one-year project is partly funded by the Dutch Government.

## Offshore hydrogen

### **Offshore Reuse Potential for Existing Gas Infrastructure in a Hydrogen Supply Chain – 2018 NEC Study – Completed 08-02-2019**

This study produced an analysis of cost profiles for various ways of transporting hydrogen produced offshore on the North Sea. A mathematical model was used to produce five different scenarios. The report can be found [here](#).

### **Offshore Reuse Potential for Existing Gas Infrastructure in a Hydrogen Supply Chain at a specific location – Proposal for a follow-up study.**

## Hydrogen utilisation via other energy sources

### **Power2Gas and the power of methane**

– *KEMA Nederland B.V./ Stedin – Completed*

The goal of the project was to demonstrate that it is possible to convert surpluses of electricity into hydrogen and via methanisation (with or without using green carbon dioxide from fermentation processes) convert it into methane and then supply this methane into distribution networks.

## 4. Applications: Industry and (Central) Electricity Production

### Greening of hydrogen in industry

#### **MegaWatt Design Delfzijl – Nouryon Industrial Chemicals/ N.V. Nederlandse Gasunie – €133,602 – 01-07-2018/01-05-2019**

This project has two goals:

1. Demonstrating and implementing a power-to-hydrogen system on a large scale (20 MW) in industrial and commercial conditions for the production of green hydrogen as a material for green chemicals, starting with green fuel. The focus must be on the preparation for making the next step in the upscaling within 5 years.
2. Demonstrating the purchase of electricity at reduced rates through advanced purchasing and arbitration strategies, combined with generating a significant increase in value by providing balancing services to the electricity network at a 20 MW-scale. The goal is a reduction of 35% on electricity costs as compared to a steady consumer operating at constant production.

#### **H2M (Hydrogen-to-Magnum) – Vattenfall/ Gasunie/ Statoil**

The goal of the H2M (Hydrogen to Magnum) project is to use hydrogen in the Magnum power station at Eemshaven in Groningen. The hydrogen is to be produced using ATR from Norwegian gas, with the captured CO<sub>2</sub> stored underground in Norway (CCS). The project consists of 3 components: 1) production of blue hydrogen for electricity generation and industrial use (“Equinor scope”), 2) application of hydrogen for electricity generation (“Vattenfall scope”), and 3) modifications in the power station for hydrogen uses, including modification of gas turbines, modification of burners, etc.

**H-vision : Large-scale application of blue hydrogen as replacement of natural gas in Rotterdam – Deltalinqs et.al.**

– €594,883 – 15-08-2018/01-06-2019

The H-vision Project has the goal of making a significant contribution to the reduction of CO<sub>2</sub> emissions in the entire Rotterdam region by introducing blue hydrogen for industrial uses as replacement for traditional natural gas, starting in the 2025-2030 period.

This project is focused on the preparation of a large-scale pilot project (the H-vision pilot project) for the Rotterdam region.

**Assessment in Future Trends in Industrial Hydrogen Demand and Transport – Quintel Intelligence B.V. – €75,000 – 01-09-2018/31-03-2019**

The goal is to inventory/predict future demand for hydrogen in industry, as well as the required infrastructure and the implications of H<sub>2</sub> use on other energy sources.

**Network services**

**HyStock: power-to-gas hydrogen at Zuidwending natural gas buffer**

– EASE/ Energy Storage NL/ TenneT TSO/ Gasunie/ Green Planet/ TU Delft/ Energy Valley/ Ministry of Infrastructure & Water Management – €11,700,000 – 2017/2019

HyStock is part of the European project “TSO 2020: Electric Transmission and Storage Options along TEN E and TEN T corridors for 2020” (2017 – 2019). Activities in this project are studies into the link between renewable energy and zero-emissions mobility with an emphasis on energy storage and network management; an electrolysis pilot project; and the drafting of a business plan for upscaling to large-scale application. The project wants to help activate the supply chain for hydrogen to mobility. The first phase is a demonstration of a 1 MW electrolyser. The goal is to learn the state of the technology and how to handle hydrogen. At the location (Zuidwending), approximately 5,000 solar panels will be installed, representing 12% of the annual capacity of the electrolyser. The other 88% is covered by green electricity from the network to maximise the number of running hours. This green electricity is supplied by third parties, and EnergyStock is providing the conversion and storage services. The hydrogen is then taken by tube trailer to the filling station Green Planet in Pesse. TenneT, with specialised contributions from TU Delft, is working with Gasunie towards the integration of electrolysers within the electricity system.

The underlying question is how to maintain the stability of the electrical system with large-scale integration of wind and solar. The specific research theme in TSO 2020 is the dynamic between the electricity system and hydrogen. An electrolyser can provide services for network voltage and balance. The project intends to study this with a 1 MW electrolyser, as an initial step towards a 300 MW upscaling.



**Cyrus Smith – Hymatters V.O.F. – €50,000 – 01-12-2018/30-11-2019**

This project is a feasibility study into a mobile unit to deliver medium and low-voltage level network support by conversion of green electricity to hydrogen. This hydrogen will then be available for local mobility (tractors, earthmovers, forklifts, buses and/or cars). A number of parties in the market have already been expressing interest in this unit for some time. This means the project objective is in keeping with the TKI objective of supporting research and development on concrete products or technologies that contribute to further energy innovation.

The envisioned unit will be able to make a contribution to meeting the following challenges in our energy system:

- capital to support the local low-end medium-voltage network, which with the intake of sustainable electrical energy will move outside the applicable voltage standards.
- Local balancing of generated sustainable electricity and local demand for electricity. By matching a portion of the supply and demand locally, more expensive “upstream” solutions can be avoided or postponed.
- Making hydrogen available locally for applications that cannot drive to a hydrogen filling station themselves, such as forklifts, earthmovers, tractors and/or landscaping equipment.

This feasibility study has the goal of establishing and validating the technical feasibility and economic value of the network interaction element of the unit. To achieve these goals, the project is engineering a 20 kW mobile unit that is built to scale in terms of the essential components and evaluated as a realistic case.

## Gas turbines and burners

### **High hydrogen gas turbine retrofit to eliminate carbon emissions**

– AKZO/ Ansaldo/ Emmtec Services/ Vattenfall Power Generation/ Opra Turbines International/ TU Delft – €499,951 – 07-01-2019/28-02-2020

The most important goal of the High Hydrogen Gas Turbine Retrofit project is to develop a cost-efficient and interchangeable combustion system with ultra-low emissions values (below 9ppm NO<sub>x</sub> and CO) for already installed and operating gas turbines (with a power output range between 1 and 300 MW). Flexibility in the fuel composition used is the primary consideration and must be able to guarantee stability in operations. This stability must be ensured for fuel variations between 100% natural gas to 100% hydrogen and every mix in-between. This is the biggest challenge, being that such extreme variation of fuel composition with differing flame reactivity can result in dramatic displacement of heat within the combustion chamber, and this in turn can lead to irreparable damage where it does not happen in a controlled way.

### **Varigas: an industrial hydrogen/natural gas combustion system**

– DNV GL Oil & Gas/ Zanting B.V./ Stork Thermeq – €? - 2016

One of the Dutch government's objectives is to increase the share of sustainable gases in the gas network to reduce the "carbon intensity" of industrial energy consumption. A potential gaseous fuel is hydrogen, which can be sustainably produced from a number of energy sources, including "surplus" wind or solar energy (Power-to-Gas). The solution proposed by DNV GL to increase the share of sustainable gases in the gas network in the future, and to reduce the carbon intensity of industrial energy consumption, is to develop a new industrial burner that can run on hydrogen, natural gas/hydrogen and natural gas while preserving safety, operational security and low emissions.

### **Proof of Concept: HYOX technology for Early Adopters**

– BKS Verkoop en Advies B.V./ Hartevelt Stomerij B.V./ Hyox B.V./ Theo Pouw Secundaire Bouwstoffen B.V. – €159,280 – Completed 31-5-2016

The HYOX project is focused on the added value of mixing of hydrogen and oxygen in thermal burners running on natural gas. The mixture that can be produced by electrolysis of water makes normal combustion run more efficiently. A relatively small amount of mixing can lead to significant reductions in fossil fuels. And an additional advantage is that it can be made on location as needed, eliminating the need for storage. The tests with individual burners should demonstrate the prospects for broader application.

## 5. Applications: Mobility and Transport

### Road vehicles

**Serial-built conversion kit for road transport: from diesel to Plug-in Fuel Cell Electric** – Garage71/ H<sub>2</sub>Consultancy B.V. / New Electric B.V. – €461,205 – 01-01-2019/31-12-2020

The objective of this TSE hydrogen project is the development of a conversion kit and pilot vehicle for a 30 kW Plug-in Fuel Cell Electric Vehicle (PFCEV) that can be used for movements in the metropolitan environment. The project is focused on the integrated drive system for generic retrofit into box-body trucks and inland waterway vessels. The higher goal, after success of this project, is an initial economic production line in the Netherlands for the serial-based production of conversion kits for the professional conversion of diesel engines to PFCEV.

**H2SHARE** – VDL/ Wystrach/ WaterstofNet/ Gemeente Helmond/ TNO/ Flemish organisation for innovation in the logistics vector (VIL)/ Colruyt Groep/ e-mobil BW – €3,500,000 – 2018/2020

VDL is developing a 40-ton truck in the Interreg project Hydrogen Region 2.0 and a 27-ton truck in the EU-project H2Share. A DAF truck is fitted with an electric engine, batteries and a fuel cell as range extender. A test truck should be on the road in a number of countries starting in 2018. Heavier trucks than these cannot currently be configured for hydrogen because the current fuel cells do not have enough power for long motorway journeys, according to VDL. To solve this issue, project partner Wystrach in Germany developed a mobile filling station for hydrogen. Apart from the technology, the project is also looking at the infrastructure and regulations needed to make a successful market launch of hydrogen trucks possible.

**REVIVE** – Tractebel, Groningen, Breda en Amsterdam, E-trucks, CEA, Elements Energy, Symbio Fcell, Swiss Hydrogen, WaterstofNet, Institute of Innovative Technologies, Suez Nederland, Stadtwerke Merano en SEAB – €8,706,255 – 01-01-2018/31-12/2021

There are multiple Dutch initiatives for developing and testing hydrogen-powered freight trucks. E-trucks Europe, an SME in Westerhoven en Lommel founded by Beukers Autoschade, started with 1 garbage truck in Eindhoven in the project Waterstofregio Vlaanderen-Zuid Nederlands, followed by 2 in project Life 'N Grab Hy!, and will soon be running 15 in REVIVE, 9 in the Netherlands (2 Groningen, 2 Amsterdam, 2 Helmond, 2 Roosendaal, 1 Breda) and the rest in Belgium and Italy (Antwerp and Bolzano). The company's truck is a light DAF truck with the engine removed and an electric engine installed with a fuel cell as range extender for a small battery package. E-trucks Europe is involved in the Duwaal demonstration project, which intends to put 100 hydrogen garbage trucks on the road in the province of Noord-Holland (see elsewhere in this document).

**JIVE2 – 23 partners from 9 countries, including the province of Zuid-Holland and OV Bureau Groningen Drenthe – €25,000,000 FHCH-JU funding – 01-01-2018/01-01-2024**

In the coming years, there will be 50 new hydrogen buses in the Netherlands thanks to the JIVE2 project with FCH JU funding. This approved project comprises 152 buses, 50 of which will be placed in the Netherlands (30 in Groningen-Drenthe and 20 in Zuid-Holland). The funding is available if the buses are delivered at a sharply reduced cost price (as compared to the previous generation). The sister project JIVE1, without Dutch participation, comprises 139 buses, bringing the total of the JIVE project to nearly buses on the road in 22 European cities.

**DUWAAL Alkmaar Boekelermeer – HYGRO/ GP Groot/ RAVO/ ECN part of TNO/ Fleetcraft/ Composite Analytica/ E-Trucks Europe BV/ Ontwikkelingsbedrijf Noord-Holland Noord – €1,953,595**

This group sets out to complete an initial hydrogen filling station in Alkmaar (GP Groot), two hydrogen freight trucks (E-trucks Europe, Fleetcraft) and a hydrogen street sweeper (RAVO). In addition, they intend to further develop the technology and experiment with new forms of mobility to increase the potential for repetition. ECN part of TNO and Composit Analytica are involved in the development of an integrated storage, transport and distribution system for hydrogen. Together with HYGRO, they are developing a model for optimising the integrated hydrogen distribution and refueling infrastructure, which should clearly demonstrate the opportunities and limitations of cold compressed hydrogen. The expectation is that the results of this research should make hydrogen cheaper for the client. The filling station at Boekelermeer in Alkmaar will be equipped with a 350-bar dispenser for heavy vehicles and a 700-bar dispenser for passenger cars. If completion is on schedule, the hydrogen will start flowing in mid-2020. The hydrogen will be delivered from a hydrogen wind turbine at Wieringermeer. Fleetcraft has the task of organising the chain-wide supply and demand of hydrogen electric vehicles, and is doing this by offering full operational lease, including hydrogen.

**Eemshaven hydrogen freight truck**

– *Theo Pouw Group, PitPoint, Zepp.solutions, Stork*

For its branch at Eemshaven, the Theo Pouw Group has plans to start running a hydrogen freight truck in partnership with PitPoint and Zepp.solutions. In this project, PitPoint is set to be the vendor and distributor of hydrogen. Zepp.solutions will develop the 700-bar hydrogen freight truck that will initially have the capacity to transport a concrete mixer. For this project, a DKTI funding package has been applied for. Stork will be handling the technical side of the interfaces. The project will also include a study of whether a filling station can be operated at Eemshaven.

## Shipping

### **Alternative fuels for shipping – Koers & Vaart B.V./PitPoint. LNG B.V. – €74,304 – 01-09-2018/01-09-2019**

The goal of this study is to investigate situations in which hydrogen and/or methanol can be used for shipping, based on the perspective of operational use, technology, safety and return.

### **FELMAR: “Marinisation” and integration of hydrogen technology for inland waterway vessels and short-sea applications – B.V. Scheepswerf Damen Gorinchem/ Future Proof Shipping B.V./ Holland Ship Electric B.V./ Nedstack Fuel Cell Technology B.V./ Stichting Maritiem Research Instituut Nederland (Marin) – €? – 2018**

Within the FELMAR (First Element Marine) Project, a consortium is working together to discover the optimal application of a PEM Fuel Cell system in an electric-drive ship. The intended end result of this pilot project is a reliable, tested, upscalable and optimised fuel cell-battery propulsion system with all relevant certificates and demonstrably suitable for application in inland waterway and coastal shipping. The system setup and the underlying generic design methodology is actively shared with the industry by making the results available; these could ultimately be used for comprehensive standardisation and certification for the whole industry. The result of the project will be a market-ready, scalable emissions-free propulsion system for inland waterway vessels and smaller coastal vessels at the end of 2019

### **Green Sailing – E-Naval B.V. – €?**

E-Naval is developing a hybrid propulsion system running on batteries and hydrogen.

### **H<sub>2</sub> Power Module for inland waterway vessels – Mobiele Stroom B.V. – €50,000 – 01-10-2018/28-02-2019**

This project will first, looking at the transport case and an analysis of various technologies for H<sub>2</sub> storage and fuel-cell concepts, determine the 2 or 3 most promising concepts for an H<sub>2</sub> Power Module for a container ship. Then, on the basis of a SWOT analysis with respect to the technology and safety, it will conduct an economic evaluation against the business case, including consideration of a container ship with diesel-electric propulsion, to determine whether H<sub>2</sub> Storage Technology offers the best opportunities for further development in inland waterway shipping. The feasibility will be determined on the basis of the size of the potential “gap” with respect to a conventional ship on the same route. This will be done using various methods, such as inventories, conceptual designs, risk assessment, cost calculation and design of business case, evaluation, and SWOT analysis. Ultimately, questions, options and conditions for a feasible O&O project will be defined and a decision on follow-up activities will be made. The activities will be carried out by Mobiele Stroom BV (MSBV), Conoship International BV (CONO) and Schipco Consultancy BV (SCBV). RINA Netherlands BV and Aqua Navis BV are contributing their specific expertise to the project where called for.

**H2SHIP** (*Interreg North-West Europe*)/ *EIFER*/ *Amsterdam Port Authority*/ *TU Delft*/ *TATA Steel Europe* – €7.21 million EU funding – 2019/2022

H2SHIP is a set of three demonstration projects for hydrogen use in shipping, and additionally the development of a blueprint for the adaptation of hydrogen for shipping in Northwestern Europe. The first stage is three pilot projects: Pilot 1 is a project in France for a local hydrogen production and distribution system to serve the fuel needs of two hydrogen fuel cell-powered passenger ships. Pilot 2 is a retrofit of inland waterway vessels with a hydrogen system in the Netherlands. Pilot 3 is performed in Belgium and is a study of hydrogen distribution on the open sea for shipping on the open sea.

**Hydrogen ship** – *Theo Pouw*, *Koedood Dieselservice B.V.*, *Scheepswerf H. Poppen Zwartsluis B.V.*, *Stork*

Theo Pouw and its partners have developed a hydrogen-powered barge 86 m long and 10.50 m wide. Koedood Dieselservice B.V. and Scheepswerf H. Poppen Zwartsluis B.V. are now working on the construction of this ship, including the fuel cell and the electric engine. For propulsion, the ship will be using a 600 kW electromotor, 500 kW fuel cell, 275 kW battery package and two 20-foot ISO containers for hydrogen storage at a pressure of 500 bar. The containers are interchangeable and can be removed for filling at a separate location. This optimises the ships' sailing time, with minimum loss of time at stops. Changing of the containers takes approximately 30 minutes and can be done at any of the 38 container terminals in the Netherlands (three of which are operated by Theo Pouw). Refilling of an empty container takes approximately 12 hours. The fuel cell is developed by Koedood and Nedstack. The technical design of the ship is feasible, although the powertrain is still in development. According to the project timeline, the investment decision will be made by the end of 2019/beginning of 2020; if that happens, the ship will be sailing by the end of 2020.

## Mobile machines

### **Economic feasibility of hydrogen fuel cell Ground Power Units at Dutch airports – zepp.solutions B.V. – €23,040**

This project investigates the economic feasibility of hydrogen fuel cell ground power units (GPUs) at Dutch airports. At present, aircraft generally get their electricity supply from diesel-driven GPUs on the ground during loading and unloading. These diesel generators emit substances (CO<sub>2</sub>, NO<sub>x</sub>) that are hazardous to both the environment and human health. A hydrogen-powered GPU would reduce emissions of CO<sub>2</sub> and NO<sub>x</sub> to zero. The end goal of the feasibility study is to find concrete answers to the following questions:

- What is the total cost of ownership (TCO) of the production, use and maintenance of hydrogen fuel cell systems in GPU applications?
- What hydrogen supply and filling infrastructure is required? A concrete overview will be drafted for at least one case study.
- What will the business model look like?

### **Hydrogen for off-grid applications**

– Recoy B.V. – €50,000 – 01-09-2018/31-01-2019

The goal of this project is to make a significant step forward in the application of hydrogen in the economy. The expectation is that hydrogen can only be competitive when it is not in direct competition with energy that can be supplied through the existing energy infrastructure for (mainly) electricity and gas, such as festivals, construction sites, supply of electricity to aircraft on a runway, etc.

## Filling stations

### **Active water-cooled hydrogen dispenser**

– LIQUAL/ Robox Heat Technology B.V. – €143,528

Investors in filling stations and end users of electric vehicles have a major interest in integrating the hydrogen infrastructure into existing filling stations to the extent possible, so that refueling with hydrogen approaches as closely as possible, or even exceeds, the practicality and comfort of refueling at a petrol station. At present, the problem is that the available hydrogen dispensers do not meet the requirements of existing multi-fuel tanking stations (MFTs). In many cases, the dispensers cannot be obtained separately and cannot be placed at a distance, or do not meet the European requirements for refueling speed, safety and ergonomics. The biggest problem is the fact that hydrogen heats up as it expands in the fuel tank, which means that refueling with hydrogen must happen at a controlled rate of speed for safety reasons. The partners expect that these problems can be solved by an active cooling system for hydrogen dispensers. Part of this involves a new technical solution, a special heat exchanger integrated into the underground pipe network for efficient transfer of the required cooling to the hydrogen in the pipe. This would make it possible to develop a free-standing dispenser that could be integrated into existing filling stations and that could be placed anywhere up to 75 metres from the hydrogen buffer. If this project succeeds, it would remove a significant technical barrier to market introduction and be a strong incentive for investments in hydrogen filling stations. It would significantly increase the user-friendliness of the hydrogen refueling infrastructure, which would itself be a considerable stimulus for driving hydrogen-powered vehicles. This puts the project right in line with the themes of the Top Sector HTSM, Automotive section, of reducing pollution and climate change by promoting zero-emissions vehicles.

### **Hydrogen filling system with electrochemical compression**

– HYET/ Hygear – €817,404 – 01-05-2018/31-05-2019

The objective of the project is the development of a hydrogen filling system based on an electrochemical compressor and testing the system in practice at the public HyGear filling station in Arnhem. The intended result is a blueprint for filling stations that HyGear can deliver commercially. The technical objectives for the system design are: Reduce investment costs by 20%; Reduce operational delivery costs at 700 bar by 30%; Purity: < 20 ppb contamination; Drying of hydrogen into water concentration < 5 ppmv.



**Hydrogen dispensing – custody transfer – Fluidwell B.V./ Its/ Trigas – €? – Completed 2018**

1. Development of a custom flow computer/controller with certifiable precision: this is the development and certification of explosion-safe electronics, embedded software and housing technology.
2. Optimisation of the coriolis measurement technique for the application.
3. Field-testing of the complete system under operational conditions.
4. In consultation with the calibration authorities, arriving at a definitive certification process description and certification of the measurement system.
5. Completion of a calibration-level precision, certified calibration set up for calibration and recalibration of the measurement system.

## 6. Applications: Built Environment

### Hydrogen for central heating boilers

**Hydrogen district Hoogeveen – BAM Infra Energie & Water B.V./ Bekaert Combustion Technology B.V./ Haskoning DHV Nederland B.V./ JP-Energiesystemen B.V./ N-Tra B.V./ N.V. KEMA/ Nedstack Fuel Cell Technology B.V./ Stichting Hanzehogeschool Groningen/ Stork Nederland B.V./ Visser & Smit Hanab Distributie B.V. – €472,359 – 01-10-2018/01-10-2019**

The objective of this project is to deliver a (techno-economic) blueprint and its underlying technology for the concrete functionality of heating of these homes with 100% hydrogen (H<sub>2</sub>) on the basis of a hydrogen central heating boiler. This blueprint and technology must be implementable in existing residential areas throughout the rest of the country. Alongside reducing natural gas consumption, this will also represent a market opportunity for the parties involved. The blueprint will be not only technological, but also include the social business case, sourcing strategy and evaluation of support among residents. The assumption is finding alternatives for the familiar sustainability questions surrounding the energy supply to new and existing residential areas. The focus for this study and its outcome will be on the demand for heating (hot water and space heating). Building a home natural gas-free is a known quantity but making an existing residential community natural gas-free demands some radical changes, for which alongside various known technologies green hydrogen offers one of the most realistic solutions. Based on experiences within this project, a retrofitted central heating boiler will also be developed for incremental testing of gas mixtures ultimately leading to 100% hydrogen. The societal aspects of this part of the study include the observation that people generally want to take more control of the energy in their lives. This study will create opportunities that can be linked to cost-price reduction, upscaling and repetition. The concrete opportunities for industry are being investigated. The application of hydrogen in new construction and existing buildings will present opportunities for upscaling to existing residential communities across the country.

**H<sub>2</sub> series central heating boiler – ATAG Verwarming Nederland B.V./ Hygear B.V. – €250,000 – 01-01-2018/30-04-2020**

The goal is to develop a burner system that can replace the current natural gas burner. This will pave the way to future manufacturing of central heating boilers for hydrogen, as well as retrofit packages for existing central heating systems.

**Project in Rozenburg and Hydrogreenn**

Demonstration project testing three different hydrogen central heating boilers. One of these hydrogen boilers will then be placed in the Hydrogreenn project in Hoogeveen in a large-scale demonstration.

**H<sub>2</sub> Ready central heating boiler – Bekaert Combustion Technology B.V./ EBM-Papst Heating Systems B.V./ Tieluk B.V – €361,051 – 01-01-2018/30-04-2020**

The goal of this project is to develop a central heating boiler, test it in practice, and produce a product ready for hydrogen as an energy source but that can also (temporarily) run on natural gas. This would be an incentive for network operators to take the step of upgrading their networks for the transport of hydrogen and natural gas.

- Step 1: working prototype of H<sub>2</sub> boiler
- Step 2: upgrade networks
- Step 3: large-scale use of H<sub>2</sub>

## Hydrogen for heating networks

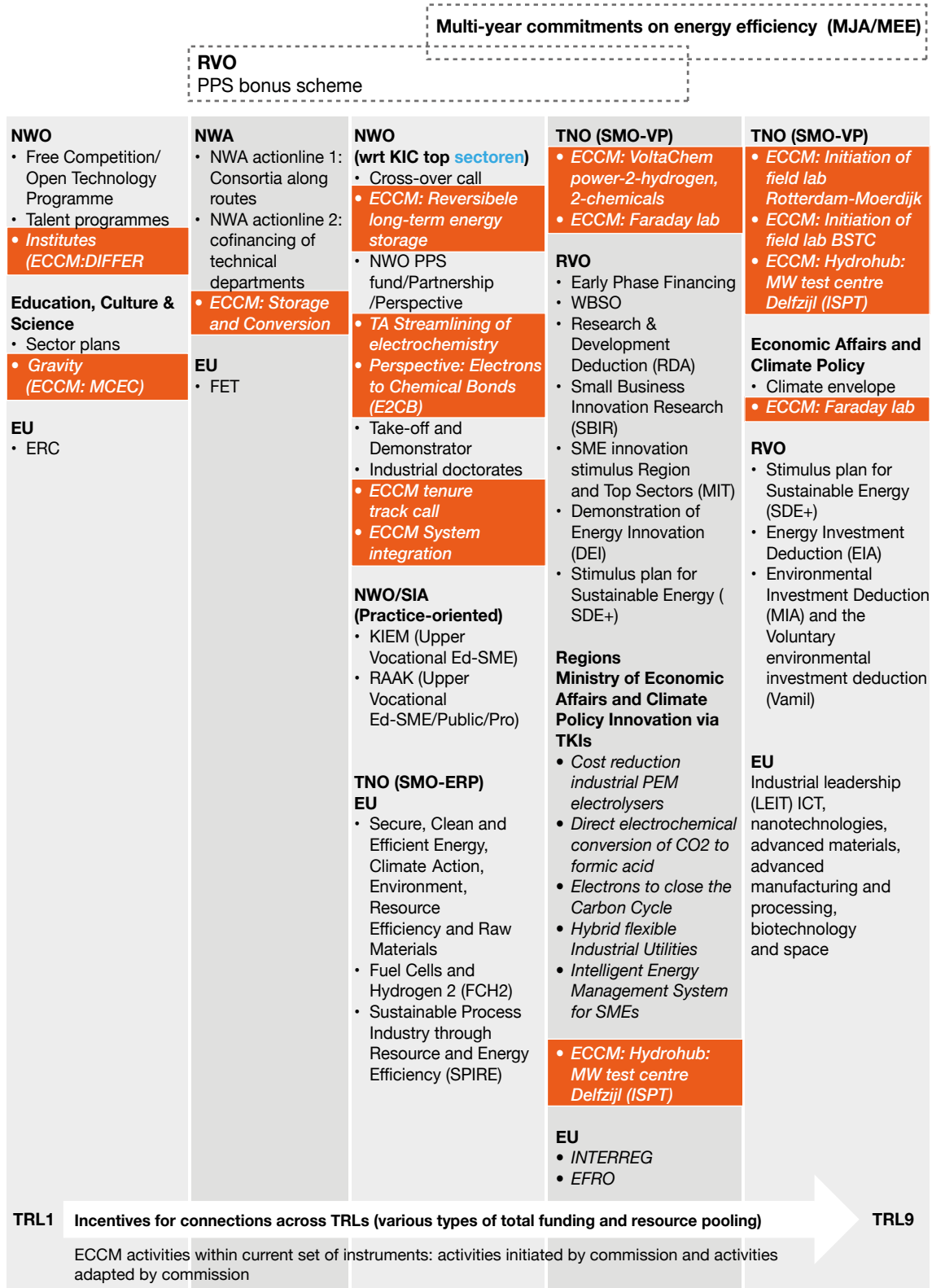
**Hydrogen for heating networks – Berenschot/ EBN/ Gasterra – Completed 2018**

A strategic study by Berenschot commissioned by Energie Beheer Nederland (EBN) and Gasterra presents a perspective on hydrogen for heating networks and could, in favourable situations, already be making a sustainable contribution to the energy supply. This pertains to heating networks that are close to the current hydrogen pipelines, and assumes supply of blue hydrogen obtained from methane in combination with CO<sub>2</sub> capture and storage. The use of green hydrogen (obtained from wind or solar power) will become profitable as from 2030 if it can be used for peak demand alongside the main source (residual heat or geothermal).

**Feasibility of hydrogen in the built environment of Middelburg – DNWG infra B.V./ Coöperatieve Windenergie Vereniging Zeeuwind UA/Delta Infra B.V. – €50,000 – 01-09-2018/15-03-2019**

In Zeeland, as part of the provincial CO<sub>2</sub> reduction plans, the province has considered constructing a heating network to be coupled with production of hydrogen from sustainable energy. This situation raised the question of the extent to which the development of a local, hydrogen-based community power station supplied with hydrogen from sustainable energy and intended for backup of the heating network could be a solution. The technical-economic feasibility of this solution is still unknown, and such a solution would be conditional on that feasibility. The consortium of DNWG Infra and Zeeuwind therefore intends to conduct a feasibility study of the hydrogen-based community power station in the municipality of Middelburg.

7. ECCM portfolio - Coordination of ECCM commission



## 8. Other

**CERTIFHY** – *Hinicio/ TÜV SÜD/ Ludwig Bolkow Systemtechnik, in collaboration with dozens of European industrial partners – Budget 1st project €550,000 – 2014/2016 and 2017-2018*

The European project Certifhy is developing and testing an EU-wide Guarantee of Origin system for green and low-carbon hydrogen. This is in the first instance a system for consumer disclosure, to show customers that they are getting what is claimed, i.e., green or low-carbon hydrogen. The initial project presented its first EU-wide “Guarantees of Origin” (GO) system for hydrogen at the end of October 2016. In the follow-up project (2017-2018), the certification system was set up and pilot projects were run testing the methodology in practice. The Dutch pilot study involved a location where chlorine electrolysis was performed with renewable electricity.

**HYLAW** – *22 European organisations including WaterstofNet and NEN – €1,110,000 – 2017/2018*

Unfamiliarity with new technologies like hydrogen and fuel cells on the part of governmental authorities and the uncertainty concerning the legislation that will be applicable to these technologies is the cause of delays and extra costs, and something that can scare away investors and customers. HYLAW has performed a systematic comparison of relevant legal frameworks and administrative processes in areas like planning, safety, installation and operation in 18 European countries and in the EU legal system; evaluated the extent of unnecessary delays and costs; identified best and worst practices; increased awareness of the influence of the frameworks and processes on the use of hydrogen and its underlying technologies; and advised on directed improvements in each of the 18 countries and at the EU level.

**Green hydrogen booster** – *Hanze University of Applied Sciences (EnTranCe), coordinator*

Project focusing on the hydrogen innovation ecosystem: promoting innovation and regional growth by setting up and conducting research and innovation projects with the SME sector. Developing a testing, learning and demonstration environment for innovations throughout the entire hydrogen value chain.

Funding application to SNN is pending.

### **Hydrogen innovation Safety programme** *(in preparation)*

The Hydrogen Safety Innovation Programme is intended to facilitate the widespread introduction of hydrogen as a new energy carrier to accelerate the large-scale safe application of hydrogen in mobility and transport. The H<sub>2</sub> Safety Programme was created to gain a clear picture of the safety risks in the entire chain and the interpretation of these risks. This picture is needed to arrive at:

- nationally coordinated measures and instruments for safety aspects and risks
- legislation and regulations
- uniform permitting
- uniform incident response and control

### **MetroHyVe** – *Dutch participants are VSL (Netherlands Meteorological Institute, Shell) and NEN – 2017/2020*

The project MetroHyVe (Metrology for Hydrogen Vehicles) is focused on the development and establishment of standards for measuring quantity and quality of hydrogen upon issue by filling stations. It is conducted by European meteorological Institute and builders and operators of hydrogen filling stations. The goal is to establish methods and instructions for, on the one hand, quantity measurement of hydrogen (how much hydrogen is delivered at the dispenser) and on the other, quality measurement and quality control of hydrogen, and to document these in ISO/CEN standards. The purity of hydrogen is important for the functioning and lifetime of the fuel cell.

### **The world of hydrogen** – *Gasunie*

Website with “all the facts, visions and scenarios in one place”. Information provision and information campaigns

### **Gas 2.0 programme Energy College** – *Drenthe College (coordinator), Noorderpoort, Alfa-college, ROC Friese Poort, Friesland College, Terra, Nordwin and New Energy Coalition in collaboration with 45 regional companies*

Hydrogen education courses for students and professionals at MBO level (vocational education)

## Annex D | Standardisation for hydrogen in the industrial and built environment

NPH2IGO (the standardisation platform for hydrogen in industry and the built environment) is currently conducting a broad inventory of the subjects for standardisation and pre-standardisation research needs relating to hydrogen. These issues are partially addressed in European research programmes and other activities, most of which include the active involvement of Dutch parties.

Participation could be more heavily supported in order to give the Netherlands a leading role.

**Table D1 | Standard designs and pre-normative research needs on hydrogen in the industrial and built environment.**

Theme	Research needs
Gas quantity measurement, calculation of energy and charging	<ul style="list-style-type: none"> <li>• Gas quantity measurement and calculation of energy (on agenda of CEN/ SFG gas quality study);</li> <li>• Charging;</li> <li>• Meters set up for large-scale users in the free domain: need for new investigation into the suitability of large-scale gas meters for hydrogen. Testing or performance and reliability of measurement equipment to withstand higher pressure (rotor and turbine meters) and above 10% metrology);</li> <li>• ATEX classification for mixtures of H<sub>2</sub> and natural gas;</li> <li>• make EVHIs suitable for variable gas composition (subject in Hydeploy and H2GRID);</li> <li>• Geographic and time-dependent differences in H<sub>2</sub>/natural gas mixtures (subject in EMPIR, metrology studies for decarbonising the gas grid, further product development of domestic and industrial hydrogen metering by manufacturers in collaboration with metrology institutes such as VSL;</li> <li>• Thermal quantity measurement (subject in in EMPIR), metrology studies for decarbonising the gas grid;</li> <li>• Hydrogen in the measuring device (subject in SensH2GRID; are there measuring sensors/techniques available for measuring the %vol H<sub>2</sub> at acceptable metering service costs?);</li> <li>• Requirements for the measuring devices (subject in EMPIR, metrology studies for decarbonising the gas grid); explore whether the current requirements for maximum measurement uncertainty of natural gas could also apply to hydrogen and hydrogen mixtures;</li> <li>• Effects on turbine meters;</li> <li>• Practical side of introduction of flow meters instead of volume meters (NBNL);</li> <li>• Introduction of MID (Measurement Instrument Directive) certified meters (Dutch code system needed under the Metrology Act);</li> <li>• Calibration of hydrogen meters (projects NMI, VSL, EMPIR)</li> </ul>

**Table D1 | Standard designs and pre-normative research needs on hydrogen in the industrial and built environment.**

Theme	Research needs
The quality of hydrogen and mixtures of natural gas with hydrogen	<ul style="list-style-type: none"> <li>• Quality requirements for transport and distribution through networks (esp. former natural gas networks). Specifications for quality requirements for end use, with limitation on residual components (as in the American system)</li> <li>• Standardisation of hydrogen/natural gas mixtures: develop roadmap outlining the next steps over time so that regulations and technology can proceed in parallel for a smooth transition. Coordination with DVGW (development of German standards)</li> <li>• “Venting” of any natural gas components still present in former natural gas networks (TU Delft/Stedin): What components can be expected and how long can this “venting” be expected to take?</li> <li>• Effect of poor/no maintenance on existing equipment: Substantiation of risk factors for risk policy, such as obsolescence or poor/no maintenance on existing equipment, when natural gas/hydrogen mixture is used in the system;</li> <li>• Effects of variations in the gas composition on equipment (CEN TC 234 working group 11)</li> <li>• Equipment standard specifications of adaptive equipment for changing concentrations of hydrogen in the natural gas: investigate the need for autonomous adjustment of equipment with permitted variation in bandwidth or change rate of hydrogen/natural gas mixtures</li> <li>• Quality requirements in applications that use hydrogen supplied via former natural gas networks</li> </ul>
Local area safety issues	<ul style="list-style-type: none"> <li>• Density requirements and testing;</li> <li>• Ignition sources;</li> <li>• Responsibility domain;</li> <li>• Leak searches;</li> <li>• Training of personnel;</li> <li>• Penetration in enclosed spaces;</li> <li>• Specific components of the network;</li> <li>• Olfactory detection, sensors;</li> <li>• Quality and composition;</li> <li>• Conversion of networks;</li> <li>• Safety measures;</li> <li>• Outage logging;</li> <li>• Chemical reactions;</li> <li>• Maintenance and management;</li> <li>• Reverse supply;</li> <li>• Incident response</li> </ul>
Standardisation of odourisation of hydrogen in the energy distribution	<p>Many aspects in regard to any odorant to be ultimately used must still be investigated. These include:</p> <ul style="list-style-type: none"> <li>• Impact on distribution lines and appendages</li> <li>• Impact on indoor lines/gas consumption equipment</li> <li>• Effect of new odorant in interaction with traces of THT (upon mixing or use of old gas lines)</li> <li>• Effect on olfactory detectability after stoppage/de-mixing</li> <li>• Olfactory detectability of gas after minimal leaks (in which pipe may effectively function as a filter for odorant)</li> <li>• Is the current system of odourisation by GTS/manufacturer, and corresponding control methodology, sufficiently effective?</li> <li>• Research into the effects of odorant on the effect and lifetime of fuel cells and development of cheap cleaning/resistant fuel cells</li> </ul>

**Table D1 | Standard designs and pre-normative research needs on hydrogen in the industrial and built environment.**

Theme	Research needs
Protocol for conversion of natural gas into hydrogen	<ul style="list-style-type: none"> <li>• Security of supply in event of loss of H<sub>2</sub> source, permissible variations and exceptions</li> <li>• Requirements on supplier of last resort (SoLR), structure of storage/supply and verification</li> <li>• Guarantees of origin</li> <li>• Monitoring of quality, installation requirements, sensors and sampling</li> <li>• Precision and frequency of sampling, caloric value and Wobbe index</li> <li>• Procedure for green light downstream switching</li> </ul>

In relation to the proposed practical approach in the MPAH, an important standardisation need is foreseen in the areas “local area safety” and “switchover from natural gas to hydrogen”. The research needs for this are still being inventoried.



## Annex E | Composition of core team

The core team put together for this project is a good representation of the stakeholders in the current hydrogen playing field. For the private sector/industry, input was sought from MMIP 8 (Electrification in industry) because hydrogen in industry (including production is an important theme and is fully covered under this MMIP. For mobility, a separate meeting was held with H<sub>2</sub>Platform in order to get the best take on their input.

### Core team members

- Jörg Gigler, TKI Nieuw Gas (chairman, writing team)
- Marcel Weeda, TKI Nieuw Gas/TNO (writing team)
- Remco Hoogma, Dwarsverband (writing team)
- Jort de Boer, TKI Nieuw Gas (writing team)
- Pieter Mans, Alliander/Netbeheer Nederland
- René Schutte, Gasunie
- Hans Warmenhoven, EBN/KVGN
- Han Feenstra, Ministry of Economic Affairs and Climate Policy
- Els de Wit, Ministry of Infrastructure & Water Management
- Dirk Schaap, Ministry of Infrastructure & Water Management
- Sarah Vaessen, RVO
- Anja Bieberle / Gerard van Rooij / Richard van de Sanden, DIFFER
- Sander Gersen / Albert van den Noort, DNV GL

