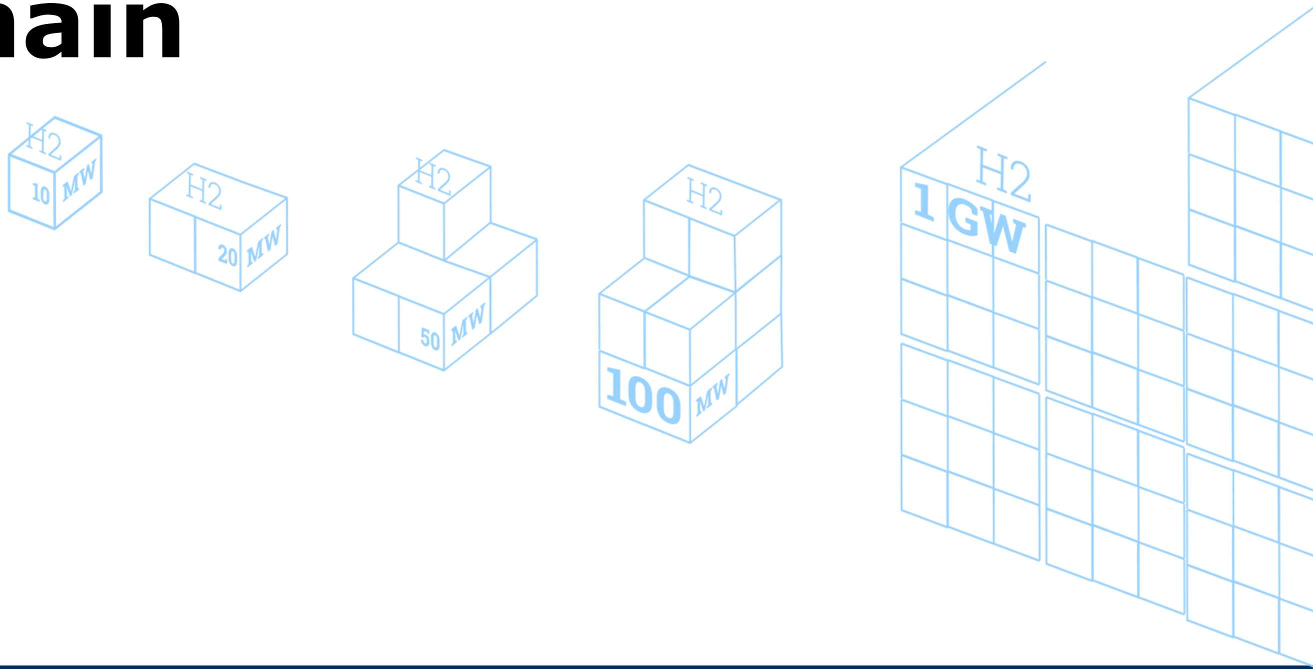
Quickscan development green hydrogen value chain

December 22nd 2022



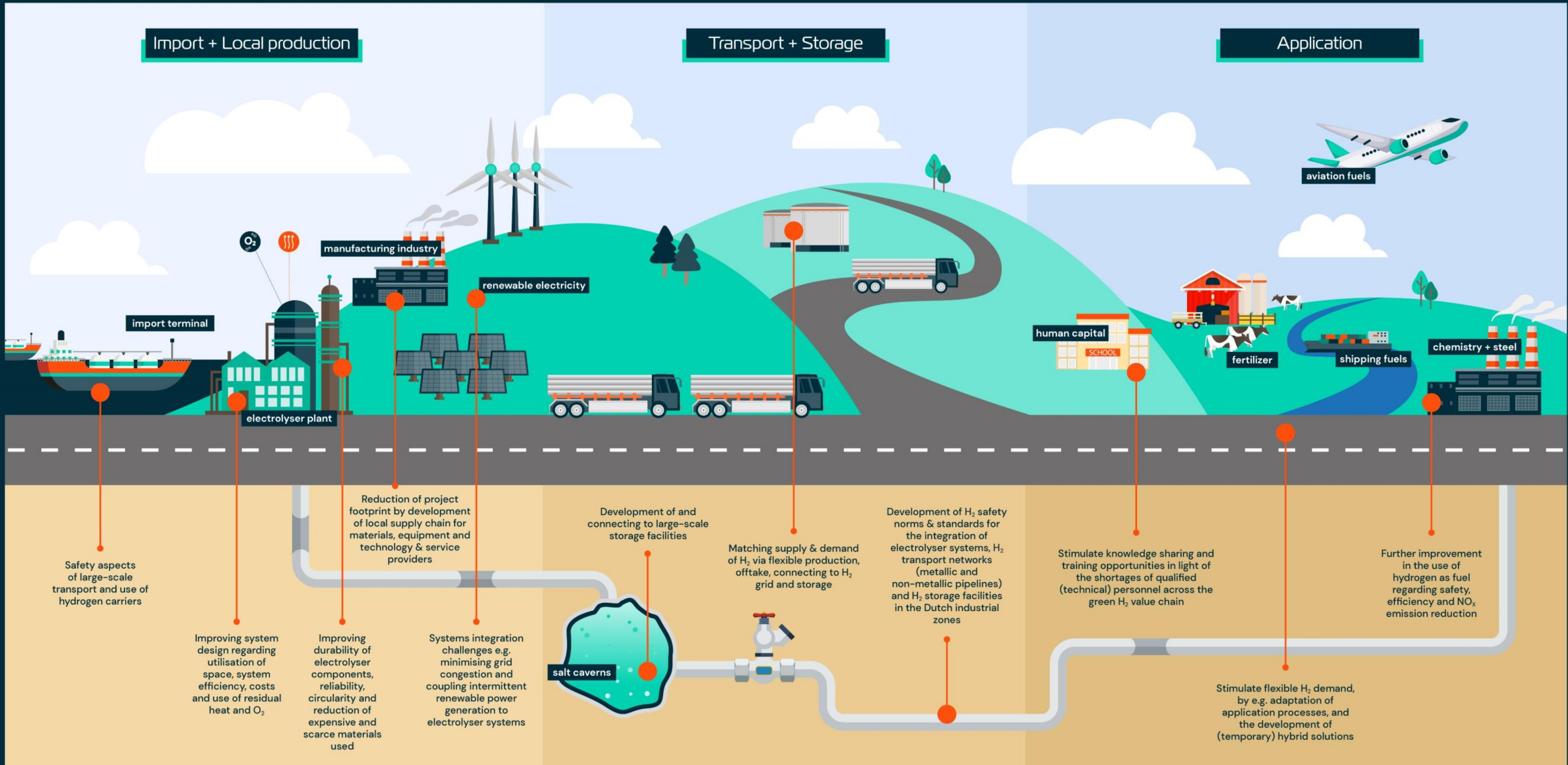
Summary

- This quickscan provides insight into challenges, risks and innovative solutions around developing both large-scale (100 MW+) electrolysis projects and the wider green hydrogen value chains in the Netherlands. These insights will support GroenvermogenNL in the development of a subsidy scheme for large-scale electrolysis projects, which are to be realised by 2026.
- One of the main overarching challenges in the development of the green hydrogen value chain is the availability of sufficient renewable electricity to power large-scale electrolyser plants, in combination with the inherent intermittency of renewables. Electrolyser systems need to run at significant load, with a minimum number of operating hours per year, in order to reduce H_2 production costs. The matching of supply and demand of renewable electricity for the production of green hydrogen presents a significant challenge.
- Matching H_2 supply and demand via flexible offtake (H_2 end-use processes), as well as buffering by connection to the H_2 grid and storage, is needed to improve the security of supply of green H_2. Green H_2 import can also contribute to the security of supply. To stimulate flexible H_2 demand, production processes using H_2 should be adapted and temporary hybrid solutions using both H_2 and other energy carriers need to be developed.
- A key takeaway is that we need to put in place transparent certification for green hydrogen. Both individual and corporate consumers need high quality certification to ensure value of green hydrogen vs grey hydrogen. The certification market for green hydrogen is still in its infancy. The first green hydrogen certificates were recently launched in the Netherlands and an international system of hydrogen certificates based on European regulations is still under discussion.
- Another important point to consider is the safety aspects of hydrogen. Safety can be divided in three main items, being (1) safety perception of H_2, (2) a lack of safety standards, including the relevant failure data especially for stacks, and (3) differences in acceptable safety risk mitigation measures. Safety norms & standards for (the integration of) electrolyser systems, H_2 transport by metallic and non-metallic pipelines, and H_2 storage facilities need to be developed.
- The technology for the transport and storage of gaseous H_2 is relatively advanced and already exists on a case-by-case basis. However, the availability of the related know-how and experience is limited. Improvements can be made by developing standards and norms available to a broader group of stakeholders and users, especially regarding Health, Safety and Environment.
- To support the green hydrogen supply chain in general, the parties receiving funding should disseminate project information (anonymously) regarding Health, Safety and Environment, technical and economical operations.
- The footprint of hydrogen projects should be reduced by stimulating development of local supply chains for materials, equipment and technology & service providers.

Summary

- The various available technologies for green H_2 production by water electrolysis need to be developed further to increase efficiency, reliability, durability and circularity, whilst reducing CAPEX. This includes the reduction of the use of scarce, expensive and unsustainable materials. These technological developments will contribute to a reduction of green hydrogen costs (LCOH).
- Locations for electrolyser projects should take space utilisation and physical integration in the local systems into account (e.g. congestion of electricity grid, residual heat, oxygen production and H_2 demand).
- Considering the current and expected future shortages of qualified (technical) personnel with knowledge of and experience with $H_{2,}$ knowledge sharing should be stimulated, and training opportunities should be offered. In addition, stimulating digitalisation, automation and the use of robots can be beneficial to minimise the demand for personnel across the green hydrogen value chain, as well as promoting consistent high quality of the product, especially in manufacturing.

Green Hydrogen in NL



OVERALL CHALLENGES: GREEN HYDROGEN CERTIFICATION, SAFETY (PERCEPTION), COST REDUCTION, AVAILABILITY RENEWABLE ELECTRICITY

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Reading guide

Aim

This quickscan provides insight into the challenges, risks and innovative solutions around developing both large-scale electrolysis projects and the surrounding green hydrogen value chains in the Netherlands. These insights will support GroenvermogenNL in the development of a subsidy scheme for large-scale electrolysis projects of 100 MW or more, which need to be realised by 2026. This subsidy scheme will accelerate the development of green hydrogen value chains in the Netherlands, from local production and import of green hydrogen, to transport, storage and use of hydrogen. Regarding the end-use of hydrogen, the focus of this quickscan is on the use of green hydrogen to produce steel, fertiliser, synthetic fuel for aviation and shipping, and use in green chemistry. Particular attention was paid to the current and potential future role of the Dutch manufacturing industry in these hydrogen value chains.

Approach

This quickscan was produced in the months November and December of 2022. Multiple sources of information were utilised to quickly gain insight into the current status of, and challenges faced by, the Dutch hydrogen sector. For this quickscan, information from interviews with relevant parties involved in the hydrogen value chain, public literature sources and own knowledge within Summit Engineering were compiled and analysed. The parties for the interviews were selected with the aim to cover production, import, transport, storage and end-use of hydrogen in the various sectors mentioned previously, as well as relevant aspects such as financing and safety. A list of the parties that were interviewed and literature sources that were used can be found in the Sources section.

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Green hydrogen value chain

1.1 Definition green hydrogen value chain

The green hydrogen value chain examined in this quickscan consists of import and local production, transport, storage and end-use of green hydrogen in the Netherlands, as depicted in the infographic on page 3. Green hydrogen is defined here as hydrogen produced by water electrolysis using renewable electricity. Green hydrogen production is considered the electrolyser plant, integration with the surrounding infrastructure and the supply chain related to the building of the plant. Import is limited to facilities in the Netherlands. Transport is limited to pipelines and storage to tanks and caverns. For the end-use of green hydrogen, various key industries are examined, where hydrogen can be used as a feedstock or fuel. These industries use green hydrogen for the production of green steel, chemicals, fertiliser, and for the production of sustainable fuels for aviation and shipping. Note that as the green hydrogen value chains are currently being developed in the Netherlands, it is unclear exactly what form they will take in the future. Statements made here are based on currently available information.

1.2 Analysis green hydrogen value chain

There are several important overarching challenges, risks and innovative solutions regarding the development of the entire green hydrogen value chain, which are summarised below.

- The 'chicken and egg' challenge. In simple terms this means that green hydrogen demand is needed to scale up production, scaling up production is needed to decrease costs and lower costs are needed to stimulate demand. The various parts of the hydrogen value chain are interdependent and need to simultaneously scale up, including also the supply chain of equipment, materials and technology providers. This obstacle was frequently mentioned in the interviews with parties in the sector. The dependencies on other parts of the value chain is an inherent challenge, which can increase risks (e.g. financial, security of supply, delays) and costs of hydrogen.

- Systems integration aspects present both challenges and opportunities. For example, how to couple intermittent renewable power generation to relatively stable production of hydrogen. Balancing supply and demand is a key issue regarding both renewable electricity and green hydrogen. In the initial stages (~100 MW electrolysers) hybrid solutions with grey hydrogen can be utilised, for instance by reducing SMR production whilst feeding in green hydrogen in the downstream production processes. Another aspect is the geographical considerations of where to locate electrolysers with respect to hydrogen demand in industrial clusters, renewable power generation (e.g. offshore wind and landing points) and local grid congestion. Grid congestion is a significant challenge in the Netherlands and where possible novel electrolyser projects should not worsen grid congestion. Systems integration can also cover reusing heat from large-scale electrolysis locally in industrial clusters or district heating systems.

- Certification of green H_2. The uncertainty around green hydrogen certification is seen as a major risk for investment. Offtake customers of green hydrogen are willing to pay a premium, however there must be no ambiguity regarding the H_2 to be green now or in the future. There are recent positive developments in achieving Dutch green hydrogen certifications, however uncertainty remains on how the EU regulations regarding green hydrogen will develop and what their impact will be on Dutch hydrogen-related projects.

Green hydrogen value chain

1.2 Analysis green hydrogen value chain (continued)

- In various parts of the value chains grey hydrogen is currently used. For these parts the safety awareness, standards and regulations are well embedded. For developing parts of the chain (e.g. electrolyser systems, repurposed pipeline infrastructure, ships, etc.) this is not yet the case. To accelerate development of the Dutch green hydrogen value chains, it would be beneficial if this would be further developed. Without more knowledge and clarity on risks, it will be challenging to set appropriate safety norms and standards. This could also result in excessive safety measures and related increase in costs.

- Significant cost reduction of green hydrogen (LCOH) is needed for it to be competitive with grey hydrogen or hydrogen alternatives. Reduction on both CAPEX and OPEX will be needed. Suggestions for CAPEX and OPEX reduction are discussed in later chapters.

- The development of a local supply chain for materials, equipment, technology and service providers for electrolysers, hydrogen transport and storage facilities should be stimulated. This contributes to reduction of the environmental footprint of hydrogen projects, stimulating the local economy and risk reduction from a geopolitical perspective as it increases independence.

- Knowledge sharing is relevant for at least two aspects (1) technical and operational knowledge to improve design and safety level and (2) for social acceptance and realistic risk perception of the general public. Risk perception is currently an obstacle to acquiring sufficient funds from investors. Lessons learned from research and pilots should be made widely accessible, whilst considering proprietary information of commercial parties.

- The expected shortages of qualified (technical) personnel with knowledge of and experience with hydrogen are another significant challenge. Investments in training facilities and opportunities are needed at all parts of the hydrogen chain, from production to end-use of hydrogen in production processes. In addition, stimulating digitalisation, automation and the use of robots can be beneficial to minimise the demand for personnel in manufacturing, operation and maintenance across the value chain.

- Innovation is needed to reduce the use of scarce, harmful and/or expensive materials across the green hydrogen value chain, but especially in electrolysers. Another consideration should be whether the materials or components used could be recycled at end of life.

- In the green hydrogen value chain various parties are present that have different perspectives on addressing liabilities and risks. A lump sum turnkey requirement is due to the immaturity of large electrolyser systems driving up prices or even causing parties to step out, due to the potential risks involved. Forming long-term strategic alliances across the electrolyser system and/or value chain could be a good way to share the project risks and prevent build-up of multiple contingencies. Governmental support in the form of loans, (offtake) guarantees, project participation or subsidies could help in mitigating financial project risks. The format and amount of governmental support that is suitable for de-risking electrolyser projects should be carefully considered. One potential route is a minimum price guarantee per kg of green hydrogen produced. This could support the initial development of the value chain.

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Green hydrogen value chain

Key takeaways for subsidy scheme

- An important aspect is how the project contributes to the development of strong green hydrogen value chains in the Netherlands. This could for example be done by forming strategic alliances, committing to long term investments in partner projects, sharing risks and extensive knowledge sharing with partners. Reliable long-term contracts between local partners in the value chain are needed to stimulate the investments needed to scale up.
- In relation to the above, another aspect to consider could be the environmental footprint of the entire hydrogen value chain related to the project. The use of local suppliers for parts and systems and supplying to local offtakers reduces both greenhouse gas emissions and transport costs and can stimulate the development of a local hydrogen ecosystem.
- Governmental support in the form of loans, (offtake) guarantees, project participation or subsidies could help in mitigating financial project risks. The format and amount of governmental support that is suitable for de-risking electrolyser projects should be carefully considered. A potential format could be a minimum price guarantee for a produced kg of green hydrogen, which could help accelerate development of the value chain.

Production and import

2.1 Introduction

The first step in the green hydrogen value chain is the origin of the green hydrogen, which is either local production or import. Local production is the electrolyser plant, including the related manufacturing and supply chain. The integration of the local production in the surrounding area is considered as part of the quick scan. Import is limited to the role it can play in security of supply and the offloading context, where the type of hydrogen carrier is considered.

2.2.1 Analysis electrolyser system

There are several challenges, risks and innovative solutions at the electrolyser plant level, which are summarised below.

- Electrolyser plants produce heat, which could be utilised to generate additional income. Heat integration in industrial clusters or district heating systems would therefore be beneficial.

- Electrolyser plants emit pure O_2. Effective use of the O_2 produced should be considered to generate a possible income stream.

- Innovation focused on cost reduction of hydrogen production is needed, where KPI's could be CAPEX, OPEX and euro/MW. A simplified breakdown of green hydrogen production costs is included on pages 17 and 18 to provide insight into the main components. Several suggestions are made in this chapter for the reduction of CAPEX and OPEX.

- Innovation focused on increasing electrolyser system efficiency (kWh per produced kg H_2) is important to bring down production costs for H_2.

- To better match the intermittent production of renewable electricity, the flexibility of electrolyser plants should be increased where possible. It also needs to be explored further how negative side effects of stack degradation can be minimised. The amount of flexibility at the level of the electrolyser will remain limited as electrolyser systems need to run at a certain load, the number of yearly operating hours, in order to keep H_2 production costs down.

- Regarding the location of electrolyser plants, look for opportunities for 'grid friendly' electrolyser integration, e.g. close to the production or landfall of green electricity. The location of H_2 demand and potential to connect to the future national hydrogen backbone and local H_2 grid should also be considered.

- Develop functionality to use the electrolyser rectifiers (reactive power) to support the grid.

- Consider the sizing of the individual electrolyser plants. Combined projects with multiple electrolyser plant locations totalling 100 MW+ could also be considered. This has some advantages, such as reduction of grid congestion and the potential to select multiple sites close to local demand. This would increase development of 10 – 100 MW projects and experience/learnings which can be used for 100 MW+ projects.

- Security of supply. One concern is the availability of sufficient green electricity at this (time)scale and availability of a grid connection in potentially congested areas. Also, it could be helpful if in offshore windfarms a certain amount of the capacity is allocated for the production

Production and import

2.2.1 Analysis electrolyser system (continued)

of green hydrogen, until the moment that sufficient renewable energy is available to operate electrolyser plants at 4000+ hrs.

- Large electrolyser systems require vast amounts of fresh water. Security of supply needs to be addressed as climate change is leading to periods where the availability of fresh water supply is being limited, in part to preserve nature.
- Another obstacle in realising electrolyser projects is the ability to obtain the right permits and the time it takes to obtain them. This includes time spent to complete all the relevant documentation and calculations.
- Further optimisation is needed of all current electrolysis techniques (e.g. AWE, PEM, SOEC, AEM) by testing new materials, components and applications. Some aspects to consider in this continued development are mentioned below.
- Improve the durability/extend the lifetime of electrolyser components and the entire electrolyser system. This also contributes to cost reduction.
- Reduction of use of scarce and expensive materials is needed, such as platinum, and especially iridium.
- Circularity should also be a key consideration. Both components and (rare) materials need to be recyclable and recycled as much as possible.
- Producing H_2 at increased pressure will reduce compression costs further down the value chain and will reduce overall compression costs. However, this introduces challenges in leak tightness and system safety aspects, which need to be managed.
- To prepare for future development of offshore electrolysis, stimulate research and innovation in e.g. use of seawater in electrolysis plants and optimising DC-DC connections offshore for coupling electrolysers to wind turbines.

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Key takeaways for subsidy scheme

Focus on developments that reduce H_2 production costs. Possible directions for this could be:

- Increased electrolyser system efficiency e.g. by:
    - Increased temperature hydrogen production
    - High pressure hydrogen production
    - Using higher current densities
- System design using fewer and less scarce and expensive materials.
- Consider stimulating the incorporation of innovative stack technology at a larger scale, for example 10% of stacks per electrolyser project of a high TRL e.g. 8. This would stimulate innovation by allowing these novel stack technologies and its suppliers to build up track record and facilitate market entry.
- Stimulate heat integration in industrial clusters or a local heat network.
- Stimulate plant designs that reduce plot space.
- Stimulate 'grid friendly' electrolysis projects by e.g. specific location choice (close to renewable power generation and possibility for grid support services via Power Electronics).

Production and import

2.2.2 Supply chain electrolyser components (stack)

An electrolyser stack consists of several components, which are designed and manufactured for their specific application. These components together form the electrolyser stack, as depicted in Figure 1. Various parties are active in the Netherlands that work on improvement of the various stack components. These improvements are related to both improved performance and durability.

Projects are executed amongst the Dutch high-tech industry, contributing to the creation of a viable Dutch supply chain for large-scale electrolyser production. Objectives mentioned are to achieve 25-30% cost reduction for levelised cost of hydrogen compared to the current state-of-the-art by bringing innovations to full implementation and roll-out by 2030.

Parties are not keen on sharing improvement data or potential areas of improvement. In general parties are looking for ways to reduce the use of scarce and expensive materials (e.g. iridium, platinum), improved performance and durability via improved coatings and development of PFAS free membranes. Parties developing specific parts, such as bipolar plates, membranes and coatings, are looking for test facilities at scale to obtain track record on durability of their innovations.

Key takeaways for subsidy scheme

Stimulate the development of a (co-located) test site to continually test new electrolysis techniques, components and materials at around 1 MW scale. This test site should preferably operate for the duration of the lifetime of the electrolyser plant to continually facilitate testing of the latest innovations. The focus here should be on low TRL (<7). A co-located test site could benefit from the existing grid connection, facilities, safety measures and permits at the site of the electrolyser plant. This could also help Dutch parties in the manufacturing industry which make electrolyser parts build up track record to scale up.

Production and import

Depending on the type of electrolyser, the stack consists of various components. For the two most used electrolysis techniques, stacks are depicted in Figure 1 below. Suppliers of the components for the electrolyser stack (Figure 2) are working to improve performance by for example applying better coatings, reducing the use of scarce materials, adjusting surfaces of the materials and experimenting with different materials.

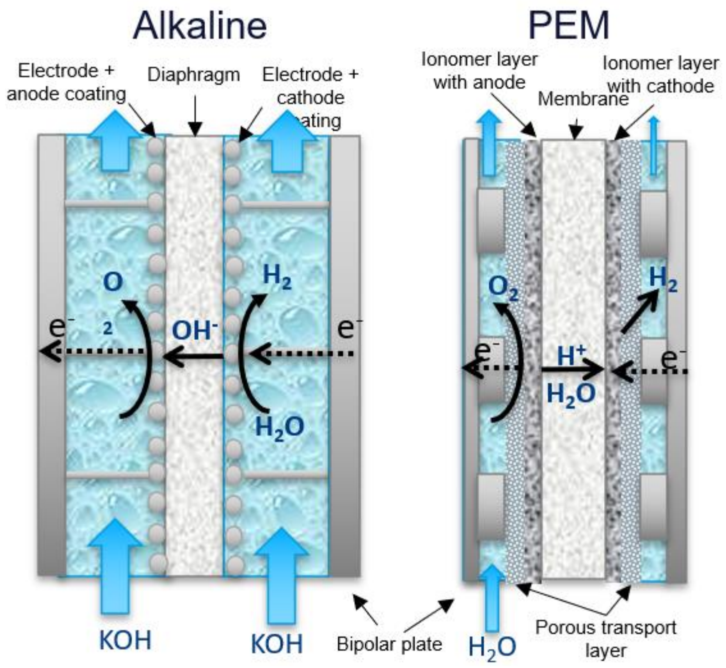

Figure 1. Components of alkaline and PEM stacks. Figure source HyCC.

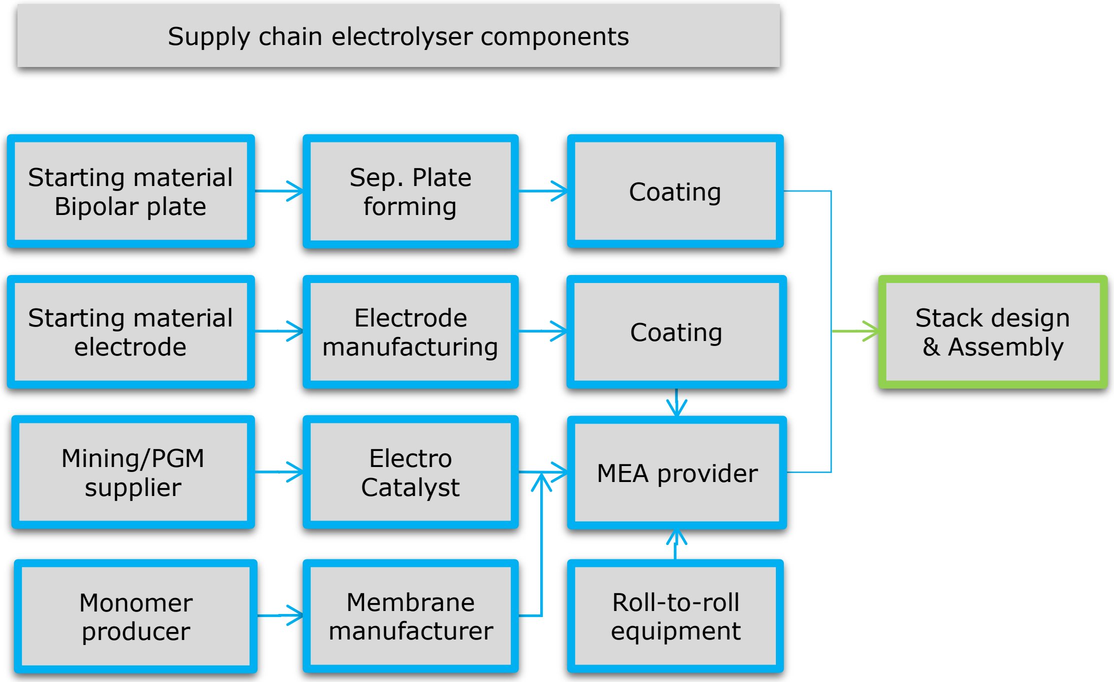

Figure 2. Supply chain of electrolyser stack components. PGM = platinum group metals. MEA = membrane electrode assembly. Figure is adapted from TNO.

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2.2.3 Supply chain electrolyser system

The electrolyser stack is the core part of the electrolyser system. The balance of plant (BoP) supports the core electrolysis process and contains various parts like rectifiers (power conversion AC->DC and control), water treatment (e.g. reverse-osmosis or ultrapure water process), H_2 and O_2 separation vessels, Pressure Swing Absorption (PSA) or Temperature Swing Absorption (TSA) to remove H_20 and other system components/services (nitrogen / Instrument air) required to have a safe and reliable operating system. The electrolyser stack and BoP have an overall control and safety system. The balance of plant is often sourced at external parties using existing technology.

Currently the electrolyser manufacturers are delivering complete electrolyser systems. The main reason being that this allows them to guarantee the overall performance. When system size increases and technology becomes better known and understood by a broader group of service suppliers in the sector, it is expected that EPC contractors and system integrators will step in more and more. They will design and integrate the systems at scale and source the various balance of plant components and stacks.

Regarding the electrolyser system, parties are looking into improving efficiency via improving rectifier operation, advanced process control and optimising balance of plant. One of the ways is to design standard size electrolyser trains, e.g. modular units of for example 10 MW, which can be multiplied in case larger electrolyser plants are required. Standardisation also allows more automated manufacturing, which can reduce quality issues during the manufacturing of electrolysers.

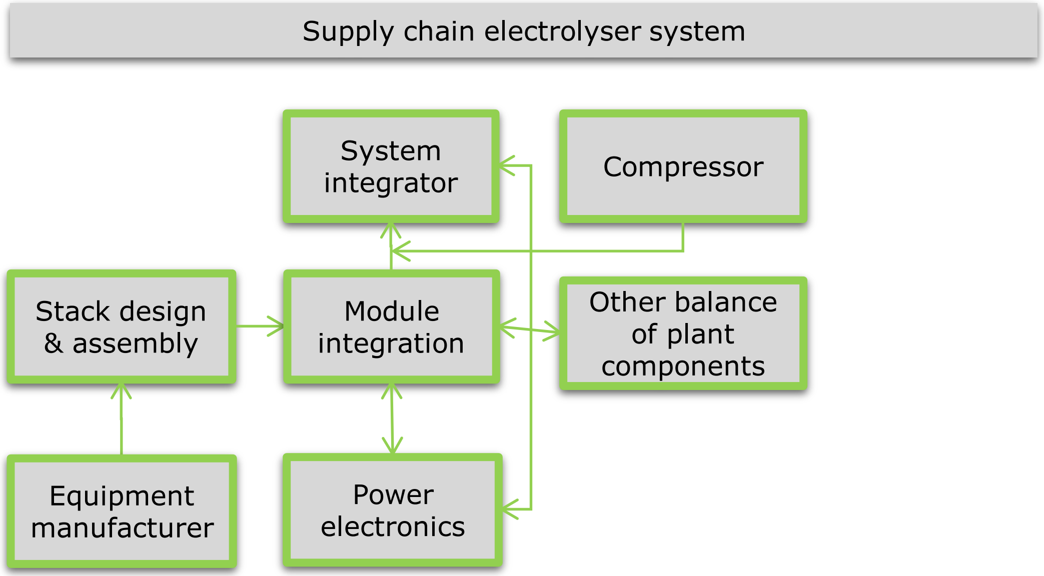

Figure 3. Supply chain of an electrolyser system. Other balance of plant components include the water purification unit, H_2 and O_2 separation vessels, PSA/TSA, IA and N2 systems and cooling water. Figure is adapted from TNO.

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Breakdown:

- Rectifier: A rectifier is a device that converts alternating current (AC) into a single-directional direct current (DC) and controls the power towards the electrolyser stack. These steps require specific knowledge regarding power electronics and are typically designed and produced at specialist manufacturers. They are key to efficient and reliable operation. Dutch companies have a good track record in supplying PE for electrolyser systems. Scaling up and project specific requirements make that each time the various aspects need to be addressed. Grid power quality requirements in combination with electrolyser electrical characteristics have a large impact on complexity and costs of PE as well. Cost reduction can be achieved by standardisation of grid power quality requirements. Rectifier technology is not really an issue and available to accommodate the needs for electrolyser systems.

- The stack design will be developed towards a standard module which can be multiplied to the required electrolyser size. The closure of the stack assembly to meet the tightness requirements is an area of development, as well as the maintenance of the individual stack assembly. To improve the quality and reduce the amount of labour, it is expected that stack assembly will be produced more and more in automated production lines.

- Balance of Plant (BoP) is currently estimated to contribute approximately 70% of the electrolyser costs, however this strongly depends on scope definition. An example of a breakdown of costs can be found in the ISPT report "A One-GigaWatt Green-Hydrogen Plant"[10]. The balance of plant consists of well-developed components and no significant cost reduction is expected based on the individual components. However, in scaling up the electrolyser systems, economies of scale will apply and opportunities to optimise the usage of BoP could lead to cost reduction.

- Compressor: Hydrogen compressors can be sourced at existing manufacturers. Larger scale H_2 compressors will need to be developed, however based on existing techniques this is not seen as a major issue.

- System integrator: Currently OEMs deliver the electrolyser systems and in scaling-up EPC contractors are involved to integrate the electrolyser and balance of plant into the project specific requirements and location. Limited technology knowledge of the electrolyser stacks and the BoP requirements makes it difficult to guarantee overall system performance and lifetime by EPC contractors.

- Various electrolyser suppliers have, or are developing, 'standard' size electrolyser systems which can be multiplied to the amount of capacity required.

- Standards and norms would help the implementation of electrolyser systems as various stakeholders (authorities, owners, suppliers) in the value chain will have a common reference. Especially safety standards, including the relevant failure data or benchmark would be very beneficial to speed up the engineering, supply and construction of electrolyser systems. Also, currently there is no internationally recognised certification scheme for electrolysers, although this under development.

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Key takeaways for subsidy scheme

- Stimulate the support and application of electrolyser system standards and norms.
- Demand from the grant receiving parties to disseminate project information (anonymously) regarding Health, Safety and Environment, technical and economical operations. This information would not only help parties involved in hydrogen production, but the green hydrogen supply chain in general.
- Stimulate electrolyser systems which integrate with other supply chains, such as for example heat, oxygen and fresh water, and reduce their footprint by applying smart integrated solutions. Integration with existing H_2 processes e.g. a hybrid solution between a SMR and electrolyser system to start integrating green hydrogen into existing processes could also be looked at.
- Encourage local balancing (improved controllability electrolyser - and/or controllable load)

Production and import

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Production costs indication

To provide insight into key drivers of the production costs for green hydrogen and the ratio between these costs components, a simplified cost calculation has been done. The figures used are meant to show the relative impact of certain changes between the scenarios.

Table 1 shows one base case scenario and three scenarios where input parameters have been changed to reflect the impact of this change in costs and ratio between cost components.

Analysis of electrolyser system efficiency is not shown here, but with increased efficiency the costs of hydrogen will reduce. However, the cost ratio will be similar to the scenarios shown here.

In the current Dutch context the overall conclusion here is that OPEX, and in particular the electricity costs, are the dominant cost driver for green hydrogen production.

Electrolysis > 100 MW	Scenario A Base case	Scenario B Increased load	Scenario C Increased E-price	Scenario D - 75% CAPEX, Increased load
Electricity price (Eur/MWh)	€ 60,00	€ 60,00	**€ 100,00**	€ 60,00
System efficiency (%)	65	65	65	65
Load (hrs/yr)	4000	**6000**	4000	**6000**
Lifetime (yr)	15	15	15	15
CAPEX (Eur/kWh)	€ 1200	€ 1200	€ 1200	**€ 900**
Maintenance (% of CAPEX)	4%	4%	4%	4%
H_2 price (Eur/kg)	€ 4,72	€ 4,17	€ 6,77	€3,90
Electricity (% of price)	65%	74%	76%	79%
CAPEX (% of price)	22%	16%	15%	13%
Maint. (% of price)	13%	10%	9%	8%
Total OPEX (% of price)	78%	84%	85%	87%

Table 1. This overview gives an indication of order of magnitude of costs and is not meant to be a financial analysis. The assumptions are based on a combination of experience, market information and estimates. See also the graph on the next slide.

- Depreciation costs are not considered
- The efficiency figure used is not the stack efficiency but the overall system efficiency. This is a combination of experience figures from 1 - 10 MW systems and supplier information
- Maintenance costs have been estimated as a percentage of CAPEX. This is an average over the lifetime of the system
- CAPEX of EUR 1.200,- / kWh has been used which is considered the average current price level for PEM electrolysers
- A scenario with 75% reduction of CAPEX is shown here, as it is not commonly recognised that CAPEX will reduce by >25% in the coming few years.

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Maintenance
CAPEX
Electricity

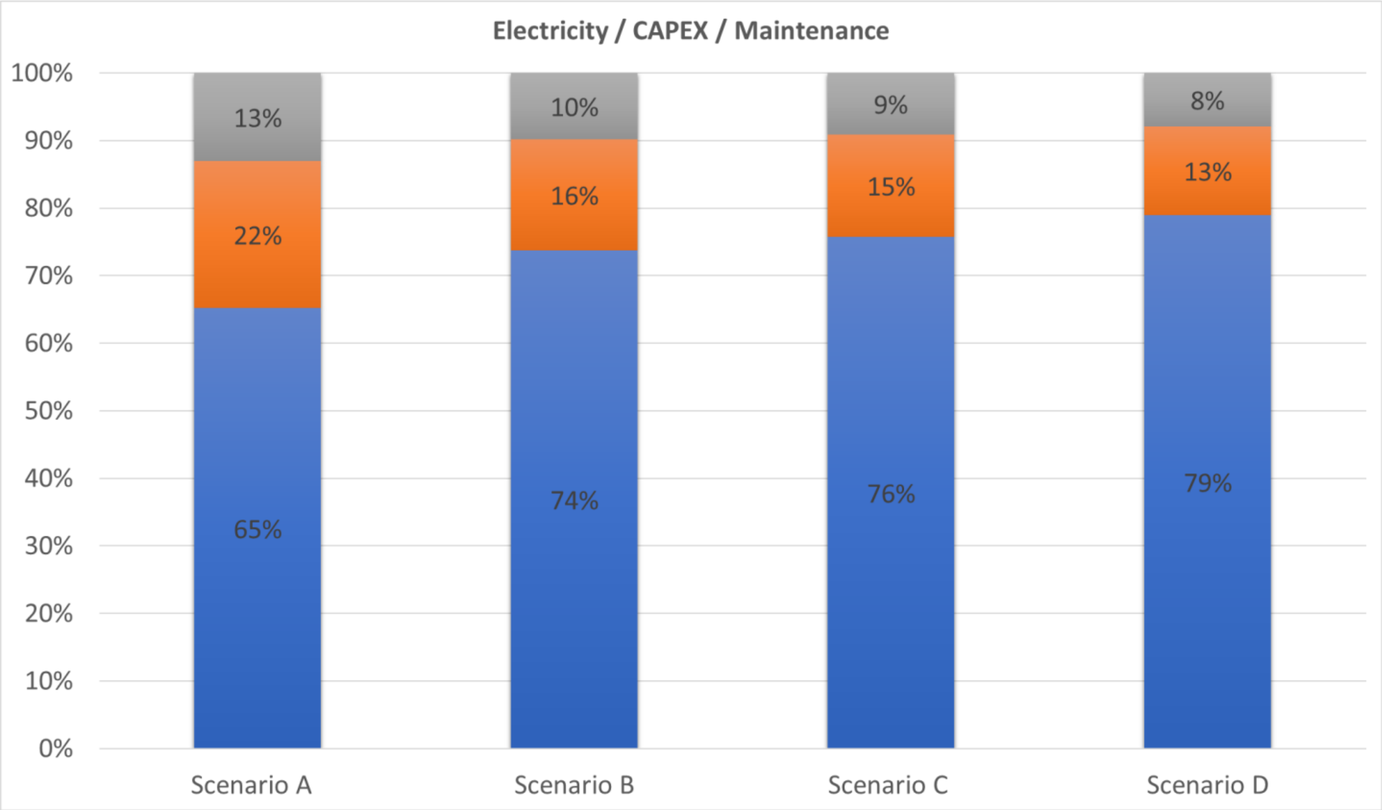

Figure 4. Scenario A: base case - Scenario B: increased load - Scenario C: increased electricity price - Scenario D: 75% CAPEX, increased load

Electricity costs vs CAPEX

Cost for hydrogen produced by electrolyser systems running at significant load (>50%) is dominated by costs of electricity at current electricity prices.

A reduction of the costs for green electricity will have the biggest impact on the costs for production of green hydrogen. However, there are few opportunities to decrease electricity costs for parties producing green hydrogen. Costs of electricity are market driven and will be based on procurement strategy and (long term) contracts. Therefore, the focus for production cost reduction will be on CAPEX and maintenance costs.

Reduction of CAPEX is expected by upscaling and automation of electrolyser production process. The scarcity of materials and hence the increase in costs dampens this effect. Therefore, reduction of the use of scarce, expensive and unsustainable materials must be further stimulated.

A reduction in maintenance cost is possible when the lifetime of the electrolyser (stacks) will increase, and the balance op plant set up will be optimized.

Production and import

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2.4 Analysis import

Import will be vital to meet H_2 demand both in the short term until 2030 and in the long term. The Netherlands is in a unique position with various ports, such as the Port of Rotterdam and Port of Amsterdam, which are developing import infrastructure at scale. Worldwide only five ports are developing plans for import of hydrogen (carriers) at scale.

There are several key challenges, risks and innovative solutions regarding import of hydrogen, which are summarised below.

- For energy security, parallel development of import infrastructure and national hydrogen production capacity is vital. Import of H_2 or H_2 carriers can be used to supplement intermittent local production of H_2 to increase security of supply for use of H_2 in continual production processes that need a constant supply of H_2.

- It is not yet clear which hydrogen carriers will become dominant. Flexibility in exploration of options for various hydrogen carriers is needed to prevent early lock-in. According to the IEA, ammonia will be the main hydrogen carrier for import and export by sea until 2030. Liquid H_2 and LOHC are not expected to play a large role until after 2030. Import of Liquid H_2 might start developing in 2027-2028.

- Ammonia seems to be the most obvious hydrogen carrier in the short term because the technology is available. The quantities required have a large impact on risks and space use. Additional storage capacity is currently being developed. Cracking of ammonia might be needed to supply pure hydrogen for balancing. On the other hand, large quantities of green ammonia are needed to produce for example green fertiliser. Whether or not this will take the lead over ammonia as a hydrogen carrier or direct use needs to be seen in the coming decade.

Key takeaways for subsidy scheme

- In which form hydrogen will be imported on the long term is unclear. However, multiple forms need to be simultaneously developed from a strategic perspective.

- It’s unclear if large scale cracking of ammonia is required in the future. If this is the case, efficient large scale cracking needs to researched and developed.

- New investments in fossil import (and storage) should be H_2 ready as much as possible.

Transport and storage

3

3.1 Introduction transport

Transport is considered to be the connection between the electrolyser plant or import terminals and the end-use and/or storage. In the quickscan, only transport of hydrogen by pipeline has been considered due to the amount of hydrogen to be transported. Transport by road is considered TRL 9 and therefore not considered to require a subsidy.

3.2 Analysis transport

After the hydrogen arrives from outside the Netherlands by ship or is produced in a local electrolysis plant, it will be transported to hydrogen consumers. For large quantities this is preferably done via underground pipelines. These pipelines connect hydrogen producers and users within industrial clusters. Eventually, there will also be a nationwide network of pipelines for hydrogen, some of which will consist of re-used existing natural gas pipelines. Besides pipelines, there is also road transport with trailers and possibly transport with barges.

For transport and storage options for hydrogen the technical issues are solved on a case-by-case basis on several locations around the globe. In the green hydrogen supply chain there several challenges, risks and innovative solutions still to be worked out regarding transport of hydrogen, which are summarised below.

- Within industrial clusters, additional pipeline connections may need to be made between producers and users of hydrogen. Non-metallic pipelines may be used for this purpose. The use of non-metallic pipelines to transport hydrogen should be included in the appropriate standards. Re-use of existing natural gas pipelines is possible in principle, but must be verified in detail for each route.
- The purity of hydrogen transported via repurposed pipelines is not always sufficient. For certain applications of hydrogen, especially those using fuel cells, strict quality requirements apply.
- General accepted guidelines for safety, e.g. what happens in case of a large H_2 leak caused by a ruptured pipeline, need to be further developed. Currently these are assessed on a case-by-case basis.
- Accurate and safe sensor technology, measurement and control equipment needs to be developed further for H_2 transport.
- The higher flow rate of hydrogen compared to natural gas can cause technical problems, requiring sound engineering.
- Attention needs to be paid to security concerns regarding H_2 transport infrastructure, e.g. cybersecurity and digitalisation.
- Local balancing of H_2 supply and demand is important, especially in the timeline considered for this subsidy scheme. Local H_2 pipeline infrastructure will have to be constructed. There are ongoing discussions on who will construct, own and operate the local pipeline infrastructure from H_2 production to local H_2 demand e.g. in industrial clusters.

Transport and storage

3

3.2 Analysis transport (continued)

- As in other parts of the hydrogen value chain, there are human capital related concerns. Around 2050, 3500 to 7000 fte will be needed in the Netherlands for technical employees for activities related to hydrogen infrastructure and distribution, according to HyDelta. Post-secondary vocational education opportunities are lacking in particular.

Key takeaways for subsidy scheme

- Support local/regional balancing developments (system modelling, interconnecting pipelines). To get insight in the amount of imbalance in a certain geographical area, it would help to develop regional system models with supply and demand profiles which can calculate the required balancing capacity. Based on this, specific measures can be developed which might include interconnecting pipelines. This is also relevant for the following section on storage.
- Develop affordable options for additional interconnecting piping (non metallic and metallic).
- Support development and standardisation of (application of) non-metallic pipelines including research/pilots if required.
- Stimulate the establishment of general standards, especially on HSE, to avoid having to work out the solution case-by-case from scratch.
- Projects which are supported by this subsidy scheme should be stimulated to offer education opportunities and/or should cooperate with (local) educational institutions.

Transport and storage

3

3.3 Analysis storage

In the Dutch context, large-scale storage currently refers mainly to storage in salt caverns. The effects of storage in aquifers and depleted gas fields need further investigation, especially on the quality of withdrawn H_2.

Storage locally and on a smaller scale is currently done in tanks or bottles under high pressure using compression, but is costly.

Matching supply and demand is key to limiting the storage capacity needed. In addition, more efficient and affordable storage technologies should be developed.

Several challenges, risks and innovative solutions regarding hydrogen storage are summarised below.

- Especially in the early phases of the development of the green hydrogen value chain, the type of and amount of hydrogen storage needed should be closely matched to the H_2 demand profile locally, where multiple H_2 offtakers are considered. Particularly in the cases where an interconnecting pipeline network and/or large scale storage e.g. caverns is not (yet) available.
- Connection to a larger regional pipeline network or to a national interconnecting network should be considered to connect to (large scale) storage facilities. See also the previous section on transport.
- Hydrogen storage in salt caverns is already done on several locations in the world. Large scale H_2 storage in salt caverns needs to be developed and proven within the Dutch context i.e. rules and regulations. Tests on large-scale storage of hydrogen in caverns are ongoing in the Netherlands, looking into safety, mechanical integrity, pressure, working methods and microbiology.
- Hydrogen storage in depleted gas fields and/or aquifers needs to be investigated, especially regarding the H_2 quality after withdrawal. In the Austrian project "Underground Sun Storage"[11] research and tests are conducted in storing H_2 in a depleted gas field.
- Research into the best material use for hydrogen storage tanks is ongoing. New materials are being examined that enable hydrogen to be stored at very high pressure or extremely low temperatures.
- Innovations focused on cost reduction related to storage are also needed to reduce LCOH where possible.
- For import terminals the rules and regulations need to be developed to store the various hydrogen "types" such as Liquid Organic Hydrogen Carriers (LOHC), Liquid Hydrogen (LH) and solid carriers.

Key takeaways for subsidy scheme

- Support research and development of new and/or promising storage technologies (e.g. LOHC, solid).
- Start developing the rules and regulations for storage at H_2 import terminals and salt caverns.

End-use

4

4.1 Introduction end-use

The Dutch industry currently consumes an estimated 180 PJ of hydrogen per year and is the second largest hydrogen consumer in the EU[3].

For the end-use of hydrogen, four industries have been considered here, these being (1) steel production (2) chemicals (3) fertiliser (4) sustainable aviation fuels (SAF) and shipping fuels.

4.2 General analysis end-use

Several overarching challenges, risks and innovative solutions regarding the end-use of hydrogen in the various industries mentioned are summarised below.

- One of the biggest challenges is the large quantities of green hydrogen needed by the Dutch industries to decarbonise. A rapid scale up of electrolyser projects, import facilities for green hydrogen and development of the wider local hydrogen value chains is needed.
- Reduction of the costs of green hydrogen (LCOH) is also crucial to stimulate the decarbonisation of the key industries mentioned.
- Matching intermittent green H_2 production to continual production processes is a challenge. This could be resolved by increasing storage solutions, but also by stimulating flexible H_2 offtake or in the beginning in a hybrid format with the existing H_2 production e.g. SMR. Innovation stimulating flexible H_2 demand is needed, for example by adapting the production processes in the key industries mentioned above.
- Lack of a transparent hydrogen trading market for green H_2. Currently the first steps towards local spot markets are being made. A transparent and working green hydrogen certification process is a prerequisite for an open trading market.
- Industrial burner systems need to be adapted to ensure they can deal with hydrogen's different combustion characteristics compared to natural gas.
- Another technical challenge is addressing NO_x emissions when using hydrogen to replace natural gas in burners. In various tests the resulting NO_x emissions have been different than expected, sometimes higher, sometimes lower. Further research is required to better understand the phenomena around the formation of NO_x emissions in hydrogen burners, also to be able to design counter measures to lower NO_x emissions.

4.3 Analysis green steel

The production of green steel requires vast amounts of green hydrogen for which several GW electrolysis capacity needs to be installed. These developments are on a different timescale, however areas of interest are:

- DRI (Direct Reduced Iron) installations which can use high percentages of hydrogen (>80%) need to be developed.
- Further development of increased temperature electrolysis (Solid Oxide) should be stimulated, as the heat could be used in the steel production process.

End-use

- The production process of steel could be made more flexible to adapt to availability of green hydrogen.
- Consider also the development of hybrid solutions (green / fossil).
- Support for (pre) engineering and study is needed.

4.4 Analysis synthetic fuels for aviation and shipping

4

- For the large-scale production of synthetic fuels, large amounts of green carbon molecules are required. This presents a considerable challenge for SAF, methanol and other carbon-based green fuels.
- Regarding aviation, green hydrogen is needed to produce drop-in hydrogen derived sustainable aviation fuel (SAF) and could be used directly in hydrogen powered aircrafts for short to medium haul flights. For both the Netherlands and across the European Union there are blending mandates for SAF.
- Shipping: in small vessels green hydrogen could be used directly, for larger vessels ammonia is more suitable. The use of methanol is split between small and large vessels.
- Shipping: development of engines running on ammonia or dual fuels (e.g. ammonia and diesel) is needed. Especially for application of long distance shipping and large deep sea vessels.
- Shipping: safety and toxicity challenges of ammonia are a concern when used at a large scale.
- Shipping: safety codes, standards and regulations need to be developed for hydrogen and derived fuels in the international shipping sector.

Fuel	Key advantages	Key limitations/risks
Biodiesel	• Can be used as drop-in fuel in existing vessels and engines	• Limited availability of biomass feedstock • Price pressure due to competing demand
Methanol (bio-methanol and e-methanol)	• Already in operation as marine fuel and engine is available • Liquid at normal condition and well-known handling	• Bio-methanol: Limited availability of biomass feedstock • E-methanol: Availability of biogenic CO2 source
Lignin fuels (New biofuel based on lignin-alcohol blends)	• Potentially the most price-competitive net zero fuel, could be almost on par with fossil fuels • Same engine requirements as for methanol	• In development stage with production still to be scaled up • Additional handling of contaminants may be required in fuel system and engine
Ammonia (green ammonia)	• Fully zero emissions fuel • Can be produced at scale from renewable electricity alone	• Safety and toxicity challenges • Infrastructure challenges at ports • Future costs depends on cost of renewable electricity and electolyzer

MAERSK

Figure 5. Comparison of fuel types for shipping. Figure is adapted from Maersk.

End-use

4.5 Analysis green chemistry

Within the chemical industry hydrogen is mainly used in the refining industry and as feedstock to produce ammonia.

- In this transition phase, hybrid solutions need to be looked at where the current grey hydrogen feedstock is (partially) replaced by green hydrogen.
- (Pre) FEED studies looking at the transition of grey into green hydrogen are required to make the transition possible, before scaling up to GW scale.
- New value chains need to be developed for high value products using green hydrogen as a feedstock (e.g. automotive, electronics, pharmaceuticals) .

4.6 Analysis green fertiliser

- NH_3 production requires large amounts of H_2, currently obtained via Steam Methane Reforming. Most of the produced ammonia forms the basis for mineral nitrogen fertilisers, but it is also used in other chemical processes. Currently there are no incentive schemes or legislation in place to stimulate the use of green hydrogen in the production of ammonia. The market for green ammonia needs to be developed.
- Taking the traditional ammonia process into account, the transition towards the usage of green hydrogen will most likely be done in steps. Starting with a hybrid form of SMR and electrolysis (+/-100 MW). This can be done by accepting a slightly lower SMR efficiency in combination with supplementing green H_2. Limiting factor is available N2. The hybrid format provides an opportunity to act as green H_2 offtake whilst having a back-up with the SMR to cope with imbalance and security of supply. From an operational point of view the hybrid form seems feasible, however requires detail verification.
- Connecting ammonia production with larger amount of green H_2 (electrolysers > 100MW) separate N2 production is required. To replace the SMR a large next step needs to be taken (electrolysers > 650MW). Besides large electrolyser systems and N2 production facilities, renewable power needs to be available.
- The production and transport (shipping) of ammonia is well developed.

Key takeaways for subsidy scheme

- Stimulate long-term H_2 offtake contracts with parties in key industries, such as steel, chemistry, fertiliser and production of fuels for aviation and shipping.
- Development of hybrid solutions is needed, as for most industries mentioned the amount of green hydrogen production required to become carbon neutral is far greater than 100 MW electrolyser capacity.
- Manage side effects of changing to green hydrogen, like additional production of N2 (fertiliser), and availability of green carbon (methanol, SAF).
- Set up regulations for a transition phase toward green industry (% green per industry per year).

Conclusions

Introduction

To promote electrolyser projects of over 100MW and to stimulate the development of green hydrogen value chains, it is necessary to reduce costs for the production, transport, storage and use of green hydrogen. There are several parameters that matter here, such as CAPEX and OPEX. Projects also calculate risks based on uncertainties regarding reliability, availability, safety, offtake guarantee, etc. In addition, demonstrating the sustainable origin of hydrogen is an important issue for the entire value chain. Although 100 MW+ electrolyser plants are a significant scale-up, the amount of H_2 produced is limited compared to the hydrogen amount required by offtakers and therefore hybrid solutions (grey/green) need to be incorporated. If these aspects are addressed and resolved where possible, scaling up in the hydrogen value chain will be accelerated.

5

Manufacturing

The Dutch (manufacturing) industry is well represented as a supplier of components for electrolyser systems. Dutch companies are also active in scaling up and improving these components.

Optimising the design of electrolyser systems and the system integration at the electrolyser plant level (e.g. BoP) could fit well with the expertise of Dutch companies.

There are currently no known Dutch companies capable of producing electrolysis systems of 100 MW or larger by 2026. However, there are several Dutch companies actively developing electrolysis systems of this scale, but these are not yet market ready in 2026 and will become available later.

CAPEX

To reduce CAPEX of electrolyser systems, the general opinion is that upscaling, standardisation and automation of electrolyser production could lead to reduction of costs due to economies of scale. Furthermore, a reduction of the use of scarce and expensive materials benefits overall cost reduction.

When scaling up electrolyser systems opportunities arise for smart system integration, leading to optimised BoP configuration, thereby reducing costs. In addition, the system design can be optimised for space utilisation and maintainability. EPC contractors and system integrators will play an important role in the optimisation.

Conclusions

5

OPEX

OPEX is defined here as energy costs (per kg hydrogen), operational and maintenance costs. The costs of renewable electricity are the largest contributing factor the OPEX for electrolyser systems running over 50% of the time.

OPEX costs can further be reduced by improving electrolyser system efficiency, for example by using higher current densities, operating temperatures or pressure, in combination with improving the reliability and extending the durability of the related key components within the electrolyser stack/system. This will subsequentially reduce maintenance costs as well.

Proper integration of electrolyser systems into the local environment can ensure that the residual heat and oxygen released during hydrogen production can be put to good use and improve the business case of the electrolyser system.

Availability of renewable electricity

The timely availably of sufficient renewable electricity at the required location is a prerequisite to accelerate the development of the green hydrogen value chain

Project risks

Due to uncertainties in electrolyser projects, risk mark-ups are factored in by various stakeholders. This makes projects financially challenging. These uncertainties include the following areas:

- Reliability/availability of electrolyser systems
- Liability within the supply chain – who is carrying which risk
- Safety
- Legislation and permits
- Purchase guarantee
- Price and availability of renewable electricity and water
- Balancing supply and demand - need for storage

Forming strategic alliances across the electrolyser system and/or value chain could be a good way to address the project risks and prevent build-up of multiple contingencies.

Conclusions

Safety

Safety items to be addressed are:

(1) safety perception of H_2 of the general public and financial parties by sharing facts and figures. This should be done by actively sharing knowledge and experience regarding hydrogen production, transport, storage and applications.

(2) Prepare or extend existing safety standards, being norms and standards for (the integration of) electrolyser systems, H_2 transport by metallic and non-metallic pipelines, and H_2 storage facilities. Specific items to be addressed are ATEX, qualifiers for Quantitative Risk Assessment, good practices to mitigate hydrogen related risks e.g. earthing, UV/IR camera's, etc.

Certification

Offtake customers of green hydrogen are willing to pay a premium, however there must be no ambiguity regarding what is meant by green H_2. To guarantee the sustainable (green) origin of hydrogen, agreements (legislation) are needed to determine when hydrogen is green. A system is also needed to record and guarantee this. If hydrogen is not demonstrably green, it is much less attractive for the market to buy and has less value. Clear certification agreements are a prerequisite for a well-functioning green hydrogen market.

Main suggestions

In the table below the main concrete suggestions for the subsidy scheme are summarised.

	Type	Description
1	Requirement	For a 100MW+ electrolyser project demand e.g. 10% innovative stack design (< TRL 9)
2	Requirement	Co-located test site for testing of lower TRL electrolyser system components / materials (< TRL 7)
3	Ranking	Integration of the electrolyser system on multiple levels (power grid integration – reduce grid congestion / heat recovery / oxygen usage)
4	Requirement	Parties receiving funding should disseminate project information (anonymously) regarding Health, Safety and Environment, technical and economical operations.
5	Ranking	Award increased overall electrolyser system efficiency (kWh per produced kg H_2)
6	Ranking	Award green hydrogen certification and transparency systems to secure the value of green hydrogen

Sources

Overview of parties that were interviewed for this report:

Air Liquide (Con / Prod)

Battolyser Systems (OEM / HiT)

Bosch Tilburg (HiT)

Demcon (OEM)

DNV GL (research)

Eurus (Prod)

Green Giraffe (Fin)

Hynetwork Services (Potential TSO)

HyCC (Prod)

HyET (OEM / HiT)

HyStock (Storage)

ISPT (research)

Lhyfe (Prod)

MTSA (SyI)

OCI Nitrogen (Con)

Plug Power (OEM)

Port of Amsterdam

Port of Rotterdam

Prodrive (HiT)

Royal HaskoningDHV (consultant)

Siemens Energy (OEM / HiT)

SkyNRG (Con)

Tata Steel (Con)

TenneT (TSO)

TNO (research)

TotalEnergies (Prod / Con)

Triodos Bank (Fin)

Triodos Investment Management (Fin)

Van Oord (Con)

VDL Nederland (OEM / HiT)

VoltH2 (Prod)

Vonk (HiT)

Worley (EPC)

Sources

References

1. IEA, “Global Hydrogen Review 2022” [Online], Sep 2022
2. IEA, “World Energy Outlook 2022” [Online], Oct 2022
3. Nationaal Waterstof Programma, “Routekaart Waterstof” [Online], Nov 2022
4. TKI Nieuw Gas, "Innovatieagenda waterstof Update 2023" [Online], Dec 2022
5. FME, “NL Hydrogen Guide” [Online], May 2022
6. HyDelta, “Hydrogen value chain literature review” [Online], Oct 2021
7. HyDelta, “Summary for policymakers: hydrogen value chains in the Netherlands” [Online], May 2022
8. HyDelta, “Innovation roadmap” [Online], May 2022
9. H2Future, “KPIs to monitor the Demonstrations and perform the Exploitation Tasks” [Online], Feb 2020
10. ISPT, “A One-GigaWatt Green-Hydrogen Plant” [Online], Jan 2022
11. Underground Sun Storage project

Appendix

Overview of types of parties involved in development of the green hydrogen value chain:

High-tech equipment & materials (HiT)

Technology providers for electrolyser systems

Original Equipment Manufacturer (OEM)

Engineering, Procurement and Construction contractor (EPC)

Transmission System Operator (TSO)

Distribution System Operator (DSO)

Consumer of Hydrogen (Con)

Producer of Hydrogen (Prod)

Port authority

Logistics providers

Financial and insurance parties (Fin)

Organisations for standardisation

Consultants

Research

summit engineering

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