GVNL Feasibility Study Endurance Test Facility

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Executive summary

This report provides insights on the feasibility of a Dutch facility for green hydrogen industrial scale production value chain endurance testing.

Market Demand

There is **significant market demand** as two thirds of responses from the market consultation flagged significant interest for an endurance test facility. The results show the urgency for such facility, and to have it **operational within the next two years**. A testing facility should **focus on Technology Readiness Level (TRL) between 6 – 8**. Open access testing facilities are of critical importance to small and medium sized companies (SMEs) to overcome system / product development and commercialisation challenges.

Testing capacity and duration

Testing facilities should have a capacity between **1-10MW** and aim for testing duration of **3-12 months**. This is mainly sustained by the fact these ranges attract many potential users now, but also ensures future proofing of the test facility.

Testing Metrics

The **key testing metrics are utility use, efficiency, degradation over time, pressure, purity, temperature**. In line with these needs is the desire to benchmark performance according to industry testing standards by an independent organisation. **The dynamic performance and start/stop cycles** occurring with renewable energy integration on electrolyser performance/stability, balance of plant (BoP) and end-user integration is also of great interest.

Component vs. full system testing

Testing should range from single component to full system testing. Single components to be tested are likely to be: **electrolysers, power electronics, BoP and compression.** Full system testing focusses on the whole hydrogen value chain but excludes water treatment and hydrogen storage.

Characteristics of the test facility

The test facility will be a **shared service**. The design of the facility needs to be modular and readily adjustable to the needs of the user. Accommodating all **major types of electrolysers (Alkaline, PEM, AEM & SOEC)**, therefore it is advised to design and construct the testing bays to enable for the various type of technologies.

Components of the test facility

Designing and constructing a test facility that caters to all potential user requirements requires significant (pre-)investments. Before taking all future user requirements as facts and designing the test facility to accommodate these needs, it is important to challenge the costs associated with these demands to the future users. This is further discussed in the recommendations below.

Organisation

The organisation of the test facility should ensure that all regulations, permitting, hydrogen offtake and HSSE aspects are secured. This requires proper organisation with operators, engineers, subject-matter experts, and a safety officer.

Unique selling points (USP) endurance test facility

Matching the market demand with what has already been covered the existing facilities in north-west Europe led to the following unique selling points of a national endurance test facility:

- Industrial scale testing at 1-10MW capacity per bay for months.
- Testing of entire systems or subsystems at TRL 6-8.
- Being able to accommodate different electrolyser technologies.
- Possibility to connect existing facilities in the Netherlands with the endurance test facility and provide a single process to go through all TRL's for green hydrogen production.

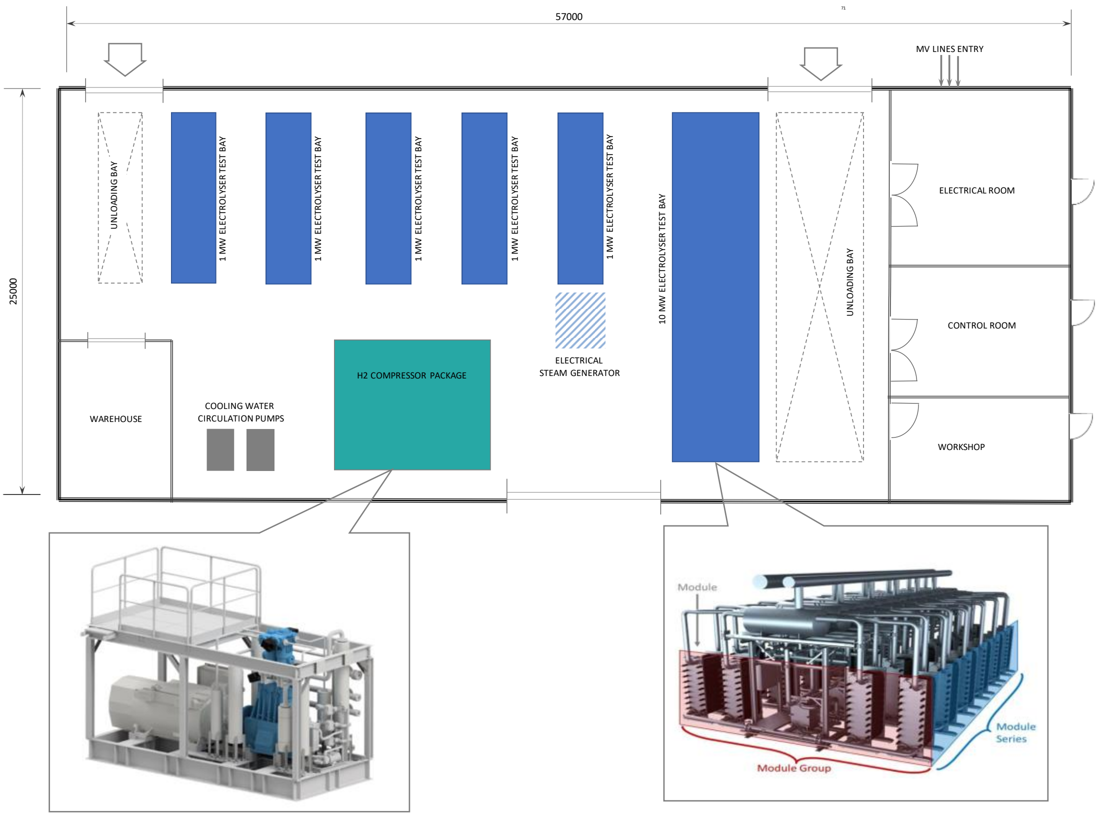
Elaboration of the USP can be found in section D.6.2.

Functional Design

For the Green Field development of a test facility, the Basis of Design should at least be in compliance with the following criteria (must-haves):

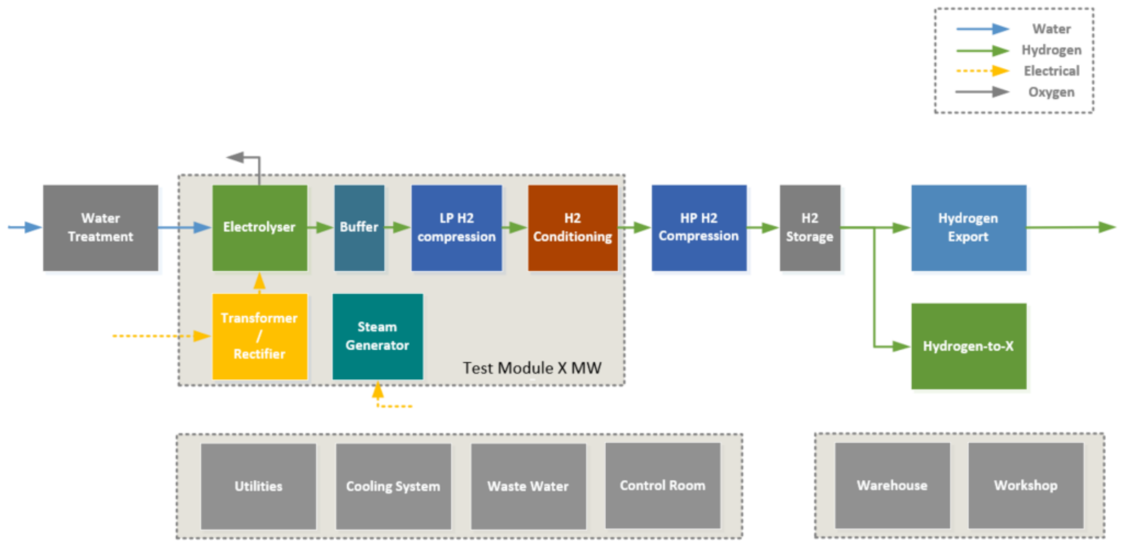
- The facility must be able to accommodate minimum of 15MW (1x10MW + 5x1MW, potentially combined into multiple MW's) electrolyser capacity.
- The facility must be able to accommodate different components of the value chain in a modular way.
- The facility must be able to run multiple and independent tests in parallel.
- The facility must be able to accommodate different (electrolyser) technologies.

Figure 0.1: Building lay-out of the green field endurance test facility main building.



Note: The HP compressor, HP storage and tube trailer docking is placed outside of the main building.

Figure 0.2: Block flow diagram of the hydrogen test facility.



Cost Estimate

Based on the functional design, specifications, and additional assumptions a cost estimate (**P50, A Class 5 AACE**[1]) was developed for a greenfield endurance test facility. PEM and alkaline electrolysis technologies are used to study the CapEx and OpEx. The basic figures for a 15MW facility:

- CapEx: 42.25 - 46.25 M€ (excluding electrolyser stack)
- OpEx: 1.58 – 1.69 M€/year (excluding utility use for the electrolyser)

Additional assumptions were made for the functional design to develop the cost estimates. Both the cost estimates for PEM and alkaline show a similar trend; the CapEx and OpEx of all components besides the electrolyser decrease per megawatt with increasing capacity. A high utilisation of the full capacity could be a significant cost reducer per megawatt of installed test capacity. Besides, financing cost will contribute significantly to the running costs of the facility. Lastly, test facility utilization rate and utility use for electrolyser testing will drastically influence the costs for future users.

Recommendations

There is a market demand for endurance testing facilities in the Netherlands. Our study shows possible clients prefer such test facility to become available within a two-year timeframe. Based on the gaps of the current study, our main conclusions, and the challenging timeframe we recommend GroenvermogenNL to **continue as soon as possible with the planning and development process of an endurance test facility in the Netherlands.**

Having an endurance test facility operational within two years is challenging. To be in line with this target, we recommend GroenvermogenNL to take **three major decisions** before June 2024.

a. **Location selection and decision:** Technical input from the location is of critical importance for further (FEED) design work. For example, the availability of an ATO (Aansluit- & Transport Overeenkomst) for grid capacity could significantly reduce the

[1] https://library.aacei.org/pgd01/pgd01.shtml#Classification%20Concepts%20and%20Principles

development period, as would the avvailability of permits. Ability to share staff with adjacent facilities would enable the reduction of OpEx.

b. **Technical concept selection:** Technical details from of the concept selection are of critical importance for the input to design work, engagement with suppliers and, subsequential, information about lead times and feasibility of the project schedule.
c. **Business model decision:** For GroenvermogenNL it is important to have clarity on the business model of the endurance test facility. This decision should provide clarity on the cost in CapEx and OpEx and the future revenues of such facility. We foresee this information to be of critical importance for the development path.

To sustain these decisions, we recommend GroenvermogenNL to start directly with the execution of **three additional studies** providing the required level of detail in information to take these decisions:

1. **Location selection Study**

   Our current study and the study of ISPT show potential locations for an endurance test facility. As is understood from other projects in the Netherlands (industrial) locations for industrial development as the development of an endurance test facility are scarce. We recommend GroenvermogenNL to **secure a site for the facility as soon as possible** as this decision will be on the critical path for the delivery time of the facility also, this decision will impact any follow-up technical/economical decisions/work.

   Based on our findings we recommend GroenvermogenNL to consider the following criteria for the site selection:

   - Site availability within (very) short notice and for at least 10 years.
   - Availability of sufficient grid connection and grid availability
   - Existing permits in place regarding hydrogen activities
   - Close proximity of hydrogen offtakers (or possibility to develop this)

   We recommend GroenvermogenNL to execute a full site selection procedure including the following steps:

   a. **Finalise selection criteria:** Objective is to create a proper list of the criteria used for site selection enabling a transparent site selection process and to make a well sustained site selection choice in the end. A draft scoring scheme with relevant site selection criteria is provided in Appendix K.
   b. **Desktop study to possible locations:** Objective is to identify a complete list of possible locations for an endurance test facility in the Netherlands.
   c. **First round of engagements:** Objective is to receive all necessary (economic/legal/technical) data possible by engaging with possible parties willing to host or lease a location for an endurance test facility.
   d. **Analysis on cost, timeline and conditions:** Objective is to shortlist the identified locations based on the defined selection criteria. Aim should be to have approx. 3 locations selected for further (in-depth) engagement).
   e. **In-depth engagements including negotiation:** Objective is to have in-depth engagements with the shortlisted parties/locations and to negotiate any terms and conditions for the lease/sell of a location.
   f. **Select a location:** Objective is to select a particular location.

2. **Technical Feasibility Study:**

For further development of the endurance test facility more detailed technical information is necessary. As part of the Technical Feasibility Study, we recommend GroenvermogenNL to develop the following items as minimum:

a. **Basic Plot Plan:** Objective of the plot plan is to have insight into the space necessary for the individual equipment of the facility and the facility in total. Ideally this is directly linked to the final location (Decision a.).
b. **Block Flow Diagram (BFD):** Objective of the BFD is to show in a schematic way what different blocks of equipment are foreseen in the facility and how they interact.
c. **Energy Flow Schematic (EFS):** Objective of the EFS is to show how the different forms of energy flow through the facility. Subsequently the EFS shows what sources of energy, goods are necessary to be brought in from external sources (e.g., Water, Nitrogen, etc.).
d. **Single Line Diagram (SLD):** Objective of the SLD is to show what power infra equipment is necessary and how electrical energy flows through the facility.
e. **HSSE study:** Objective of the HSSE study is to indicate critical HSSE aspects in the facility. Items which are foreseen to be addressed in the HSSE study are: specification of the Hydrogen/Oxygen venting or flaring, safety distances, Electrolyser leak dispersion analysis etc.
f. **Supplier engagement study:** Objective of this study is to have insight on the critical parts from the supply chain, impacting the contracting strategy, schedule and technical aspects of the facility. From other projects we know the electrolyser and compressor supply chain are extremely constraint.
g. **Level 2 execution Schedule:** Objective of this schedule is to indicate and quantify the critical path of development with the appropriate level of detail for a feasible development timeline.
h. **Permitting study:** Objective of the permitting study is to indicate specifications on the applicable permits and a risk identification on obtaining these permits.
i. **Contracting strategy:** Objective of this strategy is to indicate how the different elements in the facility need to be contracted.
j. **Technical specifications:** Objective of the technical specifications is to develop, based on the technical studies, a set of specifications which are needed for contracting and further design work.

3. **Economic Feasibility Study**

Our study provides the P50 CapEx and OpEx details. We recommend GroenvermogenNL to take a well-funded business model decision by June 2024. We foresee following information is necessary for such decision:

a. **P90 CapEx (Class II or III AACE cost estimate):** Objective is to have certainty on the investment costs for the facility. Information on this will highly be dependent on the outcomes of the technical feasibility study.
b. **OpEx estimate:** Objective is to have certainty on the operational expenditure for the facility. Both in organisation, maintenance, and operating costs (including purchase of electricity).
c. **Revenue estimate:** Objective is to have clarity on the revenues from the facility. We recommend GroenvermogenNL to have engagements with possible users of the facility to gain more understanding on the willingness to pay for the testing facility, and to sustain any estimation on the occupancy rate of the facility.

A. Introduction

A.1 Introduction

GVNL is a programme funded by the National Growth Fund of the Netherlands to accelerate the realisation of green hydrogen economy in the Netherlands. This support from GVNL will cover the production, import, transport, storage, and utilisation. For the stakeholders in this value chain, there is a common and shared interest in improving the overall system performance and reducing the Levelised Cost Of Hydrogen (LCOH). From initial discussions with market players, performed by GVNL, there seems to be a need for a facility that allows green hydrogen systems and/or components to be tested under realistic conditions for extended periods of time. Rather than having the different companies to individually organising test facilities, there is a national value in a centralised organisation, offering endurance testing facilities that is available for all stakeholders.

In June 2023, the Institute for Sustainable Process Technology (ISPT) published a report on their study *'Outcomes Study Facility Long Duration Testing for MW Electrolysers*' on possible locations and utilisation of long-term testing of hydrogen electrolysers. It concluded that there is a need for a facility for long-term testing to validate the performance of new or modified electrolysers. This test facility could play a key role in the rollout of large-scale green hydrogen production technologies and systems. On the basis of the positive advice from ISPT, GVNL continued the effort to further substantiate any future investments in an endurance test facility.

A.2 Scope of Work

The objective of this study is to:

1. Identify the market interest/demand for test facilities for green hydrogen systems and infrastructure.
2. Determine the type of testing most needed.
3. Identify the requirements of the test facility appropriate to the greatest need.
4. Determine the required organisational roles for the operation of the facility.
5. Determine the functional design and critical technical specifications of the test facility. This to serve as a basis for the cost estimate.
6. Provide a high-level indication in capital expenditures (CapEx) and operational expenditures (OpEx) estimates for the test facility.

A.3 Privacy Aspects

To comply with the General Data Protection Regulation (GDPR)[2], personal data of the respondents are not disclosed in this report. In some cases, company names are listed in this report, in those cases explicit written approval was obtained from those parties. The results from the questionnaire result are aggregated and the outcomes of the interview are not relatable back to individual parties. The section specifying the location possibilities does include the name of the entity with their written consent. This is also to ensure a transparent location selection process.

[2] https://gdpr-info.eu/

B. Project Context

To achieve the climate objectives of reaching CO_2 neutral society in 2050, and to maintain good business models for the industries, the government of the Netherlands aims to support the sustainability of the energy infrastructure and raw materials. This includes supporting the infrastructure development for the increasing demand of electricity, hydrogen, carbon capture, utilisation and storage (CCUS), heat and circular raw materials[3]. Hydrogen is seen as one of the key factors in achieving a sustainable energy system which is climate neutral by 2050.

Hydrogen has been produced and utilised in various industries for a long time. However, current hydrogen production is mainly based on natural gas reforming and still associated with high CO_2 emissions. To reduce these hydrogen production related CO_2 emissions, the Netherlands is looking into green hydrogen, i.e., hydrogen produced from renewable energy. In the case that industries and sectors cannot be decarbonised with electricity, green hydrogen offers a sustainable solution. Additionally, hydrogen can act as long-term seasonal storage, to assure energy availability in times of low energy generation. Lastly, hydrogen has the potential to transport energy over long distances[4].

Next to the policies focusing on import of hydrogen[5], the Dutch government also aims to stimulate the supply and demand of green hydrogen in the Netherlands. The government agreed in the climate agreement to provide installed capacity of at least 4 GW of electrolysers in 2030[6]. For the development of a green hydrogen economy, it is foreseen both government and industry need to invest in stimulating the demand and supply of green hydrogen.

B.1 The Green Hydrogen Value Chain and its Stakeholders

The green hydrogen value chain (Figure B.1) reaches from energy input, production, transportation, and storage and finally to the end use. Green hydrogen production needs to use electricity from a renewable energy source needs to be used. In the Netherlands the green electricity will most likely come from wind energy produced at the North Sea[7]. Different electrolysis technologies can be used to convert electricity into hydrogen, such as alkaline, Proton Exchange Membrane (PEM), Anion Exchange Membrane (AEM) and Solid Oxide Electrolyser Cell (SOEC). Relevant stakeholders for the production of green hydrogen are **electrolyser manufacturers** and **BoP manufacturers**. Next, for the transportation and storage of hydrogen, equipment for compression, liquefaction and reconversion is needed. Additionally, infrastructure needs to be in place to transport the hydrogen via trucks, ships, and pipelines. If the test facility focuses on these transport and storage technologies, **manufacturers of these compressors, pipelines and other technologies could be relevant stakeholders**. Lastly, hydrogen needs to be converted into end products such as green steel, synthetic fuels, ammonia, or converted to energy via fuel cells. Whereas the production of green hydrogen shows promising prospects to be used in the industry and transport sector, uncertainty exists on the evolution of the demand for green hydrogen. The **end users** are therefore also interesting stakeholders. Other key stakeholders of the hydrogen value chain are **project developers, operators, research institutes, branch organisations, and test companies**.

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[3] https://www.rijksoverheid.nl/documenten/rapporten/2021/11/26/meerjarenprogramma-infrastructuur-energie-en-klimaat---overzicht-2021

[4] https://www.iea.org/reports/global-hydrogen-review-2023

[5] https://www.rijksoverheid.nl/documenten/kamerstukken/2023/06/02/energiediplomatie-en-import-van-waterstof

[6] https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/national-climate-agreement-the-netherlands

[7] https://windopzee.nl/onderwerpen/wind-zee/wind-zee-waterstof/

Figure B.1: Green Hydrogen Value Chain

Challenges remain in developing and testing the technologies to make the transport of green hydrogen commercially viable. It is important for this feasibility study to get input from as many relevant stakeholders as possible, as this will help GroenvermogenNL realise an endurance testing facility to help stakeholders of the Green Hydrogen value chain in the Netherlands improve overall system performance and reduce the LCOH. All stakeholders contacted for either the online questionnaire and/or the in-depth interviews can be found in section I.

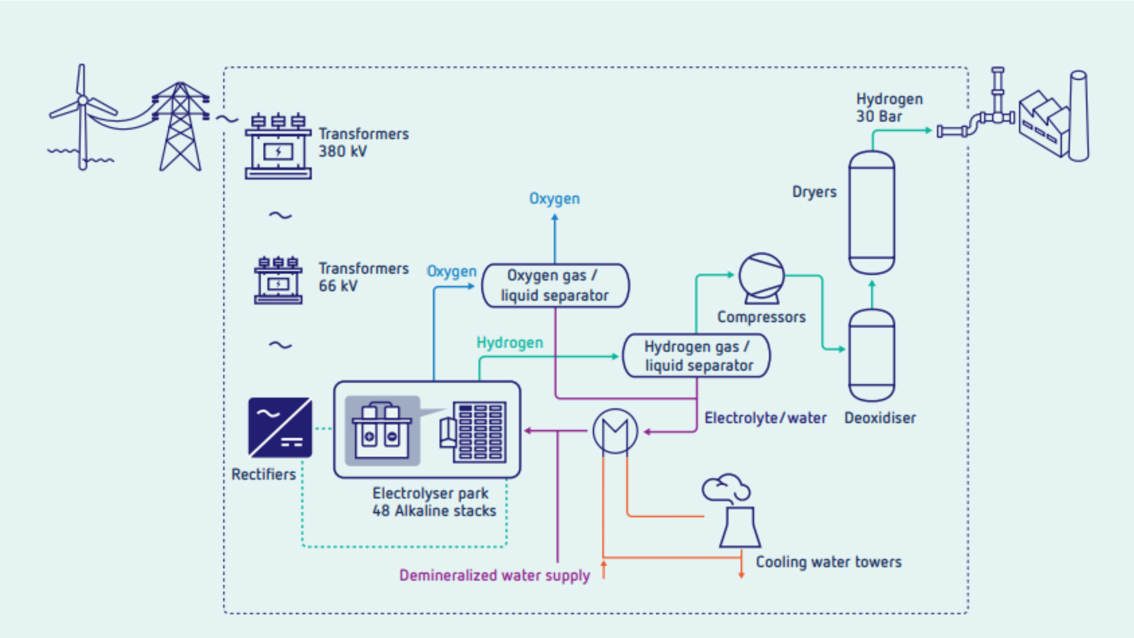
B.2 Hydrogen Test Facility

Testing facilities worldwide play a crucial role in advancing technologies from fundamental principles and technological concepts to systems validated in an operational setting. This is also the case for technologies in the hydrogen value chain, encompassing production, storage, transport, and utilisation. These facilities serve as platforms to evaluate the properties, performance, and safety of the hydrogen technologies. The functional requirements and specifications of a test facility are largely dictated by the nature and scale of the tests conducted. Testing can be done either for individual components, or for complete systems. The range of tests that can be performed includes:

- Functional tests
- Stress tests
- Endurance tests
- Integration tests
- Tests for the provision of ancillary services

Irrespective of specific functional requirements and specifications, the general configuration of the testing facility remains similar. An example of the configuration for a hydrogen production facility is given in Figure B.2, which shows the configuration of a gigawatt green-hydrogen plant designed by the ISPT. As the electrolysers work at medium voltage and use DC power, electrical installations are needed. Transformers and switchgear are used to reduce the voltage. Rectifiers are hereafter used to convert the AC power to DC power.

Figure B.2: Configuration hydrogen production facility by ISPT[8].



Electrolyser stacks are used to split water into hydrogen and oxygen. Possible electrolyser technologies include alkaline, PEM, AEM and SOEC. The electrolyser stacks are connected to the DC power supply. The electrolyser stacks use demineralised water, because of this some form of water treatment is needed on site.

The mixture coming from the electrolyser stacks still include some water and oxygen and does not have the correct pressure. Gas separation units separate the hydrogen and oxygen from the liquid. Deoxidisers are used to remove the oxygen still present in the hydrogen, drying equipment is used to remove traces of water. Compressors are used to ensure the correct pressure. Heating and cooling are needed throughout the whole process, for which heating and cooling integration systems are needed. To oversee the process a control room is needed. From here the automation, safety management and ICT installations can be overseen.

[8] https://ispt.eu/media/Public-report-gigawatt-advanced-green-electrolyser-design.pdf

C. Methodology

The methodology applied to investigate the feasibility of an endurance test facility is as follows:

1. Online Questionnaire
2. In-depth interviews
3. Develop Functional design & specifications based on the questionnaire and interviews.
4. Develop cost estimates based on the functional design & specifications and results of the questionnaire & interviews.

C.1 Online Questionnaire

An online questionnaire was deployed to gain a comprehensive understanding of the needs and desires of various stakeholders. This approach allowed for the collection of generalised data from a wide range of Green Hydrogen Stakeholders. The online questionnaire was distributed to:

- Electrolyser manufacturers
- Balance of Plant (BoP) manufacturers
- Fuel cell manufacturers
- Project developers
- End users
- Future operators
- Branch organisations
- Research institutes
- Testing companies.

The online questionnaire is structured around four key themes:

- **General Information:** this section seeks to gather basic information about the respondent's background and general views towards a hydrogen testing facility.
- **Type of Testing:** this section has the goal to gain an understanding on the type of tests the stakeholder would be interested in performing at such a hydrogen testing facility. Additionally, the requirements of these specific test to the test facility are investigated.
- **Functional and Technical Requirements:** this section delves into the specific functional needs and expectations the stakeholder would have of the testing facility.
- **Market Demand:** this section aims to understand the stakeholder's perspective on the possible market acceptance and uptake for a hydrogen testing facility and on which gap the test facility should fill within the national and international green hydrogen economy such that it does not compete with existing test facilities.

This structured approach ensures a thorough and systematic collection of data, providing valuable insights from the diverse perspectives of different stakeholders. Prior to distributing the questionnaire to the stakeholders, feedback was gathered from GroenvermogenNL to gain their perspectives on the questions and the list of the potential respondents. The questions in the online questionnaire can be found in appendix J.

Wherever possible, the data is analysed in a quantitative form. This enables the team to process the data in the form of charts, figures, and tables. For some qualitative and open-end questions, the general tendence was extracted from the respondents' answers.

From 58 approached respondents, 30 responses are received. These results from the questionnaires are discussed in D.

C.2 In-depth Interviews

Following the online questionnaires, in-depth interviews were conducted online through MS Teams with 19 stakeholders, of which the largest part also responded to the online questionnaire. The online interview was transcribed to enable cross checking of the interview results. The goal of the 45-minutes interviews was to get detailed information following the responses obtained from the online questionnaires. The interview script was tailored per stakeholder category. The stakeholder categories used are manufacturers, future operators, end users, developers, testing facilities and branch organisations. The focus for the interviews per stakeholder category can be found in Table C.1 below. The interview script can be found in appendix J.

For the results from the interview, it was not possible to extract quantitative data, therefore qualitative data is extracted from the interview transcripts. The interview transcripts were recorded using the built in feature of MS Teams, which was used for the online in-depth interviews. The results of the interview are discussed in Appendix D.

Table C.1: Online in-depth interview focusses per stakeholder category.

Stakeholder category:	Focus interview:
Manufacturer	• Challenge cost and scale of the test facility • Desires and needs concerning the test facility. • IP & data safe housing. • Knowledge and skills available on-site vs to bring in themselves. • Main reasons to use/not to use the test facility. • Cooperation in monitoring programme on data delivery.
Future operator	• Requirements for operating the test facility, both technical and economical. • Design of the test facility. • Role of the operator in the development of the facility.
End-user	• Possible role of the end-user in the development of the facility. • Willingness to accommodate the test facility on site. • Requirements for hydrogen offtake in terms of quality, quantity colour.
Developer	• Challenge cost and scale of the test facility. • Desires and needs of the developer concerning the test facility. • IP & data safe housing. • Knowledge and skills available on-site vs to bring in themselves. • Main reasons to use/not to use the test facility. • Cooperation in monitoring programme on data delivery.
Testing facility	• Niche the test facility should operate in. • Potential synergies between the test facility of the stakeholder and the new test facility. • Most important learnings. • IP & data safe housing. • Experiences with the testing market and overhead costs. • Managing downtime of the test facility. • The necessity of certification in testing.
Branch organisation	• Highest added value of a new test facility. • Potential synergies with initiatives, fundings and/or future projects.

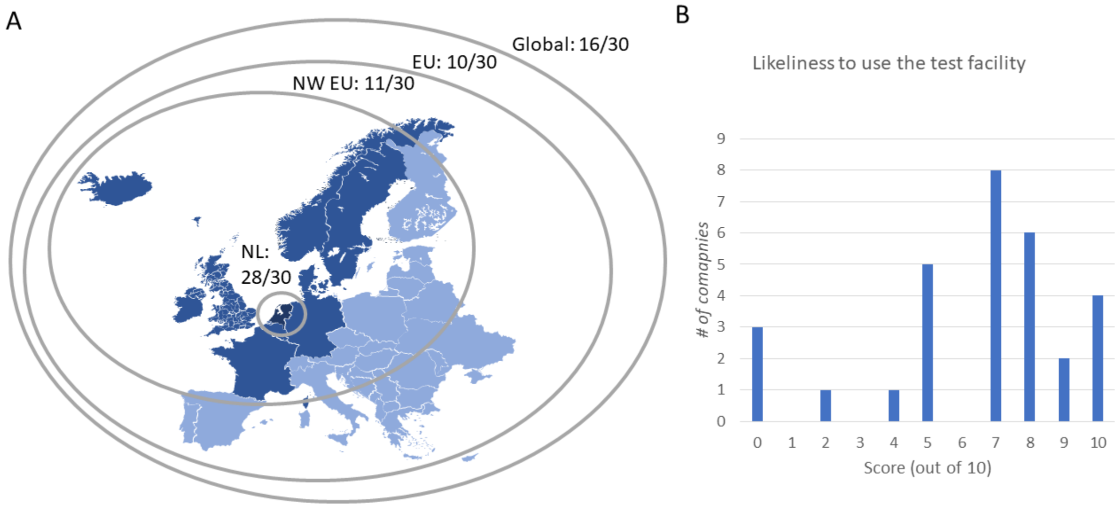
D. Results and Discussion

D.1 Market Demand in the Netherlands

To justify an investment in an endurance test facility to support the green hydrogen value chain within the Netherlands, the market interest needs to be verified. Most of the companies that responded are active within the Netherlands (Figure D.3A and Table D.2). Of these 30 respondents, 20 respondents scored the likelihood for their company to make use of such a test facility 7 or higher out of 10 (Figure D.3B). Five companies responded neutrally (5 out of 10) and the other five companies were highly unlikely going to make use of such a facility, scoring the likelihood 4 or below.

There is a significant initial interest in an endurance test facility within the Netherlands.

Figure D.3: (A) Activity locations respondents. (B) Likeliness of the respondents to use the test facility, expressed as a score from 0-10 (0 = lowest, 10 = highest).



Source: Data was collected from the online questionnaire

Mostly electrolyser manufacturers and end-user responses were obtained, while no future operators participated in this study (Table D.2). Several stakeholders did not fill in the online questionnaire but were open for an in-depth interview. Six companies did respond to our request but were not interested in participating. These results are not included in Table D.2.

Table D.2: Overview of online questionnaire results per sector.

Sector	# reached out to	# of responses	Active in NL	Active in NW EU	Active in EU	Globally active
Electrolyser manufacturer	12	9 (75%)	7	5	3	5
BoP manufacturer	10	3 (30%)	3	0	1	3
End user	7	7 (100%)	7	1	2	3
Research institute	4	3 (75%)	3	1	1	1

Sector	# reached out to	# of responses	Active in NL	Active in NW EU	Active in EU	Globally active
Fuel cell manufacturer	1	1 (100%)	1	0	0	0
Project developer	13	4 (31%)	4	3	2	3
Test facility	1	1 (100%)	1	1	1	1
Future Operators	2	0 (0%)	-	-	-	-
Risk management	2	0 (0%)	-	-	-	-
Branch Organisations	4	2 (50%)	2	0	0	0
Total	**58**	**30 (52%)**	**28**	**11**	**10**	**16**

D.2 The Urgency of Developing a Test Facility

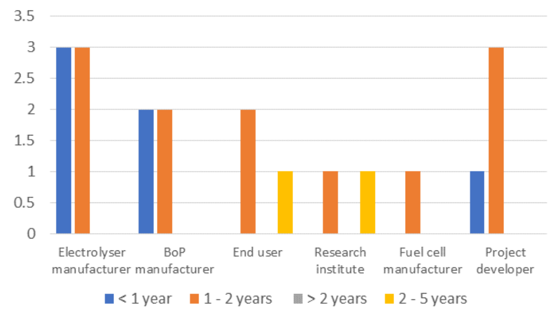
The respondents currently possess technologies with varying TRL (3-9), quite well distributed over the various levels (Table D.3). The respondents envision using the test facility for a TRL between 5 and 8, covering ~85% of the responses. For an endurance test facility, we anticipate that a TRL between 6-8 should be set up as validation could impose significant safety risks at the envisioned scale. The timeframe in which most respondents (90%) would like to use such a test facility is within the next 2 years (Figure D.4).

Table D.3: Current TRL and envisioned TRL for which the test facility should be developed.

TRL level	Current	Envisioned
1 – Basic principles observed	0	0
2 – Technology concept formulated	0	0
3 – Experimental proof of concept	4	1
4 – Technology validated in the lab	3	1
5 – Technology validated in relevant environment	4	5
6 – Technology demonstrated in relevant environment	3	6
7 – System prototype demonstration in operational environment	5	5
8 – System complete and qualified	5	6
9 – Actual system proven in operational environment	3	2

Source: Commission decision C (2014) 4995, ec.europa.eu.

Figure D.4: Timeframe that the test facility should be developed in.

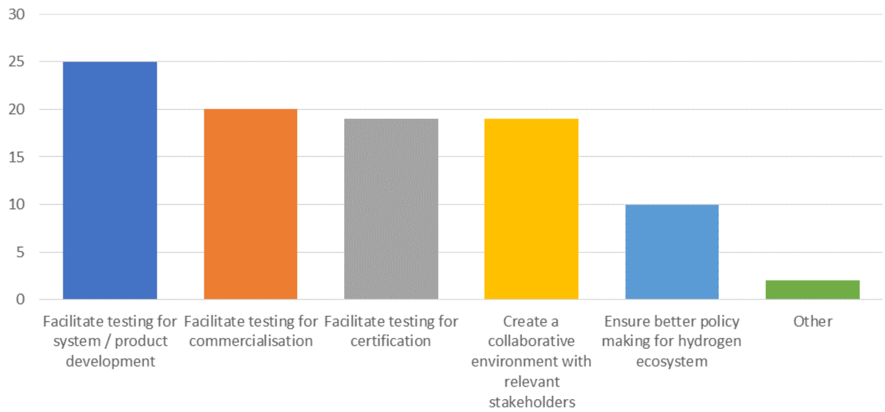


Source: Online questionnaire

The endurance test facility would facilitate testing for system/product development, commercialization, certification and create an environment for stakeholders to collaborate and exchange knowledge (Figure D.5). Ensuring better policy making for the hydrogen ecosystem was also marked as important. Based on these results, there seems to be a significant urgency to have an endurance test facility where TRL 6-8 can be tested within 2 years.

There is an urgency to develop an endurance test facility for testing TRL 6-8 available within a timeframe of <2 years for system/product development, commercialisation, collaboration, and certification.

Figure D.5: Solution that the test facility should provide.



Source: Online questionnaire

D.3 The Technical Requirements

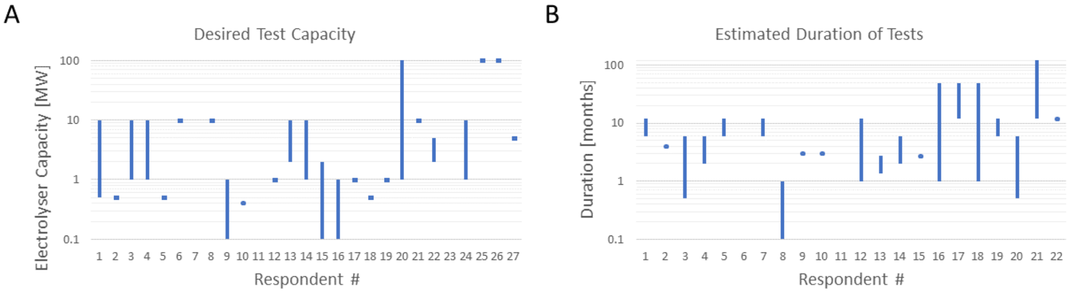
As the stakeholder spectrum is diverse, it is important to get insight in the overlapping technical requirements for such an endurance test facility to provide the highest average added value for all stakeholders.

D.3.1 Test Capacity and Duration

The desired testing capacity ranges between 0.1MW and 10MW (Figure D.6A), although a limited number of companies were interested in a test capacity of up to 100MW. The highest interest exists between 1-10MW capacity, covering 67% of the total need. The estimated testing time varies between weeks to 10 years (Figure D.6B). Considering a range between a month and a year, all interest is covered. Considering 3-12 months, 81% of the interest is covered. These results confirm that endurance testing at significant capacity is required by the industry as the respondents were not steered by the question. This range is quite broad for both the capacity as well as for the duration. Nevertheless, we argue that setting up the facility in such a manner that a large range of capacities and times can be tested, improves the futureproofing of the facility. The requirements from the users can shift upwards over the coming years when the roll-out of hydrogen technology advances.

Testing 1-10 MW capacity over 3-12 months is highly desired.

Figure D.6: (A) Desired test capacity per respondent. (B) Estimated duration of testing time.



D.3.2 Functional Requirements

For the flexibility of the test centre, it is important to know what components users would like to supply themselves and what should be facilitated on-site by the test facility. Hence, the functional requirements, i.e., what functions should the test facility have and what should be supplied to accommodate the needs of the users, is therefore investigated (Figure D.7A).

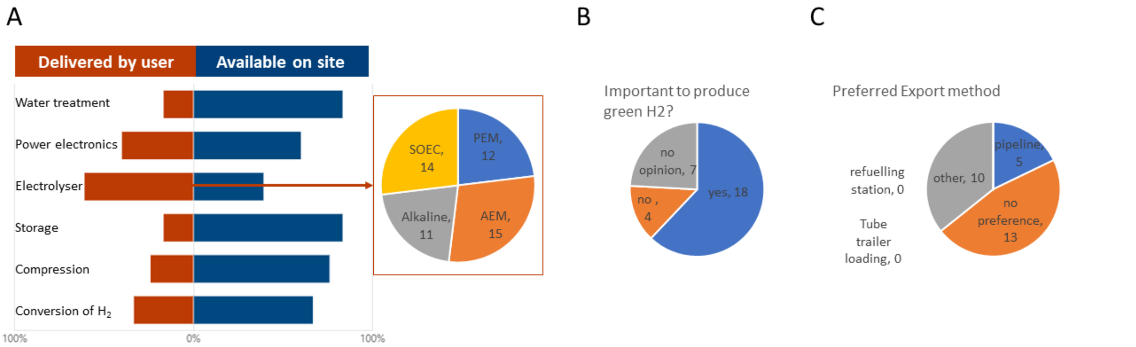
- Water treatment: low interest and should be a shared service.
- Power electronics: medium interest and potentially a shared service.
- Electrolyser: large interest and should not be provided by the facility.
- Compression: medium interest and potentially a shared service provided by the facility.
- Storage: low interest and should be a shared service provided by the facility.
- H_2-to-X: medium interest but outside of the hydrogen production value chain.

The envisioned test facility should be flexible in the design, or at least should have different testing bays for different component set-ups. Some companies are, for example, interested in solely testing an electrolyser whilst others are interested in testing full systems, from untreated water to hydrogen storage. This is also often-heard feedback from the respondents that they fear that the test facility does not have the desired flexibility to accommodate the wide variety of equipment and test.

The electricity supply should preferably be generated by green energy technologies (Figure D.7B). This is because renewable energy integration is of great interest (section D.3.3) and the higher value of hydrogen produced with renewable electricity supports the business case. Lastly, type of hydrogen export from the test facility required by the users is undecided. There is a slight preference for pipeline, but respondents generally have no preference or indicate that it should preferably be used directly on site.

Flexibility in the design of the test is required to test different set-ups, and water treatment and storage should be a shared service.

Figure D.7: (A) Overview of hydrogen value chain components that should be available on site (blue) and that respondents are interested in to test (red). (B) importance of producing green hydrogen to respondents. (C) Preferred export method.



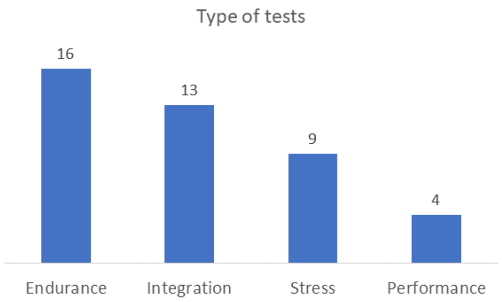
Source: Online questionnaire.

D.3.3 Type of Tests Most Needed

The types of tests most needed by the users of the test facility are listed from most significant to least desired (see also Figure D.8):

1. Endurance
2. Integration
3. Stress
4. Performance

Figure D.8: Type of testing most desired by the respondents.



Source: Online questionnaire.

A more nuanced view on the type of tests required was obtained from the in-depth interviews. Respondents need to prove their technology under realistic testing conditions over extended (i.e., 1-12 months) durations of time and at the right scale (i.e., 1-10MW). The key metrics of interest are:

- Utility use
- Efficiency
- Degradation over time
- Pressure
- Purity of H_2
- Temperature

In line with these needs is the desire to benchmark performance according to industry testing standards by an independent organisation. The dynamic performance and start/stop cycles occurring with renewable energy integration on electrolyser performance/stability, balance of plant and end-user integration is also of great interest. Hence, these types of tests should be facilitated by the test facility.

Lastly, the respondents were asked if testing for safety should be included. Even though there seems to be a significant demand, it was not advised to do that at the endurance test facility by numerous respondents. Considerations were that testing for safety should be performed on component level, the risks are too high at the envisioned capacity (1 - 10MW) and should be performed by a specialized company. Hence, it is unadvisable to facilitate testing for safety.

The test facility accomodate endurance, system integration and renewable energy integration tests.

D.3.4 Organisational roles

From the in-depth interviews, several organisational roles were assigned to the test facility by the interviewees. These organisational roles should be taken up by the test facility to assure smooth and safe integration and operation of the technology under review. These include:

- **Staffing -** During the interviews, stakeholder mentioned several functions that need to be provided in the test facility:
  - **Operators:** dedicated operators should be present to monitor the ongoing tests.
  - **Engineers:** engineers will be required to help set up the equipment and perform routine checks.
  - **Safety officer:** safety officer will ensure safety requirements are adhered to by different parties. Safety officer will need to have knowledge on, not limited to, chemical industry standards on safety and operation, project-based safety risk assessment, centralised risk control.
  - **Subject Matter Expert (SME):** an expert will be needed, especially for a test facility open for third parties, referred to as an open test facility hereafter. This expert will be responsible to monitor the test facility, collect knowledge and knowledge sharing.
- **Regulations and permitting -** One of the main advantages of testing at an open facility is that the test facility would be responsible to arrange the regulations and permitting. The entire spectrum of testing should be covered under the permits from the facility so that companies can commence with the tests as fast as possible.
- **Hydrogen Offtake -** Ensuring hydrogen offtake is regarded as a requirement for testing to suppress costs and have as little environmental impact as possible. It is suggested that the test facility should arrange the hydrogen offtake in the contract so companies willing to test do not have to arrange the commercial aspect themselves with an off taker.

D.4 Advantages and Disadvantages of an Endurance Test Facility

The advantages and disadvantages of an open test facility should be weighed and serve as a basis to formulate the niche in which the test facility should operate. For both the added value as well as the concerns some overarching topics could be deducted and are discussed below. Both the online questionnaire and the online in-depth interview data were processed.

The advantages of a test facility relate to de-risking investment, accelerate product development, and connect stakeholders.

The disadvantages of a test facility relate to high testing costs, IP issues, long development time and lack of test capabilities.

De-risking investment

The most mentioned added value is related to overcoming the investment hurdle or sharing the cost between users, which has several knock-on effects. The capital and operational expenses of a pilot set-up for hydrogen production is significant (see section F). Mostly small and medium-sized companies struggle with overcoming the investment hurdle. When going from lab-based testing to full scale pilot testing, cost drivers must be considered, such as a suitable grid connection, that are not as demanding on a lab-scale but crucial at scales of a megawatt. Moreover, constructing a pilot set-up for proving a single technology for a time span of months adds to the investment hurdle. Some respondents mentioned that it is not economically viable for them to build their own pilot set-up. An open test facility offers a solution in the sense that only the part(s) of interest must be supplied, and the rest of the infrastructure is present. Cost of testing at an open test facility is lowered even further if other users could test other components of the value chain at the same time and because multiple users could use the facility back-to-back. The OpEx costs could therefore be shared over multiple users and the CapEx costs only must be partly covered by the single-time user. Related to this is that hydrogen offtake to suppress the OpEx cost is considered a great added value. Coming to an agreement with a buyer for the produced hydrogen and exporting it, is considered a large hurdle for companies to arrange on their own initiative. An open test facility could have hydrogen offtake arranged which is a key added value, not only for small and medium-sized companies, but also for larger companies due to the size of the electrolyser capacity. To get the highest value for the hydrogen, preferably green hydrogen is produced for fuel cell applications. Lastly, the clear testing cost at a test facility lowers the risk for companies advancing their technology to higher TRLs.

Contrary to this is that the **cost of testing** is often mentioned as one of the largest concerns with an open test facility. Generally, companies mention that a trade-off exists between paying extra for using an open test facility and constructing their own pilot-scale plant. Hence, the costs of testing must be reasonable for companies to be attractive, and it is advisable to challenge the cost of testing to the future users to confirm their interest.

Accelerating product development

Proving technology under realistic conditions is a requirement from the industry, especially from the perspective of an end-user of the technology. An example from one of the respondents is that assumptions are being made on reliability of the new technologies. Product verification at an **independent test facility creates trust for investors**. Lowering the barrier to enable the verification of key performance indicators shortens product development times and accelerates product introduction. The same principles hold for project developers interested in testing full systems. Having the testing infrastructure and hydrogen offtake arranged enables for faster system integration. Besides, the development of a privately-owned pilot requires permitting, hazard and operability study (HAZOP) & layers of protection analysis (LOPA), safety standards, operators, a testing site with utilities/power etc which is not core business most of the time. To be able to test at an open facility where all these aspects are arranged as well could significantly accelerate product development to the highest TRL. Respondents see this **faster market introduction** as a competitive advantage edge for the Dutch supply chain and could help develop the Dutch ecosystem to produce green hydrogen.

Connecting stakeholders

An open test facility could serve more purposes than sole product verification. Respondents mention that a great added value could be to have stakeholders interact at this test facility. The test facility could function as a centre to speed up standardization and certification, share knowledge and experience on best non-confidential practices and connect partners in the value chain. Giving the open test facility more functions than sole product verification could add to the likeliness of companies to use the test facility over constructing their own. Furthermore, consortia are mentioned as a way to collaborate for accelerated product development. Some companies indicate that collaborations are a requirement for them to be able to test. The test facility could act as a key player to connect the different parties. At the same time, the concern exists that complexity of the system increases significantly.

Intellectual Property (IP) / Confidentiality / Data

IP / Confidentiality issues have been frequently raised by respondents and should be considered when setting up the test facility. In the highly competitive market, companies are very reluctant to share any sort of information. Several companies indicated that they are not willing to test with competitors at the same premise, or that testing bays should only be accessible to authorized personnel. It is not regarded as a “showstopper” if these issues are mitigated by setting up appropriate bilateral non-disclosure agreements (NDAs) with the test facility. Also, in a collaborative environment with multiple stakeholders NDAs mitigate the concerns. An important remark is that also utility use and production rates should be protected as performance parameters could be deducted from these values. Hence, it is important to separate these data streams.

TNO is assigned as the national monitoring body for test results in power-to-gas facilities. The question was asked to the stakeholders if they would be willing to share results under the protection of an NDA and if they would be willing to release some of the data for academic research. Most companies are open to have TNO monitor the data, under the restriction of an NDA. Several companies are open to discuss the exemption of data for academic purposes. A few companies are not willing to share any of the data as they are, for instance, in a patenting process. This topic should be discussed more in depth with the potential users of the test facility and is not regarded as a “showstopper” in this stage of the process.

Development of the test facility

The stakeholders regard the development pace of the facility as a concern. The fear is that it will take too long to meet and adhere to regulatory standards, codes and permits and companies have already passed the stage for which the test facility will be constructed. Stakeholders have indicated that past hydrogen projects in the Netherlands have not seen continuation due to regulatory and permitting issues and are looking outside the borders of the Netherlands for future projects. Hence, the development of a test facility faces the same risks.

Capabilities of the test facility

An often-raised concern is that the facility would not be able to meet the test requirements of the users. The test requirements are discussed in section D.3 and should be covered as reasonable as possible in the functional design. Specific focus on full hydrogen value chain components compatibility is needed during the design/procurement phases.

D.5 Potential Locations for an Endurance Test Facility

[redacted]

[redacted]

D.6 Positioning the Endurance Test Facility

D.6.1 Knowledge Position within Dutch Green Hydrogen Ecosystem

With this rapid evolvement of green hydrogen production, governmental bodies are seemingly struggling with how to deal with policy and regulation. During the in-depth interviews, several examples were given where permits for new pilot facility took years to be granted. This is a huge roadblock for companies in the development of their business, and they are thus looking over the borders to develop projects. An open endurance test facility, where all permits are in place, provides a short-term solution to the still existing issue that policy and regulations are lagging. Companies wanting to develop a full-scale facility in the Netherlands would still face policy and regulatory issues in this final step. An interesting mention during one of the interviews is to involve (local) governmental bodies, fire departments and certification bodies in the development of such a test facility. This could facilitate permitting, improve the safety of the design and raise general support for facilitating new green hydrogen production plants. Making the test facility also “open” for these organisations provides a learning opportunity from a regulatory and policy perspective. This could help shorten development times of new initiatives and make it more attractive for Dutch and global companies to look within the borders of the Netherlands for new projects. Further research would be required to confirm these statements.

Learning from the performed experiments provides significant value to the entire Dutch green hydrogen ecosystem. Several stakeholders mention that it is highly unwanted that a single party can test and walk away with all the learnings as it does not benefit the ecosystem. Safety, certification, policy and regulation, education/training and academic research should be able to advance as well. Setting up the terms and conditions in such a way that some of the data or site access is accessible for third parties could bring significant value to all stakeholders.

Involvement of (local) governmental bodies, fire departments and certification bodies in the development of such a test facility could facilitate permitting, improve the safety of the design and raise general support for facilitating new green hydrogen production plants.

D.6.2 The Market Position within the Netherlands and North-West Europe

The niche the test facility should operate in according to the results of the online questionnaire and in-depth interviews is:

- Testing capacity between 1 and 10 MW
- Allow for testing over a period of 3 to 12 months
- High flexibility in the possible tests and technologies
- Focus on endurance and integration testing at TRL 6-8.

To ensure no overlap with existing hydrogen test facilities within North-West Europe, the market demand is matched to what is offered at existing testing facilities A high-level overview, covering the component/technology tested, size of the facility, main test types, possible regulations and standards and additional features if included, of the currently existing facilities in the Netherlands can be found in Table H.9 and of North-West Europe can be found in Table H.10.

Within the Netherlands, the main open testing facilities (MegaWatt test centre and Faraday Lab TNO) do not operate at scales above 1 MW. The H2 Lab from Kiwa focuses on automotive related hydrogen parts. The other (demo) projects in the Netherlands are either not open for third-party testing or not operating at the needed scales. Notable projects planned/operating at similar scales are the GZI Next in Emmen by Shell and the Sinnewetterstof project from Alliander. However, these are not open to other companies for testing. Expanding the view to the rest of North-West Europe, more hydrogen testing facilities can be found. ZBT GmbH in Germany tests at 150 kW, HyCentA Research in Austria at small scales, Norwegian Fuel Cell and Hydrogen Centre up to 10 kW, IFE Hynor Hydrogen Technology Centre in Norway up to 33 kW and Brande Hydrogen in Denmark until 400 kW.

Fraunhofer is testing at the respondents' scales of interest, i.e., 1 to 10 MW. In their test centre Hydrogen Lab Leuna full electrolysers until 5 MW can be tested, at their Hydrogen Lab Bremerhaven 12 bays will be realised of 2 MW each and finally the Hydorgen La Görlitz where electrolysers until 2 MW will be tested. The Hydrogen Lab Leuna is the only of these three facilities that is already in operation. Fraunhofer will thus possibly be testing at similar scales and is open to third parties testing their components. However, it was found in the interviews that a concern with the development of this test facility is that the utilisation rate will be very high, and this will result in long waiting lists. Moreover, for a number of interviewees the distance to the testing location must be practical, especially when (sub)systems will be tested for extended periods of time. A detailed premarketing study should make clear what the maximum allowable travel distance is.

An important added value of a national endurance test facility could be that the full package of testing components across all TRL's can be offered. Connecting existing open testing facilities, such as Faraday Lab and MegaWatt test centre, and the endurance test facility, would enable the ensure good continuation from one facility to the next and accelerate the development cycles. This cooperation with existing testing facilities adds to the commercial value of all these testing facilities.

Concluding, the unique selling points for the endurance test facility will be the following:

- Industrial scale at 1-10MW capacity for months of testing time.
- Testing of entire systems or subsystems at TRL 6-8
- Being able to accommodate different electrolyser technologies
- Possibility to connect existing facilities in the Netherlands with the endurance test facility and provide a single process to go through all TRL's for green hydrogen production.

There is no open testing facility available in NL that can accommodate the test needs of the respondents in this study.

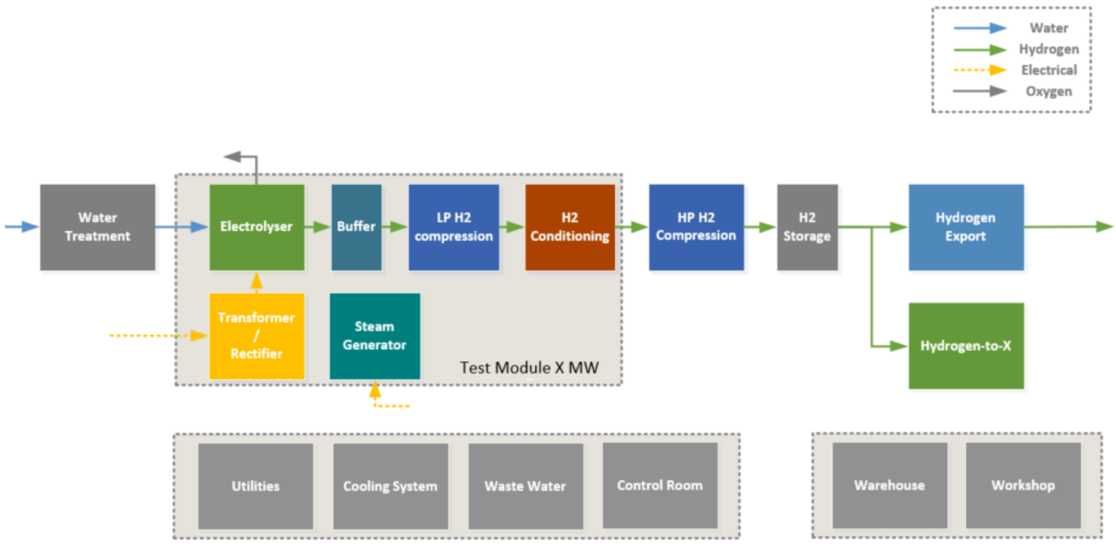
E. Functional Design and Specifications

E.1 Introduction

A high-level and broad overview of the technical requirements from potential users is collected and described in section D. Some of these requirements impact the functional design and specifications of a future test facility. Several must-have criteria that impact the design of the test facility are taken up into the design at this stage. These include test capacity, test availability and the ability to accommodate various technologies. A functional design of the test facility, incorporating these must-haves, was made based on the feedback from stakeholders, expert judgment, and in-house knowledge. The functional design provided in this report can be regarded as a greenfield test facility, covering all the basic requirements of a test facility built from scratch. The functional design and specifications, including the block diagram, building lay-out and equipment lists, serve as a basis to score potential locations on. Any site-specific requirements or synergies have to be included in or excluded from the design once the site selection is made.

There is a significant demand to be able to test between 1-10MW for extended durations, i.e., 3-12 months with various technologies and component set-ups. The functional design as described here offers the capacity to test 6 different modules, 1 x 10 MW and 5 x 1 MW electrolyser capacity. The different modules allow for the desired flexibility in the testing capabilities and ensure availability of testing time for several users in parallel. The large 10 MW testing bay should be regarded as a max capacity, which could also be used for testing lower capacities, covering the entire range between 1-10MW. The smaller 1 MW testing bays could be tailored to specific technologies, e.g., a dedicated testing bay for SOEC, but are regarded as general testing bays in this stage of the process.

Figure E.9: Hydrogen Test Facility block diagram



As a basis for the functional design and specifications, a block diagram of was constructed (Figure E.9), including the main components for the production of hydrogen via electrolysis and shared services. For simplicity, only one testing module is shown in the figure as the other testing modules consist of the same components. To produce hydrogen via electrolysis, typically the following components/subsystems are required:

- Water Treatment
- Test Modules (1 X 10 MW and 5 X 1 MW electrolyser capacity) consisting of:
  - Electrolyser
  - Transformer/Rectifier
  - Buffer
  - Low pressure (LP) hydrogen compression
  - Hydrogen conditioning
  - Optional: Steam generator for SOEC.
- High pressure (HP) hydrogen compression
- Hydrogen export
- Hydrogen storage
- Wastewater
- Utilities
- Cooling System
- Control Room
- Workshop
- Warehouse
- Optional: Fuel Cell

The above listed components/subsystems are discussed in further detail in the following sections to get a better understanding of the functional requirements of such test facility.

Assumptions

As this study is a (pre)feasibility study, assumptions had to be made to come up with a functional design. In general, the worst-case scenario was taken to consider the upper end of potential requirements. The general assumptions are:

- The size of the Test Facility totals 15 MW electrical power input (1 module 10 MW + 5 modules of 1 MW). This allows for flexibility in the type of tests that can be facilitated.
- Sea water is used for electrolysis. This would need desalination and is the costliest in terms of resources and equipment use.
- Electrical connection: 380 kV grid connection
- Type of electrolysers that could be tested:
  - PEM
  - AEM
  - Alkaline
  - SOEC
- “Hydrogen-to-X” module included in test facility

E.2 Water Treatment

The main functional parameters of the Water Treatment system are the following:

- Raw water to be treated is seawater, 35,000 ppm salinity.
- The conductivity of treated water (feeding the electrolysers) shall be lower than 0.05 μS/cm, based on the most stringent prescriptions by electrolyser manufacturers known to date.

- The nominal capacity of the water treatment plant shall be 2.6 m^3/h treated water, corresponding to the requirement for operating five electrolyser units rated at 1 MW plus one electrolyser unit rated at 10 MW.

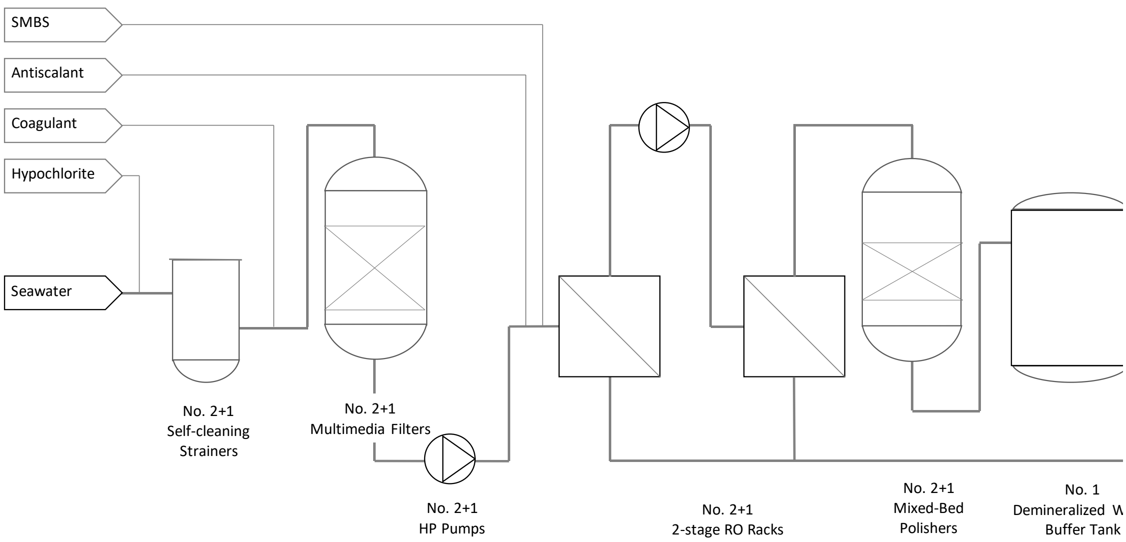
The system shall provide adequate equipment redundancy and capacity split to achieve the necessary availability level and improve the turndown ratio.

The envisaged configuration includes the following components:

- Seawater intake with coarse screening (common with the Cooling Water System)
- Seawater feed pumps (2 x 100%)
- Seawater pre-treatment lines, including strainers and multimedia filters (3 x 50%)
- Chemical dosing system
- HP pumps (3 x 50%)
- 2-stage Seawater Reverse Osmosis (SWRO) skids, with booster pump (3 x 50%)
- IX polisher lines with resin regeneration system (3 x 50%)
- Demineralized water buffer tank
- Demineralized water delivery pumps (3 x 50%)
- Brine discharge and dilution system (common with cooling seawater discharge).

A simplified flow diagram of the presently considered configuration (for reference and budgeting purpose only) is shown in Figure E.10.

Figure E.10: Flow diagram of the Water Treatment Plant



The following features should be noted:

- The multimedia filters are periodically backwashed to remove entrained material. Backwash water effluent (not shown in the simplified flow diagram) is processed by the Wastewater Treatment System.
- The mixed-bed polisher resins are periodically regenerated with chemicals by an auxiliary subsystem (not shown in the simplified diagram) to remove the anions and cations absorbed

by the resins during each cycle. The regeneration effluent is processed by the Wastewater Treatment System.

- It is observed that, for PEM electrolysers, a stream of water is recirculated from the anode part of the stack for cooling purpose. Considering the chemical aggressivity of hot demineralized water, it is expected that metallic ions may be released from the metallic parts of the circuit, such as electrodes and stainless-steel pipes. For this reason, it is normally requested to install a column with ion-exchange resins in the recirculation line downstream the cooler, aiming to prevent accumulation of dissolved metallic ions in the electrolyser circuits. In the case of the test facility, it is advisable to integrate such ion-exchange columns in the Water Treatment System, located outside the Main Building (see section E.10). The advantage lies in sharing the auxiliary systems for regeneration / rinsing of the resins (chemical tanks, pumps, neutralization tank, containment, etc) already provided for the mixed-bed polishers. Additionally, this solution enables to keep the chemical transfer systems segregated from the electrolyser area, as suggested by safety considerations.

E.3 Test Module

The envisioned test facility is designed to be able to test different modules in parallel. As a base case, Mott MacDonald assumed the test facility could host 6 test modules, namely 1 X 10 MW and 5 X 1 MW electrolyser Test Modules. Each test module shall be flexible enough to:

- Test integrated systems or single components.
- Test different types of electrolyser technology (PEM, AEM, Alkaline or SOEC) which all impact the layout of the BOP differently.

Each Test Module is defined as the assembly of the following individual components/subsystems:

- Electrolyser
- Transformer/Rectifier
- Buffer
- Low pressure (LP) hydrogen compression
- Hydrogen conditioning
- Optional: Steam generator for SOEC.

These components are individually discussed in the following sections.

E.3.1 Electrolyser

The electrolyser is the fundamental subsystem to produce green hydrogen. The electrolyser consists of an assembly of electrolysis cells, commonly referred to as an electrolyser stack. In such a cell, water is split electrochemically into hydrogen and oxygen over electrodes, separated by a membrane to conduct ions and separate the formed O_2 and H_2. Essential for the operation of low-temperature electrolysis techniques is the recirculation of unreacted water. The water passes through a heat-exchanger to dissipate reaction heat. A feed of demineralised water is mixed with the recirculated water and fed back into the electrolyser. In the case of PEM, this flow is fed through an ion-exchange resins column (in the water treatment system) that make sure it is at correct level of purity (stacks are very sensitive to water contamination). Auxiliary hardware such as pipes and valves are needed, which must be up to spec for hydrogen purposes. Lastly, the instrumentation needed for safe operation and data gathering in such a test facility is more demanding than in a normal plant. Hence, additional pressure- and temperature sensors, flow meters, electrical meters etc. needs to be installed. The electrolyser shall include different components. Considering a PEM, following components shall be included:

- Stack
- Hydrogen / liquid separator
- Oxygen / liquid separator
- Recirculation pump
- Heat exchanger
- Piping & fittings
- Valves & switches
- Instrumentation (pressure- and temperature sensors, flow meters, electrical meters)

E.3.2 Transformer and Rectifier

The electricity characteristics needed for the electrolyser stacks depends on the technology but will likely be between 1200 and 1500 V DC. For this test facility it is assumed that it is connected to the high voltage (HV) grid of TenneT. TenneT transmits electricity between 110 kV and 380 kV, depending on the location in the Netherlands. Because of this, the electricity of the grid needs to be converted to the requirements of the electrolyser stack tested. For this the following electrical equipment is forecasted:

- Bay availability in HV substation
- HV cable connection
- Tarif metering

A step-down transformer is needed to convert the HV electricity from the grid, between 110 and 380 kV, to the MV electricity required by the electrolyser stacks. Additionally, switchgear and circuit breakers will be necessary. A rough estimate of 25MVA rated power is made for the transformer, as electricity is needed for the electrolyser stacks, but also for the rest of the test facility. The following electrical equipment is forecasted:

- Electrical protection panel
- HV equipment
- MV cable connection
- MV switchgear
- Transformer cooling, either natural air ventilation or cooling system

Each test bay needs its own rectifier to convert the AC power to DC which is needed for the electrolysis. Assuming five 1 MW test bays and one 10 MW test bay, six rectifiers are needed. This will be one 10MVA rectifier and five 1MVA rectifiers. It is advised for the rectifiers at the test bays to be flexible, as this will prevent the need for new rectifiers whenever a stack is placed which needs a different voltage level compared to the previous stack tested.

Additional power is needed for auxiliary systems in the test facility, such as lighting, small power and CCTV. For this, the following electrical equipment is forecasted:

- MV/LV transformer
- LV switchgear
- LV cable connection

E.3.3 Hydrogen Buffer

A small buffer tank should be included to stabilise the hydrogen pressure and flow rate, caused by the different operating modes, and the transitions, of the electrolyser.

E.3.4 Low pressure hydrogen compression

In the case that the outlet pressure of hydrogen from the electrolyser is around atmospheric, a low-pressure hydrogen compressor is required for the downstream processing of the hydrogen. It is forecasted that the pressure should be increased from 1 atm to, for instance, 30 bar. The compression system will consist of 1 or more stages, based on the desired pressure ratio. Furthermore, intercooling is included to cool down the hydrogen temperature and diminish the energy required to pressurize the hydrogen. A pulsation dampener could be included in the system to mitigate instability of flows. This device helps to smooth out abnormal pulsations or spikes. Instrumentation will be needed to control and operate the LP compression. The following equipment is forecasted:

- 1 or more compressors (depending on vendor package)
- Intercooling system
- Dampeners
- Pressure sensors
- Temperature sensors
- Flow meters
- Piping & fittings
- Valves & switches

E.3.5 Hydrogen Conditioning

The produced hydrogen usually requires treatment to make it suitable for use in other applications. In general, some water and oxygen impurities are present in the hydrogen outlet which potentially need to be removed. Oxygen can be removed by a deoxygenation step in a deoxidiser, where a catalytic reaction takes place between H_2 and O_2, thereby producing H_2O. Further downstream, a dryer is required to remove the residual water and get the hydrogen purity needed (for instance 99.999% hydrogen purity needed for PEM-based fuel cell). The dryer could operate according to the following principles:

1. Water condensation by cooling down the hydrogen gas
2. Remove the remaining water over a molecular sieve.

The hydrogen conditioning will include the following components:

- Deoxygenation
- Dehydration
- Pressure sensors
- Temperature sensors
- Flow meters
- Piping & fittings
- Valves & switches

E.3.6 Optional Steam generator for SOEC

In the case any of the testing modules makes use of SOEC technology, steam needs to be supplied for operation. Hence, the steam generator is also included in the functional design. The steam can be generated by means of a burner or an electrically heated system. The selection of either one should be based on the requirements and boundary conditions. An important consideration is the availability of waste steam from a potential industrial facility close to the test facility. The characteristics of this steam, *i.e.* temperature and pressure, are very important and will impacting the design of the steam generator system. SOEC electrolyser need superheated steam, therefore a superheater will need to be included in the system.

E.3.7 High Pressure Hydrogen Compression

A high pressure (HP) hydrogen compression system is forecasted to pressurize the hydrogen from relatively low pressures, for instance 30 bar, to high pressure. In this report, 500 bar has been assumed to be the HP hydrogen storage pressure. Furthermore, intercooling is included to cool down the hydrogen temperature and diminish the energy required to pressurize the hydrogen. A pulsation dampener could be included in the system to mitigate instability of flows. This device helps to smooth out abnormal pulsations or spikes. Instrumentation will be needed to control and operate the LP compression. The compression technology selection, e.g., membrane or reciprocating, will be based on the vendors technical / commercial offers.

Components:

- Mass flow hydrogen: 300 kg/h

The system will include:

- 1 or more compressors (depending on vendor package)
- Intercooling system
- Dampeners
- Pressure sensors
- Temperature sensors
- Flow meters
- Piping & fittings
- Valves & switches
- Control system
- Purge system

E.4 Hydrogen Storage

An assumption was made that the hydrogen storage system will consist of arrays of cylinders, grouped in packaged assemblies for ease of transport and stockage. Each cylinder will be capable of storing hydrogen up to a pressure of 500 bar.

Below the main assumptions:

- Storage capacity is needed for 24h of H_2 production at 15MW electrolyser capacity equivalent.
- H_2 prod = 6450 kg / 24h
- H_2 vol. = 210 m^3 at 25 °C

For safety reason, the hydrogen storage will have to be placed outside of the main building. More details about this system and building needs will be provided in section E.10.

The main components of the system will be:

- Gas tanks
- Valves & regulators
- Piping and fittings
- Safety hardware (detectors, vent system, fire & gas control system)

E.5 Wastewater

There are several processes that produce wastewater. Assuming a PEM electrolyser system under test, wastewater will come mainly from two processes:

- Water purification – high in mineral content
- Gas purification – low in mineral content

On top of these two sources, effluent from compression systems (LP and HP) will have to be taken into account as well as wastewater from maintenance activities. The wastewater will be treated by a general water treatment system, consisting of the following components/subsystems:

- Attenuation pond
- Wastewater recirculation pumps
- Screening and grit removal
- Oil/water separator
- Clarifier/thickener
- Sludge pump
- Sludge tank

E.6 Hydrogen Export

The hydrogen export method is assumed to go via tube trailer. The tube trailer reaching the facility needs a dedicated lane with suitable flooring and curvature radii allowing to enter and get out of the loading bay easily, thereby avoiding complex manoeuvres. The hydrogen is supplied from the hydrogen storage to one or more loading bay(s). The number of bays is yet to be decided based on the actual production capacity of the test facility. Assuming that the tube trailer max pressure is limited to 500 bar pressure, i.e., the assumed hydrogen storage max pressure, a nominal tube trailers has a hydrogen capacity of 500 kg. The production of hydrogen from the test facility at peak load is estimated at 6450 kg/day. Hence, the hydrogen export system should be designed to be able to process 13 tube trailers per day. Assuming 2 hours loading time for each tube trailer as a worst-case condition, at least two export bays would be required. This is the worst-case scenario, assuming the 6 test modules working at the peak capacity totalling 15 MW. Within a loading bay, a dedicated dispenser is placed, and it will be used to load the tube trailers.

E.7 Hydrogen-to-X

In this study, a “Hydrogen-to-X” system is included in the design of the test facility as it was of interest for some of the participants of the questionnaire/interviews. At this point in time, it is uncertain if this will end up in the final design of the test facility but has been added for completeness. “Hydrogen-to-X” system options are amongst others:

- Fuel cell technology
- Ammonia synthesis
- E-fuel synthesis

For instance, assuming a 1 MW fuel cell, about 60 kg/h hydrogen (purified) could be used to generate 1 MW electricity (assuming 50% efficiency conversion).

E.8 Cooling System

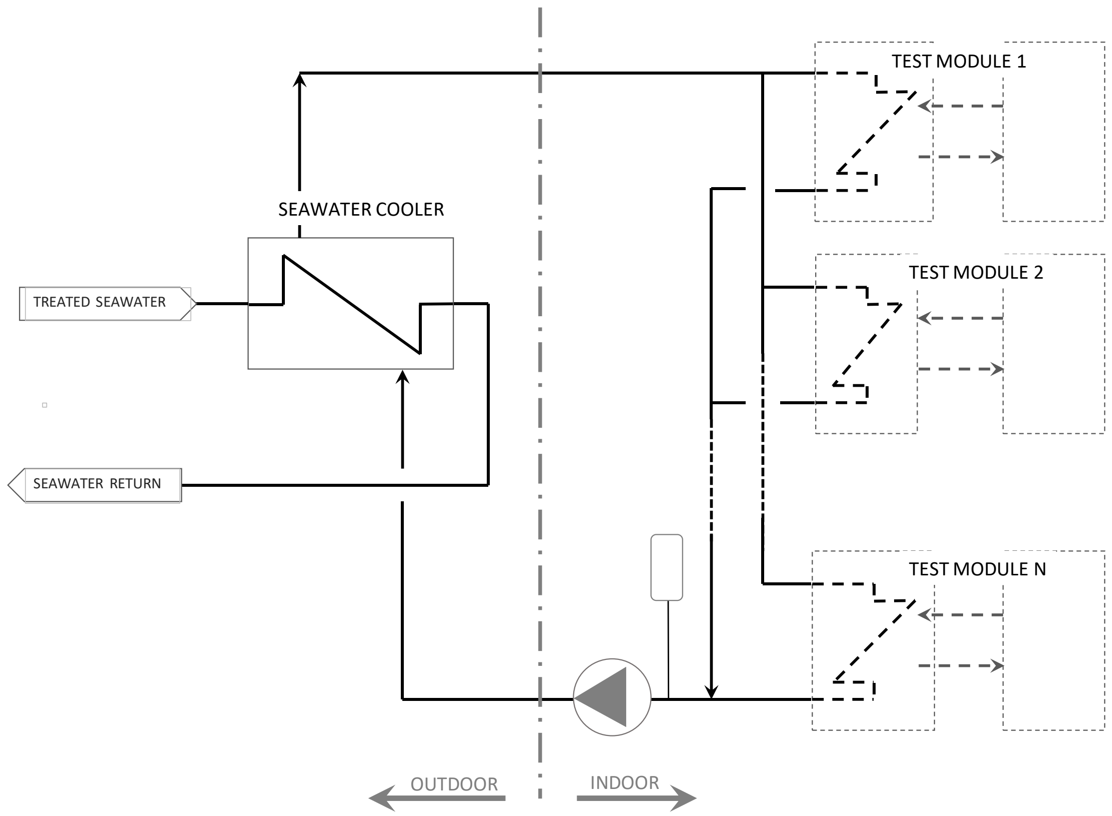
The heat flux released by the test facility in the Main Building (Section E.10.1) at peak load, *i.e.,* all six electrolysers in operation, for a total absorption of 15 MW, is mainly produced by two sources:

- Heat flux from the electrolysers, estimated at 4,200 kJ/s (corresponding to an average energy consumption of 55 kWh per kg H_2).
- Heat flux from the hydrogen compressor, roughly estimated at 1,000 kJ/s.

Minor heat dispersions, such as the ones released by pump motors and LT transformers, are assumed to be evacuated by the ventilation system of the building.

Under the assumption that the test facility is located close to the coast, the most cost-effective cooling medium appears to be seawater. Considering the relatively small amount of heat load, a once-through cooling system is envisaged, according to the scheme shown in Figure E.11.

Figure E.11: Schematic diagram of the cooling system



As shown in the diagram, an intermediate closed-loop circuit (circulating fresh water, such as osmosed water) has been interposed between the seawater cooler and the exchangers of the tested modules. In this way, the seawater circuit and the modules have been hydraulically segregated, thus preventing corrosion issues related to materials selection in the tested modules. Additionally, the extension of the seawater circuit has been kept outside the Main Building, aiming at assuring a safe operation of the facility.

The above-mentioned solution requires the installation of the following subsystems and equipment:

- Seawater submerged intake and pump basin (common to the water treatment unit).
- Seawater pumping station (2 x 100% vertical centrifugal pumps) .

- Seawater chlorination system, based on sodium hypochlorite dosing.
- Self-cleaning seawater strainers, 2 mm mesh size (2 x 100%).
- Seawater cooler, shell-and tube heat exchanger with Titanium tubes and stainless-steel shell.
- Interconnecting piping and valves of the seawater recirculation system.
- Seawater outfall structure:
- Cooling water circulation pumps (2 x 100% horizontal centrifugal pumps).
- Interconnecting piping and valves of the closed-loop cooling system.
- Instrumentation for monitoring and control of the system.

The estimated flow rates of the cooling water streams at the peak heat load of 5,200 kJ/s are 740 m^3/h for seawater (6°C temperature increase in the cooler) and 300 m^3/h for the cooling water system (15°C average temperature increase in the coolers of the facility).

E.9 Test Instrumentation & Control (I&C)

The instrumentation needed for a test facility is of particular importance as, on top of the instrumentation needed to operate a hydrogen production plant, it is needed to carry out specific tests needed by the test facility users.

Typical Instruments needed for such kind of facility are:

- Temperature measurement system based on technologies such as thermocouples and resistance temperature detectors.
- Pressure measurement system via different possible gauges accordingly to operating requirements.
- Flow meter measuring gas and liquid mass flow rates in the system (basing on technologies like Coriolis, differential pressure, etc).
- Level measurement system for drums, tanks, etc.
- Gas analyser such as gas chromatography and/or gas analysis standard systems detecting specific impurities in gas.
- Electrical parameters measurement system for current, voltage and energy measure.

In addition to the instrumentation itself, the facility will need to be provided with a control system (likely based on DCS, Distributed Control System, technology) to be able to operate and monitor it.

Signals from the test facility will need to reach the control room which will include the equipment such as marshalling cabinets, DCS cabinets and Human Machine Interface to allow operators to control/supervise the test facility.

Of high importance will be the data logging system which will furnish the raw test data results for the following postprocessing

E.10 Buildings and Civil Structures

E.10.1 Main Building

The Main Building in the test facility will be designed to enable proper indoor installation of the following items:

- No. 5 bays, each for the test of one electrolyser module rated at 1 MW, including electrical rectifier, H2 conditioning equipment, water cooler with recirculation pump, LP compressor (if required), interconnecting piping, valves, and field instruments.

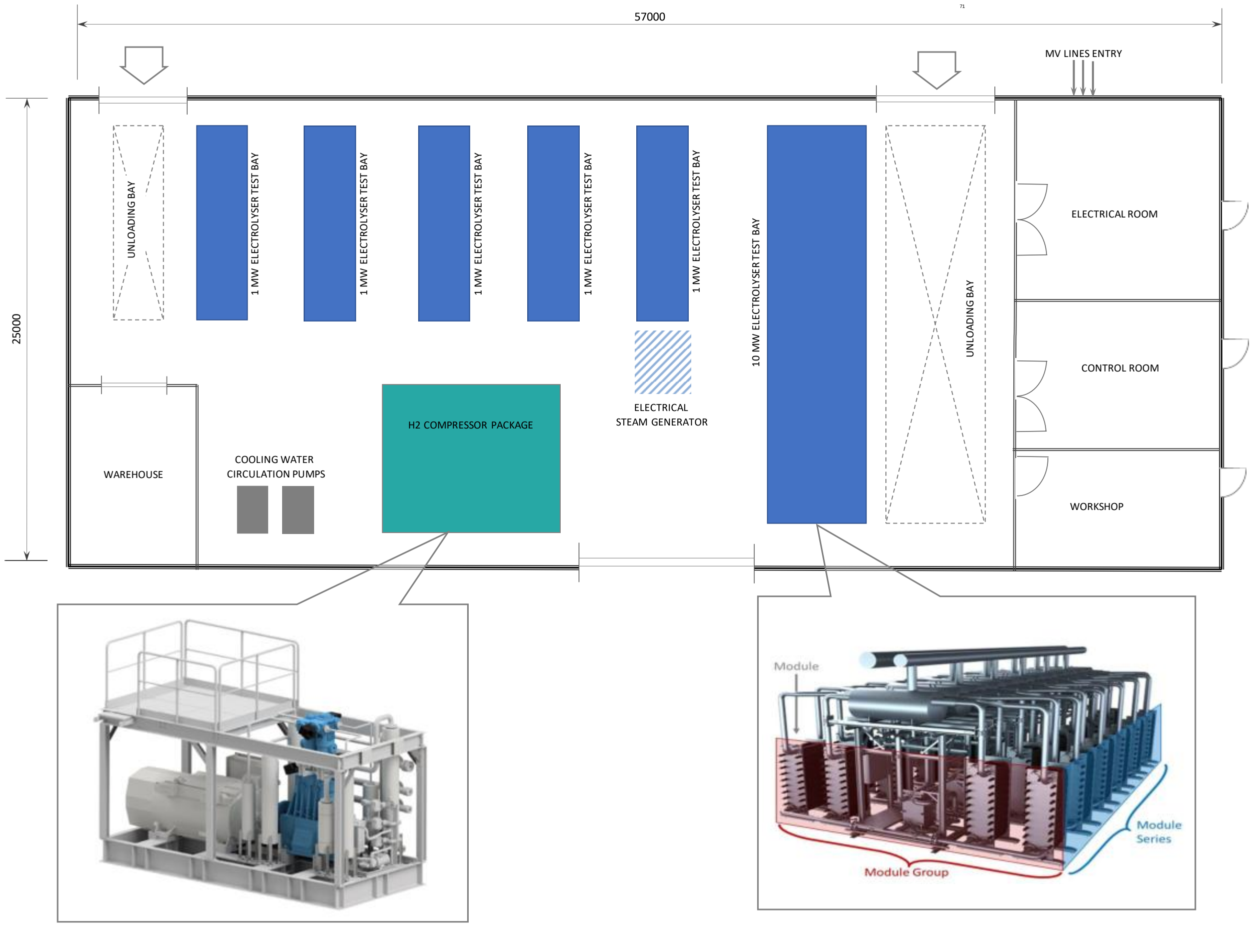
- No. 1 bay for the test of one electrolyser module rated at 10 MW, including electrical rectifier, H2 conditioning equipment, water cooler with recirculation pump, LP compressor (if required), interconnecting piping, valves and field instruments.
- No.1 hydrogen compression package with coolers.
- No. 1 electrical steam generator.
- An Electrical Room, suitable for the installation of the equipment necessary for the safe operation and control of the electrical distribution system of the facility, including MV switchgears, motor control centres (MCCs), auxiliary panels, uninterruptible power supply (UPS), MV/LV transformer.
- A Control Room, suitable for the installation of the equipment necessary for the safe operation, control, monitoring and data logging of the modules being tested, including marshalling cabinets, distributed control system (DCS) cabinets, doubles-screen desks for three operators.
- A Workshop.
- A Warehouse.
- Overhead crane(s) for lifting heavy equipment and carrying them to a suitable unload bay.

A preliminary assessment of a suitable layout for the Main Building is presented in Figure E.12. The arrangement shown there has been prepared for reference and budgeting purposes only and in no way it constitutes a construction requirement.

The building footprint is expected at around 1,500 m^2 with 10 m ceiling clearance.

Given the nature of the involved process, the design of the building shall be developed in **strict compliance with the safety standards** established for indoor environments with H_2 release risk. The recommendations presented in ISO 22734-1 “Hydrogen generators using water electrolysis process” shall be complied with. It is notably emphasized the criticality of the protection methods to prevent the accumulation of ignitable mixtures.

Figure E.12: Preliminary assessment of a suitable layout for the Main Building.



Source: https://hyfindr.com/marketplace/systems/hydrogen-storage-systems/hydrogen-storage-system-h2max-pods/

E.10.2 Office Buildings

The Office Building of the facility is intended to accommodate:

- Offices for administration and technical staff
- Meeting Room
- Kitchen
- Laboratory
- Toilets / showers.

It is assumed to be a two-storey building with 300 m^2 floor area.

E.10.3 Hydrogen Storage Platform

The hydrogen storage system will be constituted by arrays of cylinders, grouped in packaged assemblies for ease of transport and stockage. Each cylinder will be designed to withstand 500 bar pressure.

For the purpose of reference and budgeting at this stage of the project, we have considered to utilize H2MAX^{TM} Pods, one of the many products in the market for this application see Figure E.13.

Figure E.13: Example of H2 cylinder assemblies.

Such "pods" shall be stored outdoors in the facility area, at a location allowing easy truck loading / unloading of the pods. Considering that, at peak load, the electrolysers of the test facility produce about 6,500 kg H_2 per day, it will be necessary to install forty-two of such pods for a 24-hour storage. The platform for the stockage of such pods will have a surface of around 350 m^2 withstanding an overall weight of 220 tons.

E.10.4 Chemical Storage Building

A small building for chemical storage (about one hundred m^2 footprint) shall be incorporated in the project. According to usual practice, the following chemicals should be considered:

- Sodium hypochlorite for seawater chlorination
- Ferric chloride for seawater pre-treatment
- Anti-scalant product for SWRO membranes
- Products for periodical cleaning of SWRO membranes
- Sodium metabisulphite for chlorine removal
- Potassium hydroxide for electrolyser alkalinity adjustment and acid effluent neutralization
- Hydrochloric acid and sodium hydroxide for regeneration of polisher resins.

E.11 Utilities

The following common utility services shall be integrated in the test facility:

- Fire water system
- Emergency power system
- Nitrogen system
- Compressed air system

E.11.1 Firefighting Systems

The firefighting system for the test facility shall be designed considering the nature of the involved processes (hydrogen generation, compression, stockage and transfer) and the location of the involved equipment (electrolysers, compressors, H_2 cylinders, electrical panels).

According to general practice for firefighting in industrial facilities, the following items will be part of the system:

- Fire detection system
- Fire alarm system
- Fire alarm control panel
- Firewater reservoir
- Firewater pumphouse
- Firewater pipe network
- Hydrants
- Sprinklers
- Portable fire extinguishers

It is understood that the above sub-systems will be complementary to the adoption of proper safety measures to prevent flame ignition and propagation, including adequate ventilation of areas subject to risk of hydrogen pockets formation. It is assumed that the hydrogen generation room and the hydrogen storage area will be classified according to IEC 67009-10 “Explosive atmosphere - Classification of areas” and that equipment within classified areas will comply with the requirements of IEC 60079-0 “Electrical apparatus for explosive gas atmosphere”.

The design of the firefighting system shall be developed in accordance with NFPA standards.

Some details on the implementation of the above-mentioned systems in the firefighting design of the test facility are provided below.

- Given that hydrogen is colourless, odourless, that it burns with a nearly invisible flame and releases little radiant heat, thermal imaging cameras and flame detectors should be adopted for early detection of H_2 ignition occurrences in the areas where hydrogen leaks may occur (notably electrolysers, H_2 compressor, cylinders storage).
- In case of detection of high H_2 concentration or ignition in the electrolyser test room, the electrical feed to the concerned equipment shall be automatically disconnected, with the purpose to extinguish the hydrogen feed source. An automatic sprinkler system shall be also installed in the test room of the facility to prevent propagation of the flame to nearby equipment.
- In the Electrical Room and Control Room, ignition conditions in the panels shall be detected by heat detectors / flame detectors / fuses and shall be extinguished by inert gas (such as CO_2).
- Acoustic and visual alarms shall be provided in case of fire hazard.
- Based on the existing site constraints, the firewater reservoir can be constituted by an existing low-salinity water body (pond, river, lake), by an existing basin or by a dedicated firewater tank (underground or aboveground). The necessary minimum water capacity is estimated at around 1,000 m^3.
- The pump house shall include an electrical firewater pump, a jockey pump (having the purpose to keep the required pressure level in the circuit) and the related interconnecting piping, accessories, and instrumentation. Depending on the availability level of the main electrical feed, a stand-by auxiliary diesel firewater pump and related fuel storage tank could be provided.
- The firewater pipe network shall include a ring around the Hydrogen Storage Platform and another parallel ring around the Main Building / Office Building area. Hydrants with hose reels shall be connected to the underground pipelines, in suitable positions enabling to cover all exposed areas. The sprinkler systems in the Main Building and in the Office Building will be also connected to the firewater pipe network.

- Portable fire extinguishers filled with CO_2 shall be located in proximity of electrical equipment and other sources of fire hazards in the Main Building, Office Building and Chemical Storage Building.

E.11.2 Emergency Power System

In case of failure in the supply of electrical power from the grid, it is necessary to provide a temporary source of power to assure the safety of the personnel in the facility and to enable a controlled shut down of the process equipment.

To this aim, it is envisaged the provision of an uninterruptible power supply (UPS), a system intended to store electrical energy in batteries during normal operation and make it available during blackouts. It comprises a rectifier / battery charger, an inverter, a rack of batteries and a static switch for transferring the load from the grid to the battery and back.

The UPS will feed during blackouts the emergency lights in the buildings, the light appliances in the Electrical Room, Control Room and offices, the Control System (including local transmitters, DCS and human machine interfaces (HMIs)) and the motorized valves. By a very rough assessment, it should be rated to provide 10 kW power output for 3 hours. It is envisaged the selection of UPS operating in double conversion (online) mode with Li-Ion batteries.

E.11.3 Nitrogen System

Purging with nitrogen (as inert gas) is necessary before injecting or generating hydrogen inside a closed space filled with air, to avoid release of hydrogen fires due to reaction with oxygen. It is also necessary before opening to atmosphere a circuit containing hydrogen. In the case of electrolysers, compressors and connected piping, this operation is required at each shut down for maintenance.

Given the relatively small size of the involved circuits, it is envisaged to use for this purpose nitrogen cylinders at 200 bar pressure, 30 to 50 litres volume. The cylinders can be stocked in a dedicated area and connected at site as necessary, without the need for fixed circuits.

E.11.4 Compressed Air System

Compressed air is required in the facility for instrument service (notably positioning of pneumatic valves) and, occasionally, for operating pneumatic tools. Compressed air quality shall be as a minimum Class 1 according to ISO 8573-1.

Compressed air shall be produced by a package including:

- Reciprocating, direct drive, oil-free compressor, rated at 5 Nm^3/h air to 10 bar g
- Intake air filter
- Buffer vessel for compressed air
- Air desiccant
- Local instruments

Compressed air shall be distributed inside the facility by a network of 1” pipes.

E.12 Safety Features

Regarding safety, following systems needs to be included in the test facility:

- Flare/vent system
- Fire and gas control system (see section E.11.1 for more details).

F. Cost Estimates

The Class V estimate for the CapEx of a 15 MW test facility is 46.25 M€ for a fully PEM testing facility and 42.25 M€ for a fully alkaline testing facility.

The Class V estimate for the OpEx of a 15 MW test facility is 1.69 M€ per annum for a fully PEM testing facility and 1.58 M€ per annum for a fully alkaline testing facility is expected, excluding the revenues for the produced H_2.

F.1 Introduction

Using the inputs from the functional requirements in section 5 and some additional assumptions, a cost estimate was prepared. A **Class 5 AACE (P50) status 'Mid-point' cost estimate**[9] was performed for PEM and alkaline electrolysis technologies to compare the CapEx and OpEx. CapEx and OpEx are estimated in Euro based on Q4 2023 prices.

This cost estimate gives an indication of a greenfield test facility might cost if all components would need to be purchased, with the exception of the electrolyser stack. With this cost estimate, drivers for CapEx and OpEx can be identified and optimised when the project reaches a later stage. The OpEx estimates can be used to challenge these costs to future users of the test facility.

The CapEx and OpEx are calculated for two cases, a test facility using only PEM electrolysers and a test facility only using alkaline electrolysers. It should be kept in mind that the costs given are indicative and should be taken with care. Additionally, the two cases are not intended to be compared, but rather to show the indicative costs for components as the test facility will eventually not be designed for one specific technology.

The CapEx is calculated based on internal information available within Mott MacDonald. The CapEx is divided into several components, these are: the BoP, the power infrastructure, site civils & buildings, hydrogen storage and hydrogen export. The CapEx is firstly calculated for a test facility with a size of 10 MW, which is used as a base case. After this, the CapEx is scaled down to 5 MW and up to 15 MW, in steps of 1 MW.

The OpEx is calculated as a percentage of the CapEx. This value for the OpEx includes both the constant OpEx (operations, maintenance etc.) and variable OpEx, excluding water and electricity costs associated with hydrogen production. The OpEx reflects a typical benchmark value only. By taking the hydrogen production out of the OpEx, the variable element of OpEx is not specific to any operating regime/level of consumption determined as applicable to the facility. Similarly, no specific market price assessment has been factored into the OpEx valuation for utilities costs.

F.2 Exclusions and Assumptions

Additional assumptions are needed for the cost estimate as the final design of the test facility will be largely influenced by the chosen site, the operator and the design and layout of the test facility. The components excluded from the cost estimates and the assumptions made for this can be found in Table F.4.

[9] https://library.aacei.org/pgd01/pgd01.shtml#Classification%20Concepts%20and%20Principles

Table F.4: Exclusions and assumptions for the cost estimates.

Exclusion	Assumptions
Owner's project and/or development costs and 3rd party services	Costs too specific to make an estimate at this stage.
Land purchase costs and/or land lease	The test facility will likely be located at an existing facility, it is assumed that this will not increase the costs of the test facility.
Price increases	Cost estimates presented for costs of Q4 2023, price escalation and inflation would be addressed in a financial modelling stage.
Export pipeline and export metering	Export via tube trailer assumed, for this space is allocated in the plot plan. For this reason, costs for a pipeline and metering are not included.
Export business / hydrogen revenues	The CapEx and OpEx associated with truck and/or tube trailer export and export via shipping not included.
Grid connection	The test facility will likely be located at an existing facility, it is assumed that the grid connection is already in place and that this does not increase CapEx.
Water connection	The test facility will likely be located at an existing facility, it is assumed that the water connection is already in place and that this does not increase CapEx. It is assumed that the test facility is located close to the sea and sea water is used as raw water.
Waste heat recovery system	Any heat generated in the electrolysis process is assumed not to be used in a waste heat recovery system.
Overall project contingency	As a Class 5 cost estimate is made, contingency allowances have been included for within the build-up of the estimated rates and prices. No additional Project Contingency Allowance has been applied.

F.3 PEM System Cost Estimates

Considering the assumptions in Table F.4 and the functional design specification, the CapEx and OpEx are calculated as can be seen in Table F.5. The cost of the electrolyser is 0 as it is assumed that the stack will be supplied by the user. The OpEx given in Table F.5 does not include the variable costs associated with electrolyser testing, i.e., utility use for hydrogen production. Any experimental cost influences are thus removed from the cost estimate.

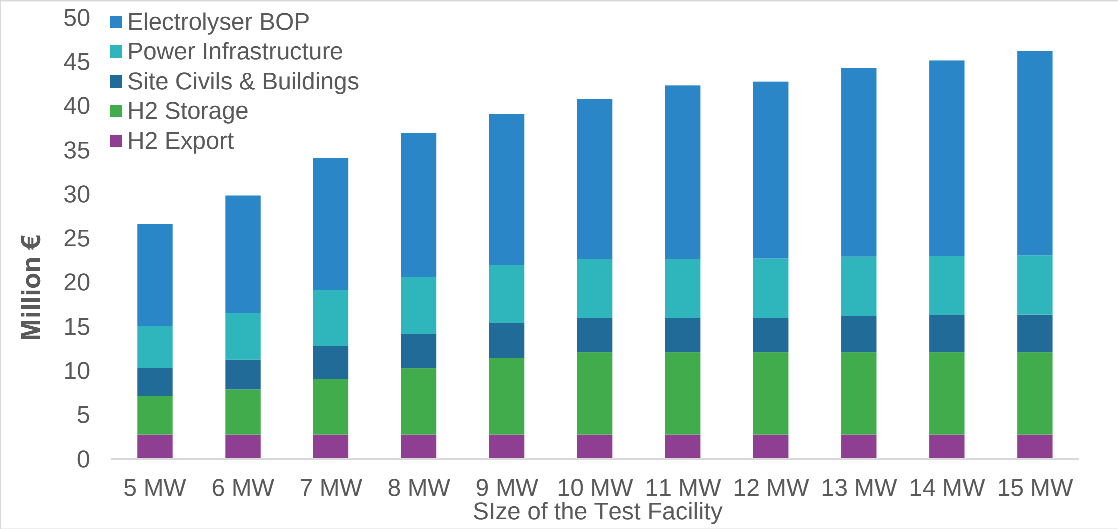
Table F.5: CapEx and OpEx for a hydrogen test centre using PEM electrolysis (€ million).

	5 MW	6 MW	7 MW	8 MW	9 MW	10 MW	11 MW	12 MW	13 MW	14 MW	15 MW
Electrolyser stack	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Electrolyser BoP	11.54	13.37	14.98	16.31	17.13	18.12	19.68	20.07	21.40	22.15	23.15
Power Infrastructure	4.77	5.27	6.34	6.46	6.59	6.65	6.65	6.70	6.72	6.72	6.72
Site Civils & Buildings	3.19	3.37	3.73	3.93	3.93	3.93	3.93	3.93	4.13	4.23	4.28
H2 Storage	4.35	5.10	6.30	7.50	8.70	9.30	9.30	9.30	9.30	9.30	9.30
H2 Export	2.80	2.80	2.80	2.80	2.80	2.80	2.80	2.80	2.80	2.80	2.80
Totals (€ million)	**26.65**	**29.90**	**34.15**	**37.00**	**39.15**	**40.80**	**42.35**	**42.80**	**44.35**	**45.20**	**46.25**

OPEX (€ million per annum)	**5 MW**	**6 MW**	**7 MW**	**8 MW**	**9 MW**	**10 MW**	**11 MW**	**12 MW**	**13 MW**	**14 MW**	**15 MW**
	0.95	1.06	1.21	1.32	1.40	1.46	1.52	1.54	1.60	1.64	1.69

The CapEx for the different size scenarios is visualised in Figure F.14. Looking at the price difference for the 5 MW and 15 MW test facility, this figure clearly shows that costs associated with the power infrastructure, site civils and buildings and hydrogen export rise only slightly, while the costs for the BoP and hydrogen storage increase significantly until 10 MW. To decrease the costs of the test facility, it is beneficial to see which of these components can be shared amongst the different testing bays. As the CapEx and OpEx per MW is relatively lower at full capacity of the test facility, it seems to be beneficial to increase the size of the facility. This however is a trade-off, and the utilisation of the test facility should always be optimised with the costs and benefit from shared services.

Figure F.14: CapEx (in million €) for a hydrogen test centre using PEM electrolysis.



F.4 Alkaline System Cost Estimates

A similar cost estimate has been done for a test facility with a 10MW alkaline electrolysis as a base case. The assumptions used can be found in Table F.4. Using these assumptions and the functional requirements from section E, cost estimates are calculated and can be found in Table F.6. The OpEx given in Table F.6 do not include the variable costs associated with electrolyser testing, i.e., utility use for hydrogen production. Any experimental cost influences are thus removed from the cost estimate.

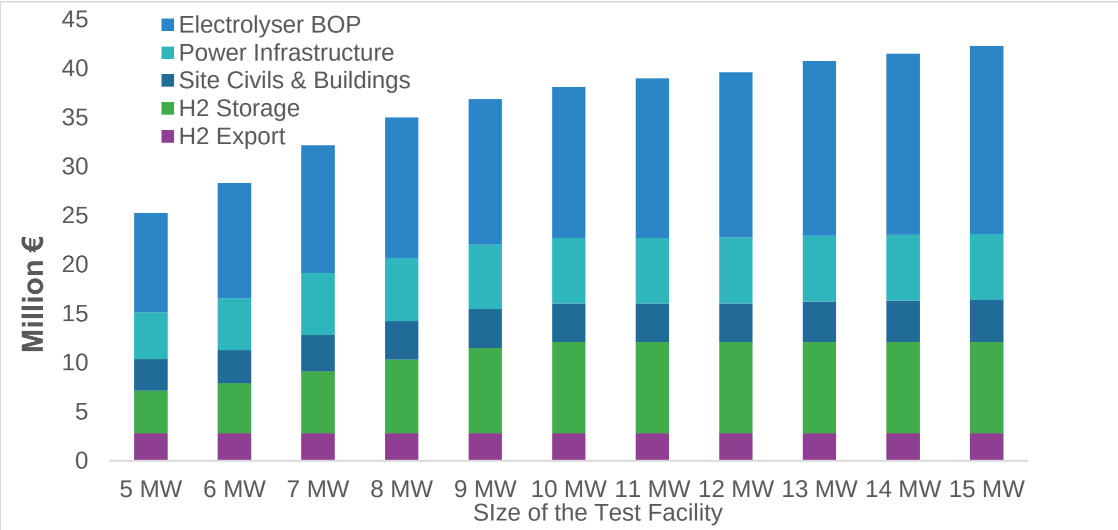
Table F.6: CapEx and OpEx of a hydrogen test centre using alkaline electrolysis (€ million).

	5 MW	6 MW	7 MW	8 MW	9 MW	10 MW	11 MW	12 MW	13 MW	14 MW	15 MW
Electrolyser Stacks	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Electrolyser BOP	10.14	11.76	12.98	14.31	14.83	15.42	16.28	16.87	17.80	18.45	19.15
Power Infrastructure	4.77	5.27	6.34	6.46	6.59	6.65	6.65	6.70	6.7	6.7	6.7
Site Civils & Buildings	3.19	3.37	3.73	3.93	3.93	3.93	3.93	3.93	4.13	4.23	4.28
H2 Storage	4.35	5.10	6.30	7.50	8.70	9.30	9.30	9.30	9.30	9.30	9.30
H2 Export	2.80	2.80	2.80	2.80	2.80	2.80	2.80	2.80	2.80	2.80	2.80
Totals (€ million)	**25.25**	**28.30**	**32.15**	**35.00**	**36.85**	**38.10**	**38.95**	**39.60**	**40.75**	**41.50**	**42.25**

OPEX (€ million per annum)	**5 MW**	**6 MW**	**7 MW**	**8 MW**	**9 MW**	**10 MW**	**11 MW**	**12 MW**	**13 MW**	**14 MW**	**15 MW**
	0.91	1.02	1.15	1.26	1.33	1.39	1.42	1.45	1.50	1.54	1.58

A similar trend can be seen as for the PEM system, costs of all components are rising until 10 MW, but as the size of the facility further increases only costs for the BoP (primarily) is rising. Figure F.15 shows the costs for the different components in the test facility.

Figure F.15: CapEx (in million €) for a hydrogen test centre using alkaline electrolysis.



F.5 Electricity Connection and Transport Costs

As a considerable part of the utility costs will comprise of the electricity connection and transport costs, this will have a major influence on the CapEx and OpEx of the test facility. The CapEx for an electricity connection is not included in the cost estimates of this section, whereas the variability of the electricity use is not included in the OpEx estimate.

The CapEx will depend on whether the connection is directly to the Transmission System Operator (TSO) or to one of the Distribution System Operator's (DSO's), as the costs differ for the different entities. The CapEx for a new grid connection to one of the DSO's ranges from approximately €300.000 to €400.000 for a connection up till 10 MVA in 2023[10,11]. Above 10 MVA the costs can be retrieved on demand. However, most large electricity users in the Netherlands (referred to as 'grootverbruikers') are directly connected to the high voltage grid of TenneT. The costs for a new connection to the high voltage grid of TenneT are not publicly available and will need to be retrieved on demand.

The location of the test facility will determine if a new grid connection is needed or if an existing connection can be used. Finding a location with an existing grid connection will significantly lower the CapEx and will speed up the commissioning of the test facility.

The electricity transport costs will depend on the type of contract in place with the TSO or DSO. Whether a constant price (€/month/installed capacity) or a variable price (€/kW) is more beneficial will depend on the utilisation of the test facility. The volume discount for large electricity users is abolished starting 2024 and can therefore not be used by the test facility[12].

F.6 Cost overview for running and using the greenfield test facility.

This section aims to provide GVNL with an indication of the running costs of such a greenfield facility and the costs that users will have to pay for a certain capacity.

[10] https://www.liander.nl/grootzakelijk/tarieven?ref=22611

[11] https://www.enexis.nl/zakelijk/aansluitingen/nieuwe-aansluiting-aanvragen/tarieven-nieuwe-aansluiting#kostenelektriciteitsaansluiting

[12] https://nl.hardware.info/nieuws/85387/autoriteit-consument-a-markt-vanaf-2024-geen-volumekorting-meer-voor-grootverbruikers-van-elektriciteit

F.6.1 Indicative running costs of the test facility

An overview of the costs is presented in Table F.7. Explanation of cost build-up is as follows:

- 'CapEx' is the investment associated with a greenfield PEM test facility without an electrolyser stack (which is brought in by the user).
- 'OpEx Facility' includes the fixed costs of running the greenfield test facility.
- 'OpEx Experimentation' includes the variable costs of running BoP for hydrogen production, excluding utility use for the electrolyser. This is assumed to be handled by the user directly.
- 'OpEx Total' is the sum of the OpEx facility and Experimentation.
- 'Financing costs' includes the amortisation of the CapEx investment over a period of 30 years with an interest rate of 8%.
- 'Staff costs' includes the following personnel to operate a hydrogen test facility:

Functions	Estimated annual costs (EUR)
Facility Director (1 person)	150,000
Planning and Logistics Manager (1 person)	50,000
Administrational Staff (1 person)	50,000
Warehouse technician (3 persons)	3 x 50,000
Test Engineer, safety officer and subject matter experts (3 persons)	3 x 100,000
Test Technicians / Operators (6 persons)	6 x 100,000

These estimates, based on in-house knowledge, are given to provide an indication of staff costs and could vary with size of the facility, the number of bays developed, and the potential shared services etc. For simplicity, a constant number of staff was chosen for 5 - 15MW test facility capacity and provided in Table F.7.

- 'Running cost facility' is the sum of the OpEx total, the financing costs and staff (see bullet below). The running costs presents all the costs for the operation of the test facility, excluding utility use for the electrolyser.

Table F.7: Overview of the costs for a greenfield PEM facility, all in m€/annum.

Facility Size	5	6	7	8	9	10	11	12	13	14	15	MW
CapEx	26.6	29.9	34.2	37.0	39.2	40.8	42.4	42.8	44.3	45.2	46.3	m€/annum
OpEx - Facility	0.95	1.06	1.21	1.32	1.40	1.46	1.52	1.54	1.60	1.64	1.69	m€/annum
OpEx - Experimentation	0.34	0.38	0.43	0.45	0.45	0.46	0.49	0.48	0.49	0.49	0.50	m€/annum
OpEx - Total	1.28	1.44	1.64	1.77	1.85	1.92	2.01	2.02	2.10	2.14	2.19	m€/annum
Financing costs	3.02	3.39	3.87	4.19	4.44	4.62	4.80	4.85	5.03	5.12	5.24	m€/annum
Staff costs	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	m€/annum
Running cost facility	5.60	6.13	6.81	7.26	7.59	7.85	8.11	8.17	8.42	8.56	8.73	m€/annum

F.6.2 Indicative costs for future users

From the perspective of a user of the test facility, there are two major cost drivers. The first one is the utility cost of hydrogen production. To calculate the electricity costs per MW of electrolyser capacity, the following assumptions were made:

- Electricity costs: 100 €/MWh
- H_2 value: 3 €/kg
- Efficiency hydrogen production process: 60%
- Electricity consumption per unit hydrogen: 50 kWh/kg H_2

This results in:

- H_2 revenue: 36 €/MWh
- Utility costs: 0.56 m€/MW*year (Electricity costs minus H_2 revenue per megawatt of electrolyser capacity per year)

The second cost driver is the test facility utilisation rate. The test facility will face running costs which will have to be covered by the users of the facility. The total cost for running a 15MW test facility is ~ 8.73 m€/annum, which must be factored for the capacity used by the user and the test facility utilization rate.

To indicate the effect of these two variables in a more comprehensive manner, the example that 1MW electrolyser is tested in a 15MW facility (Table F.8) is explored. The utilisation rate of 1MW in a 15MW facility is ~7%. This implies that if, e.g., the total test facility utilization rate is 70%, ~10% of the 8.73 m€/annum running costs will be charged to the user. On top of that, the costs will increase with increasing electrolyser run time, as presented in the vertical column of Table F.8.

Table F.8: Overview of the costs where 1MW is tested in a 15MW facility.

Costs (k€/week)		**Test Facility Utilisation Rate**									
		10%	20%	30%	40%	**50%**	60%	70%	80%	90%	100%
Electrolyser run time	0%	105	53	35	26	21	18	15	13	12	11
	50%	117	61	43	33	28	24	21	19	18	17
	100%	123	67	48	39	33	29	27	25	23	22

G. List of Abbreviations and Definitions

Abbreviation	Definition
AC	Alternating Current
AEM	Anion Exchange Membrane
atm	Atmosphere: unit of measurement equal to the average air pressure at sea level at a temperature of 15 degrees Celsius
AWE	Alkaline Water Electrolysis
BoP	Balance of Plant
CapEx	Capital Expenditures
CCUS	Carbon Capture, Utilisation and storage
CO_2	Carbon Dioxide
DC	Direct Current
DCS	Distributed Control System
DSO	Distribution System Operator
FID	Final Investment Decision
GVNL	GroenvermogenNL
GW	Giga Watt
HAZOP	Hazard and Operability study
HMI	Human Machine Interface
HP	High Pressure
H_2	Hydrogen
HV	High Voltage
IP	Intellectual Property
ISPT	the Institute for Sustainable Process Technology
kJ	Kilo Joule
kV	Kilo Volt
LCOH	Levelised Cost of Hydrogen
LOPA	Layers of Protection Analysis
LP	Low Pressure
LV	Low Voltage
mS	Micro Siemens
MCC	Motor Control Centre
MVA	Mega Volt Ampère
MV	Medium Voltage
MW	Mega Watt
NDA	Non-disclosure agreement
Open test facility	Test facility open for third-party use
OpEx	Operational Expenditures
PEM	Proton Exchange Membrane
ppm	Parts per Million
SOEC	Solid Oxide Electrolyser Cell
SWRO	Seawater Reverse Osmosis
TRL	Technology Readiness Level

Abbreviation	Definition
TSO	Transmission System Operator
UPS	Uninterruptible Power Supply
V	Voltage

H. Existing Test Facilities related to Hydrogen

The endurance testing facility intended to be developed by GroenvermogenNL should be complementary to existing test facilities. To properly place the endurance testing facility in the testing environment in the Netherlands, a high-level overview of the currently existing facilities in the Netherlands is needed.

Table H.9: Hydrogen Test Facilities in the Netherlands

Test Centre	Component / Technology Tested	Main Test Type	Other Features	Regulations and standards
Hydrohub MegaWatt Test Center in Groningen – Institute for Sustainable Process Technology[13].	Full-scale experiments small industrial PEM and alkaline electrolysers.	Stress testing with the goal of increasing the electrolyser efficiency, focussing on optimisation, and testing of new materials.	Material and component suppliers for membranes, anodes, electrodes, pump, and so on, can test the impact of the process on their parts.	-
H2 Lab – Kiwa[14].	Automotive related hydrogen parts.	Testing and certification services of automotive components.	Hydrogen tests can be performed in extreme conditions up to 1,100 bar. Tests can be performed between 50 and 120 degrees Celsius.	Testing facility accredited conform ISO 17025.
Faraday Lab in Petten – TNO[15].	Electrolysis technologies such as PEM, alkaline, SOEC and AEM.	Small-scale research with a focus on new materials and components.	Open innovation lab, TNO works together with manufacturers of electrolysers and their suppliers.	-
High Pressure Gas Testing Facility (GASTEF) in Petten[16].	High pressure (vehicle) tanks for hydrogen and natural gas.	Fast filling tests, gas cycle tests and permeation tests.	Part of the EU Science Hub.	Tests according to the European Regulation EU 406/2010 on type-approval of hydrogen vehicles and by other international regulations and standards such as UN Regulation No. 134 or ISO and SAE standards.
Technology Centre in Groningen – DNV[17].	Full scale implementation of hydrogen as a fuel	-	Not limited to hydrogen, also investigating	-

[13] https://ispt.eu/projects/hydrohub-megawatt-test-centre/
[14] https://labinsights.nl/artikel/waterstofeconomie-getest-en-beproefd-bij-kiwa-nederland/
[15] https://www.tno.nl/en/technology-science/labs/faraday-lab/
[16] https://joint-research-centre.ec.europa.eu/laboratories-and-facilities/high-pressure-gas-testing-facility_en
[17] https://www.dnv.com/oilgas/laboratories-test-sites/technology-centre-groningen-the-netherlands/gas-technologies-ccs-hydrogen.html

Test Centre	Component / Technology Tested	Main Test Type	Other Features	Regulations and standards
	for industries and households. Furthermore, flow equipment is qualified in a 100% hydrogen flow loop.		Ammonia, bio methanol and biogas.	
Stack Test Centre in Helmond	Large electrolyser stacks (>250kW)			
H2 Hub Twente	Hydrogen technologies.	Depends on the tester, possibilities for production, storage and usage of hydrogen.	Collaboration place for industry and education.	-
GZI Next in Emmen – Shell[18].	4.4 MW electrolyser plant, possibility to upgrade to 10MW.	Integration tests of hydrogen production with solar energy.	350 bar hydrogen filling point on site. Start of build in 2024.	-
Hydrogen Field Lab in Flevoland – ROGER	Hydrogen based technologies which will be tested in their field lab which will be integrated on ROGER's hydrogen plant in Flevoland.	Real-world testing in an operational environment.	Objective is to advance the development and commercialisation of hydrogen-based technologies.	-
Sinnewetterstof – Alliander & Groenvermogen[19]	1.4MW electrolyser	Real-world testing of the integration of hydrogen production with solar energy.	Objective is to use hydrogen production to help solve net congestion.	-
Field Lab Industrial Electrification in Rotterdam	Electrolysers in an industrial environment. Small scale.	Integration tests using hydrogen and CO2 to make new fuels and chemicals. Feasibility studies.	Focused on the overall electrification of industry.	-
Energy Demo Field at IPKW in Arnhem – Connectr	PEM fuel cells tested by Nedstack.	TBD	IPCEI grant received for the development	-
HyDelta 2	Hydrogen transport.	Integration of hydrogen in the existing gas transport and distribution infrastructure.	-	-
SWITCH in Lelystad	Small scale hydrogen generation on farms.	Optimising energy management systems and controllers for hydrogen generation on a weak renewable grid.	Cooperation of TNO and WUR.	-

[18] https://gzinext.nl/waterstof/
[19] https://sinnewetterstof.nl/

Table H.10: Hydrogen Test Facilities in the rest of North-West Europe

Test Centre	Component / Technology Tested	Main Test Type	Other Features	Regulations and standards
LTU Green Fuels[20] - Sweden.	Electrolysis and use of residual heat	Residual heat saving and usage. Energy and cost efficiency studies.	Lease infrastructure for external projects and will be a national infrastructure for research in green fuels. Not yet operational.	-
VKhylab – Beglium.	Liquid and gas hydrogen, hydrogen carrying molecules, laboratory scaled models to industrial size.	-	Operational in 2026-2027.	TBD, qualification tests planned.
Spadeadam in England – DNV	Hydrogen	Hydrogen safety research	Conducting full scale testing to assess the consequences of major hazards and their effects.	Blast test: ISO 16933, ASTM F1642-04, GSA. Ballistic testing: VSAG12, VPAM-BRV.
ZBT GmbH in Germany[21]	Fuel cells, hydrogen technologies, electrolysers.	Materials and components testing. Test and degradation analysis. Gas analysis in the HyLab quality laboratory.	Wide variety of tests. Test size currently approximately 150 kW.	-
HyCentA Research GmbH in Austria[22]	Production, distribution, storage and application of hydrogen. Small scale.	Fuel cell system testing, high pressure tests up to 1000 bar, H2 refuelling for 350 and 700 bar with cold fill, test cells for component and subsystem testing, hydrogen quality laboratory.	Modern research infrastructure with highly qualified staff at the facilities of Graz University of Technology.	-
Harfleur laboratory in France – SGS[23]	Hydrogen refuelling stations, production sites, or any other site using hydrogen up to 700 bars of pressure.	Purity testing.	Performing testing, inspection and certification.	EN 17124, ISO 14687 and SAE J2719
Norwegian Fuel Cell and Hydrogen Centre[24]	Fuel cells, electrolysers. Up to 10kW.	Tests on cutting edge materials and components through to validating performance and durability of	Both a low and high temperature lab.	-

[20] https://www.ltu.se/
[21] https://www.zbt.de/en/the-zbt/
[22] https://monitor-industrial-ecosystems.ec.europa.eu/
[23] https://www.sgs.com/en/news/2022/11/sgs-opens-an-advanced-hydrogen-laboratory-in-france
[24] https://www.sintef.no/projectweb/nfch/about/

Test Centre	Component / Technology Tested	Main Test Type	Other Features	Regulations and standards
		established technologies.		
IFE Hynor Hydrogen Technology Center in Norway[25]	PEM, Liquid hydrogen, fuel cells. Up to 33kW.	Testing of different hybrid electric topologies, and emulation of different load profiles.	Tests at high pressure, up to 200 bar.	-
Brande Hydrogen in Denmark – Siemens Gamesa	Electrolyser, 400kW.	Integration test with wind turbine of 3MW. Safety tests for standardisation.	Pilot plot also investigated energy management systems.	-
Hydrogen Lab Bremerhaven – Fraunhofer IWES[26]	Electrolysis coupled to wind energy, 12 modular test benches for containerised electrolysers up to 2MW each.	Grid integration analysis, dynamic research and validation, independent analysis of performance in a dynamic environment.	Coupling to virtual grid of dynamic nacelle testing laboratory. Not yet operational.	-
Hydrogen Lab Leuna – Fraunhofer IWES[26]	AEL, PEM, SOEC	Electrolyser system tests up to 5 MW. Stack test benches up to 46 kW. Gas analysis, materials analysis.	Hydrogen utilisation via local pipeline.	-
Hydrogen Lab Gorlitz – Fraunhofer IWES[26]	Electrolyser stacks up to 2 MW.	Electrolyser stacks, pipe storage test bench.	Site power supply of 12 MW. Start of operations planned for 2024.	-

[25] https://ife.no/en/laboratory/ife-hynor-hydrogen-technology-center-ife-hynor/

[26] Masterclass: Testing, Certification and Qualifications of Electrolysers. Dr. J. Höflinger, K.V. Schalk.

I. Stakeholder List

List of contacted stakeholders, covering the green hydrogen value chain. Thirty stakeholders of this list have participated in this study.

[redacted]

[redacted]

J. Interview Questions

J.1 Online Questionnaire

Question Number	Question
1	The hydrogen activities of the company are located in (multiple answers possible):
2	In which sector would you categorise your hydrogen activities (multiple options possible)?
3	Would you be open to a follow up interview, either face to face, online or in a hybrid form?
4	Do you want your answers to be anonymised when used for research purposes in the feasibility study for a hydrogen test facility in the Netherlands?
5	GroenvermogenNL intends to facilitate endurance testing facilities for components in the green hydrogen value chain, which is used for long term testing to validate the performance of new and adjusted hydrogen systems. What is your opinion on this? Please elaborate
6	If you are currently testing components of the hydrogen supply chain, at which technology readiness level as depicted in the figure would you place your testing phase?
7	Additionally, for what phase do you envision the use of a test facility?
8	In what timeframe should such testing facility be starting to perform tests?
9	In what timeframe would you want to start using such a testing facility?
10	Which components would you like to be tested in the test facility?
11	What should be the minimum size (in terms of electrolyser power consumption in MW) of such a test facility?
12	The tests that can be carried out at the test facility can be divided into several categories, for example: stress tests, endurance tests, integration tests or tests related to the supply of ancillary services. Which test categories do you think are relevant for a hydrogen test facility?
13	Furthermore, what specific test(s) would be valuable to you? Please link your own test(s) to the categories in question before.
14	What is the estimated duration of the tests that you would perform?
15	Which components for the test facility need to be delivered by the user and which components should be available on site?
16	What type of electrolysis would you want to test (multiple options possible)?
17	Is it important for you that the hydrogen is produced from renewable electricity to label it as green hydrogen?
18	What is your preferred way of exporting the hydrogen from the testing facility?
19	What would be the major added value(s) of a hydrogen test facility?
20	What would be the major concerns of using the test facility?
21	How likely are you to utilise the hydrogen test facility for the tests you want to perform?
22	What solutions should a hydrogen test facility provide to ensure commercialisation of hydrogen technologies (multiple answers possible)?
23	TNO is assigned for National monitoring of test results in P2G facilities. Would you be open to share the monitoring results under the protection of an NDA? Additionally, would you also be open for the use of these results in academic research? Please comment.

J.2 Interview Questions In-depth Interviews

J.2.1 Questions Branch Organisations

Number	Category	Question
1	**General**	Outlook hydrogen value chain

Number	Category	Question
2	**General**	Are there any synergies you can think of between this project, and future projects or fundings taking place in the Netherlands?
3	**Market uptake**	In what niche should a new test facility operate?
4	**Market uptake**	In what are/sector would the added value be the highest?
5	**Market uptake**	In what timeframe should this be developed?
6	**Type of testing**	What type of testing is needed to overcome the large hurdles in the hydrogen value chain? How should standardisation and certification be used by the test facility?
7	**Organisational roles and responsibilities**	What resources and support can the branch organisation provide to a test facility?
8	**Economy Test Facility**	What should the economic model of the test facility look like?

J.2.2 Questions Developers

Number	Category	Question
1	**General**	What challenges do you encounter in hydrogen projects, and how could this endurance test facility help overcome these challenges? How could the test facility reduce risks for your projects?
2	**General**	What are the key factors that influence your decision to choose to test at a test facility?
3	**Market Uptake**	What are the key market barriers for the adoption of hydrogen technologies?
4	**Market uptake**	How should confidentiality issues be mitigated when testing at the test facility? How should data safe housing be organised?
5	**Market uptake**	How important is the location of the testing facility to you?
6	**Type of Testing**	What are the main metrics you want to test in the production of hydrogen? Is it important to benchmark these metrics?
7	**Type of Testing**	Do you want to test for safety, certification & reliability?
8	**Organisational roles and responsibilities**	What knowledge and skills should be available on site which you can't/won't bring yourself? What support do you expect from the test facility staff?
9	**Organisational roles and responsibilities**	What role in the development of the facility do you see for your company?
10	**Economy Test Facility**	If the test facility would be developed for a 1-10MW scale, roughly costing …-… per week to test, would you be willing to use it then?
11	**Technical specifications / requirements**	What requirements do the tests impose on the test site?

J.2.3 Questions End Users

Number	Category	Question
1	**General**	Would you be willing to accommodate the test facility on site? If so, would you be open to share site specifications (this does not have to become public information)?
2	**Organisational roles and responsibilities**	What role do you see for your company in the development of the test facility?
3	**Technical specifications / requirements**	What are the requirements of the hydrogen offtake? Green? Quantity? Pressure?

Number	Category	Question
4	**Technical specifications / requirements**	What safety issues do you envision? How to cope with these?
6	**Economy Test Facility**	What are your economic interests of facilitating the test facility?
7	**Economy Test Facility**	How would you manage downtime in terms of hydrogen production from the test facility?
8	**Economy Test Facility**	How do you think the hydrogen should be priced?

J.2.4 Questions Future Operators

Number	Category	Question
1	**General**	What challenges do you envision in the operation of the test facility? How could these be overcome?
2	**Market Uptake**	In your opinion, how should the test facility be designed/organised to have the highest market uptake?
3	**Technical specifications / requirements**	What are desired quality metrics? How to assure these qualities?
4	**Technical specifications / requirements**	What are specific site requirements? How important is the location of the testing facility to you?
5	**Organisational roles and responsibilities**	What knowledge and skills can you bring as a future operator and what should be brought in by the users?
6	**Organisational roles and responsibilities**	How would you fill in your role as an operator of the testing facility?
7	**Organisational roles and responsibilities**	How do you envision the protection of the intellectual property and data of the users? How would you do this with multiple users at the same time?
8	**Organisational roles and responsibilities**	What safety issues do you envision? How to cope with these?
9	**Economy Test Facility**	What are your economic interests of operating the test facility?

J.2.5 Questions Manufacturers

Number	Category	Question
1	**General**	What are the key factors that influence your decision to choose to test at a test facility?
2	**Market Uptake**	What are current testing facilities lacking?
3	**Market uptake**	How should confidentiality issues be mitigated when testing at the test facility? How should data safe housing be organised?
4	**Market uptake**	How important is the location of the testing facility to you?
5	**Type of Testing**	What are the main metrics you want to test in the production of hydrogen? Is it important to benchmark these metrics? Do you want to test for safety?
6	**Organisational roles and responsibilities**	What knowledge and skills should be available on site which you can’t/won’t bring yourself? What support do you expect from the test facility staff?

Number	Category	Question
7	**Organisational roles and responsibilities**	Would you consider testing with other companies at the same time? What if this would reduce costs?
8	**Economy Test Facility**	What would you be willing to pay per week for testing at scales between 1 – 10MW?
9	**Technical specifications / requirements**	What requirements do the tests impose on the test site?

J.2.6 Questions Testing Facilities

Number	Category	Question
1	**General**	Which improvements would you include if you would start a new test facility today? What are key considerations for GroenvermogenNL to consider for the new test facility?
2	**General**	What is the added value of an “open” test facility concerning the hydrogen value chain?
3	**Market uptake**	In what niche should a new test facility operate to ensure it does not compete with current facilities now and in the future?
4	**Type of testing**	What necessity exists for testing for certification and safety? How does this translate to the type of tests performed at the testing facility?
5	**Technical specifications / requirements**	Which safety measures are taken at your testing facility?
6	**Organisational roles and responsibilities**	How do you organise the data safehouse? How could this be done at the new test facility assuming it is (partly) open to multiple companies with their own intellectual property?
7	**Organisational roles and responsibilities**	What are the biggest organisational challenges in operating a test facility?
8	**Organisational roles and responsibilities**	What is the role of the company testing and the test facility with respect to the tests?
9	**Organisational roles and responsibilities**	Would you be open in collaborating with the new test facility? How could this collaboration look like?
10	**Market uptake**	What are the key factors that determine the economic viability of a test facility in the market? What makes a test facility attractive for companies?
11	**Economy Test Facility**	What is the economic model of the test facility? What are your experiences with the overhead costs of a test facility?
12	**Economy Test Facility**	How do you minimise the downtime of the testing facility?

K. Site Selection Criteria

For the site selection, a multicriteria decision analysis is proposed. A non-exhaustive list of selection criteria is provided in Table K.11. The result of the multi-criteria decision analysis is a score for every site. The overall score for a site can be expressed as the sum of the level 1 criteria values multiplied by the respective relative weighting:

$$(Eq.K.1)\ Score = \sum^{l} C_{1,l} * W_{1,l}$$

Where C_1 and W_1 are the value of the criterium, and the weighting assigned to that specific level 1 criterium. The level 1 criteria values are calculated in the same manner. The value for the level 2 criterium is multiplied by the relative weighting of that criterium with respect to the other criteria.

$$(Eq.K.2)\ C_1 = \sum^{n} C_{2,n} * W_{2,n}$$

In other words, defining the level 1 and level 2 criteria and weighing these relative to one another provides a transparent scoring system for a location selection. In the case that economics is considered more important than future proofing, this criterium could be given a higher relative weighting. The same holds for the level 2 criteria. Once a sufficiently exhaustive list of selection criteria is constructed, and the weighting is determined for every criterium, the analysis can be performed.

Table K.11: Non-exhaustive site selection criteria for a multi-criteria decision analysis.

level 1 Criteria	**Economics**	**Realisation & Tech feasibility**	**O&M**	**Future proofing**
Level 2 Criteria	CapEx	Development time	Staffing	Future expansion capacity
	OpEx	permitting complexity	Shared services	modularity
	Pre-investment	Grid connection (Y/N)		SOEC synergy
	H2 offtake	Grid capacity		
		Plot size and condition		

mottmac.com/netherlands