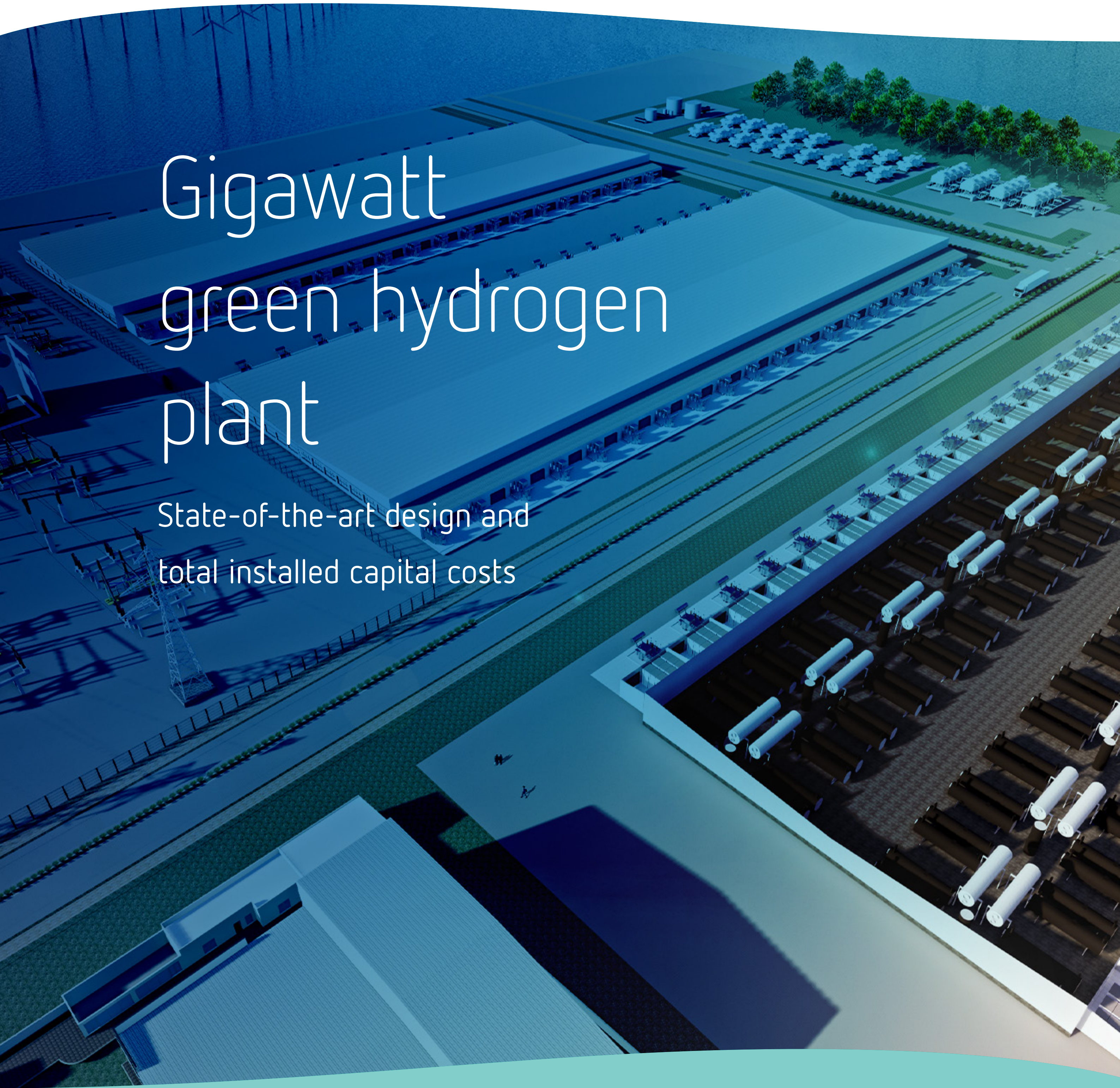
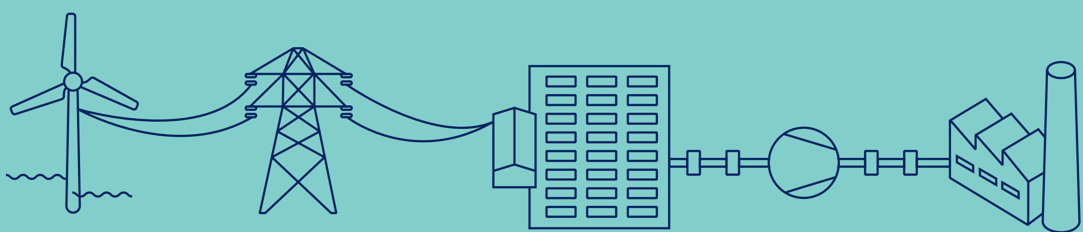
Public report

Hydrohub Innovation Program



Gigawatt green hydrogen plant

State-of-the-art design and total installed capital costs



Summary

There is a sense of urgency for green hydrogen to achieve the European Green Deal and realise Europe's clean energy transition. The EU ambition is to install at least 40 gigawatt (GW) of renewable hydrogen electrolysers by 2030, producing up to 10 million tonnes of renewable hydrogen.[1]
Clearly, this requires upscaling of water electrolysis technology. The current state-of-the-art is at 10 MW scale, whereas GW scale green hydrogen plants are needed. For instance, a 1 GW green hydrogen plant could produce around 10% of the present annual hydrogen demand of the (petro)chemical industry in the Netherlands.

The technical study presented here is part of the Hydrohub GigaWatt Scale Electrolyser project that aims to reduce capital expenditures (capex) and deliver conceptual designs (blueprints) for GW water electrolysis facilities in the five main industrial clusters in the Netherlands. We have prepared a baseline design with a cost breakdown as first phase of the project to assess the economics of a GW green hydrogen plant which can be built in 2020. This design was completed for both Alkaline and PEM electrolyser technology. In the next phase of this project we will develop advanced design options for further reduction of the capex.

We demonstrated in this report that the capex is higher than usually reported because of different definitions. If we use similar definitions, like direct costs for system supply and installation, our cost estimate is in line with reported values. For end-users (owners, investors and operators) complete and real costs are applicable meaning that total installed costs must be taken into account for final investment decisions.

We determined **Total Installed Costs** (TIC) for a greenfield GW green hydrogen plant in a port area in the Netherlands. This includes all direct costs for equipment, materials and installation on site.
Also, services need to be added, divided in indirect and owners costs, and a contingency provision, which is commonly applied to cover risks and unknown scope. The total installed costs breakdown and direct costs distribution are given in figure 1 and 2 for Alkaline and PEM technology.

Our conclusion is that the total installed costs of a GW scale industrial electrolysis plant amount to 1400 €/kW for Alkaline electrolyser technology and 1800 €/kW for PEM electrolyser technology. This includes indirect and owners costs as well as contingency for investment decision. The costs of power supply and electronics, balance of plant, and utilities and civil are equally important as the cost of Alkaline electrolyser stacks. The costs for PEM stacks are higher and are about the same as the sum of the other areas. Cost reductions are therefore needed in all mentioned areas.

[1] https://ec.europa.eu/commission/presscorner/detail/en/ip_20_1259

Capex cost breakdown Alkaline technology

Total Installed Costs 1400 Euro/kW

Direct Costs 800 Euro/kW

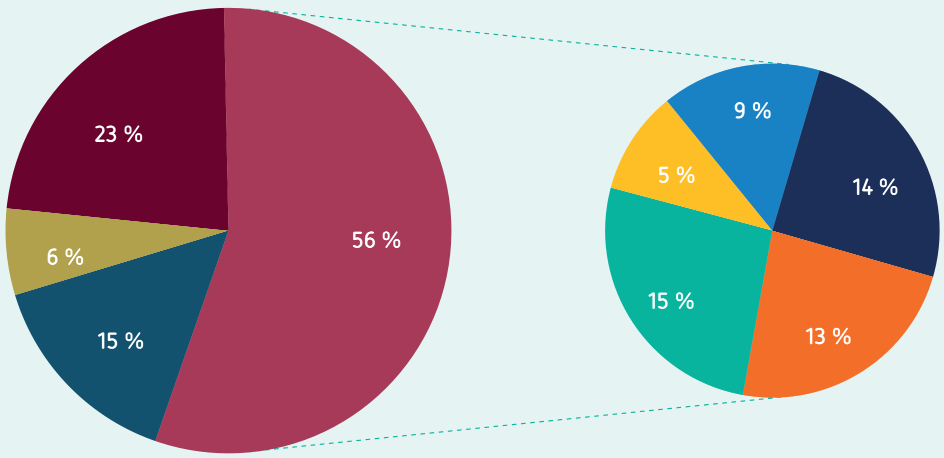


Figure 1: Breakdown of the total installed costs for 1 GW green hydrogen plant based on Alkaline technology.

Capex cost breakdown PEM technology

Total Installed Costs 1800 Euro/kW

Direct Costs 1000 Euro/kW

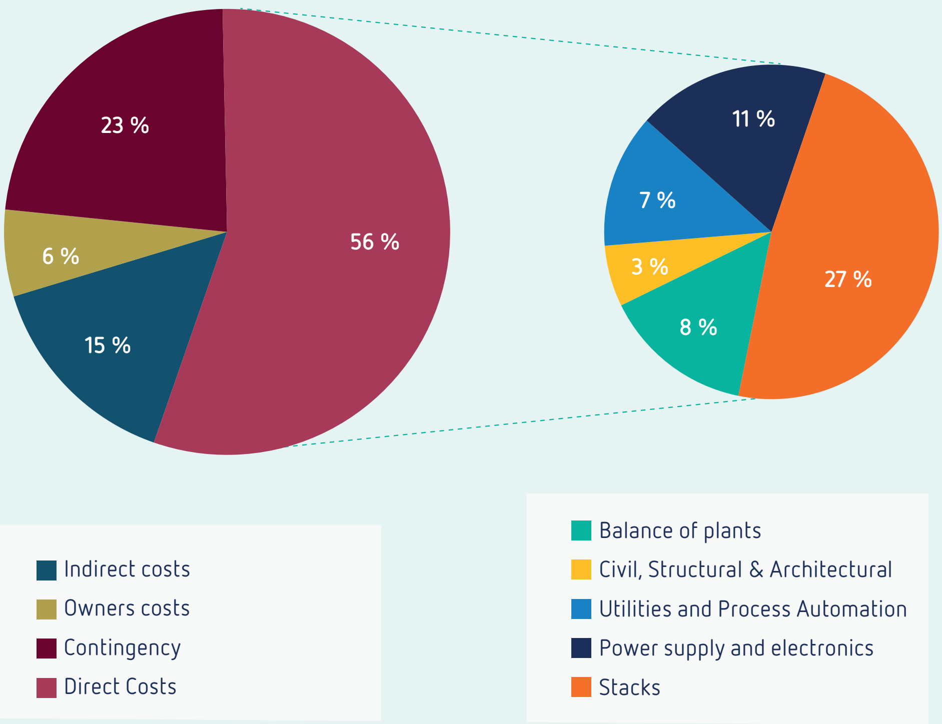


Figure 2: Breakdown of the total installed costs for 1 GW green hydrogen plant based on PEM technology.

Table of content

Introduction

Green hydrogen can replace natural gas as energy carrier and industry feedstock to reduce CO_2 emissions. This transition requires very large volumes of green hydrogen and investment in many gigawatt (GW)-scale green hydrogen plants. These plants will be powered by wind and solar power. An example is the $5 Billion Production Facility with water electrolysis and ammonia production with over 4 GW of renewable energy in the Kingdom of Saudi Arabia, for which a first agreement has recently been signed.[2]

In the Netherlands, the ambition is to realise 3-4 GW green hydrogen plants in 2030.[3] One of the pioneering projects is the joined development of Ørsted and Yara aiming at replacing fossil hydrogen with renewable hydrogen in the production of ammonia.[4] The produced hydrogen is either delivered directly to industrial end-users or transported through a hydrogen pipeline (backbone), which allows for transport and buffering. The national gas grid operator Gasunie is working on the realisation of hydrogen infrastructure envisaged to be operational in 2025. This infrastructure connects the five Dutch industrial clusters with each other, with storage facilities in the Netherlands and with the adjacent infrastructure at the border points.[5]

The ISPT (Institute for Sustainable Process Technology) is leading a consortium with industrial partners, namely DOW, Gasunie, Nouryon, OCI Nitrogen, Ørsted, Yara, and knowledge institutes, working together in the Hydrohub GigaWatt Scale Electrolyser project. The aim is to reduce the capex and levelised costs of hydrogen[6] (LCOH) produced by water electrolysis towards 2030.

We developed a state-of-the-art design and cost estimate for a 1 GW water electrolysis plant producing hydrogen in an industrial cluster the Netherlands in 2020. Alkaline and PEM electrolyser technologies are considered as these are most mature. This study is building on a previous regional study[7], which delivered user requirements for a GW plant in the Netherlands through potential locations, industry demand, plot plans and infrastructure connections. This design provides the present reference level (baseline) for the next phase of this project. In this next phase we will develop advanced design options to further reduce the capex.

For the levelised costs of hydrogen besides capital expenditures also operational expenditures (opex) are important. That is going to be another chapter in this Hydrohub GigaWatt Scale Electrolyser project.

[2] https://www.acwapower.com/news/air-products-acwa-power-and-neom-sign-agreement-for-5-billion--production-facility-in-neom-powered-by-renewable-energy-for-production-and-export-of-green-hydrogen-to-global-markets/

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

[4] https://orsted.com/en/media/newsroom/news/2020/10/143404185982536

[5] https://www.gasunienewenergy.nl/projecten/waterstofopslag-hystock/market-consultation-hydrogen-storage

[6] Levelised Costs of Hydrogen (LOCH) refers to the total of discounted capex and opex divided by annual hydrogen production and is expressed in Euro/kg H_2

[7] Public summary I, Integration of GW green hydrogen plants in five industrial regions, ISPT, 2020 https://ispt.eu/publications/?project-tag=SI-20-07

Starting points of the baseline design

A large group of experts from industry, engineering and academia worked together in multidisciplinary teams per area to define the scope and to deliver a baseline design. Special attention was given to the interfaces to ensure the operational viability of the system. For each area a consortium partner took the lead, with other partners in a support role and ISPT as coordinator and technical supervisor.

The starting points of the baseline design are:

- Greenfield plant in the Netherlands.
- Projected location is heavy industry port area with saline atmosphere.
- The plant uses offshore wind power delivered at a 380 kV connection point with 1 GW capacity. The connected electrical load is 1 GW, powering all primary and auxiliary equipment. Electrical losses in the plant are taken into account.
- Typical wind profile for wind park in the North Sea is shown in figure 3.[8] This profile has been adapted to meet 1000 MW electricity supply to a 1 GW green hydrogen plant and amounts to 4000 GWh annually.
- Additional back-up electricity supply is provided to meet a minimum load of 15% to maintain gas purity and minimise the number of start/stops and in this way avoid adverse impact on stack lifetime (especially for Alkaline electrolysis technology).
- For Alkaline technology we assume 4.4 kWh per Nm^3 hydrogen as nominal electricity consumption, based on new stacks. For PEM technology we considered 4.9 kWh/Nm^3 meaning that PEM has lower efficiency and more heat losses.
- For Alkaline stacks we assume that these operate at atmospheric pressure resulting in the need for mechanical compression. For PEM stacks we assume a pressurised operation mode, which omits the need for mechanical compression and associated power consumption.
- The electrical losses in the unit operations surrounding the electrolysers amount to 8% and 5% for alkaline and PEM technology respectively. This includes losses in the transformers and rectifiers, auxiliary power consumption and the costs of mechanical compression (for alkaline).
- The nominal hydrogen output amounts to approximately 18 tonnes per hour (200,000 Nm^3/hr), depending on the applied electrolyser technology, electrical losses and efficiency assumptions. To be exact, for Alkaline this is 18.8 ton/h whereas for PEM this is 17.1 ton/h.
- The hydrogen is delivered at 30 bara pressure and purified (de-oxidised and dried) to 99,99 % purity and max. 30ppm (vol) water.
- All oxygen produced is vented (oxygen offtake is optional).
- Residual heat is cooled down in cooling towers (heat recovery for district heating is optional).
- Demineralised water is produced in Reverse Osmosis units based on pretreated fresh water.

[8] Ørsted, Actual Generation Offshore Wind North Sea, capacity 957 MW, 2018

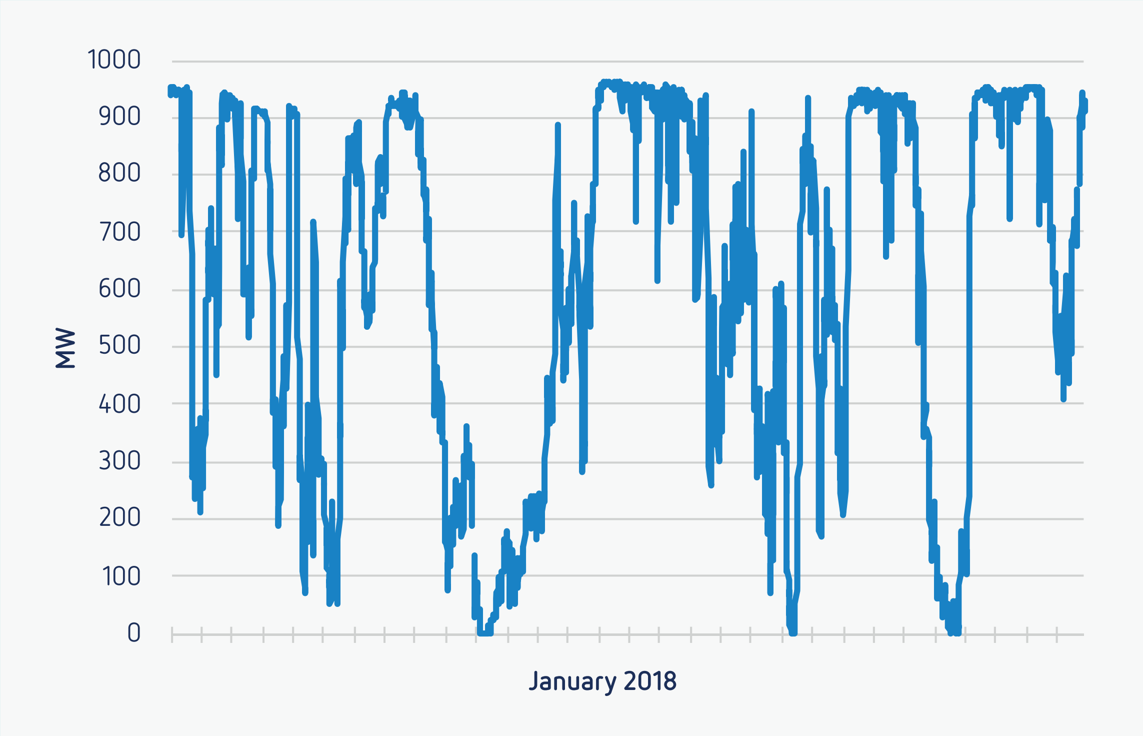


Figure 3: North Sea wind profile illustrated for the month of January, year 2018 is used in full capacity calculation (source: Ørsted)

Modular design of a 1 GW green hydrogen plant

Based on the described starting points a modular state-of-the-art design was made in this study. Figure 4 depicts a block diagram for the GW green hydrogen plant (Alkaline). A greenfield plant design is made, excluding 380kV transport and hydrogen backbone.

Figure 5 and 6 schematically show modular designs for Alkaline and PEM plant configurations. The figures illustrate how large numbers of electrolyser stacks are grouped with shared transformer-rectifiers, separators and gas treatment.

There are differences between Alkaline and PEM as PEM requires more electrolyser stacks and no compressors.

The state-of-the-art 1 GW green hydrogen plant is visualised in an artist impression for Alkaline technology in figure 7.

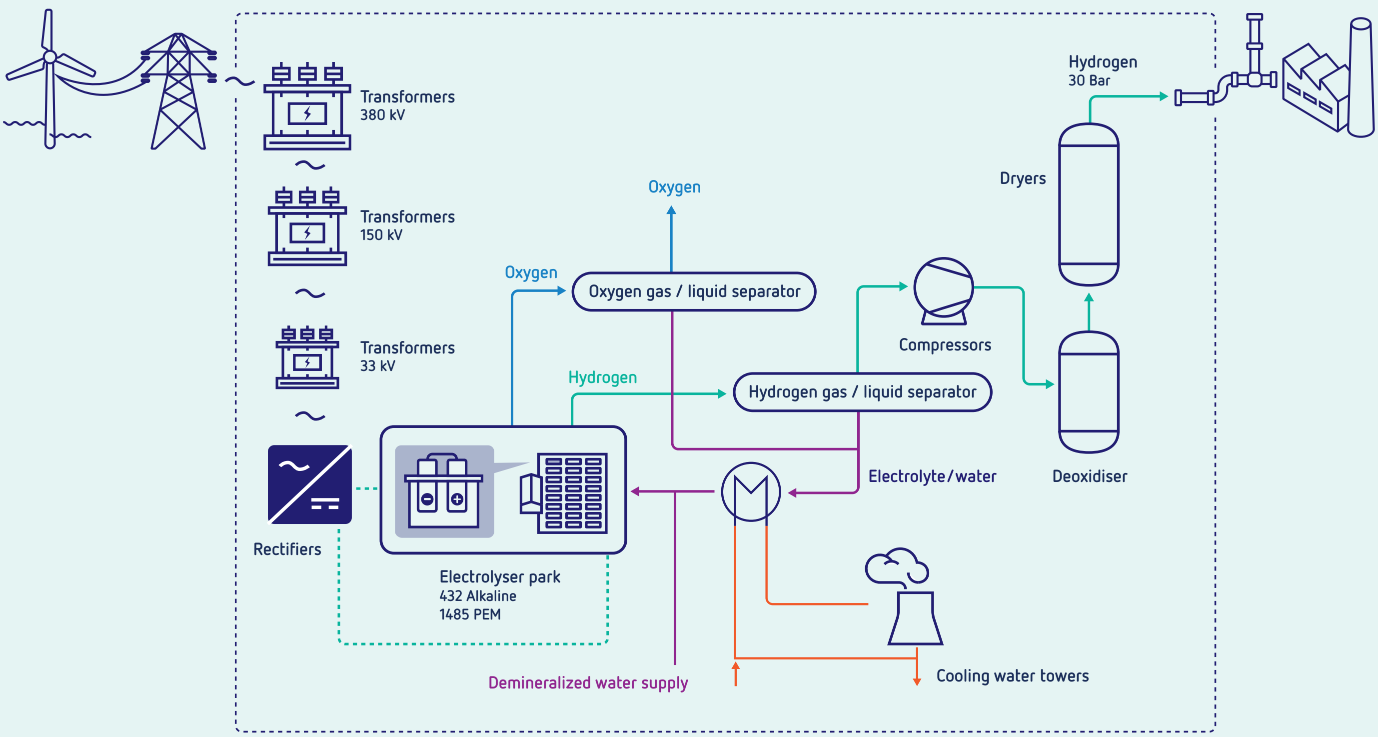


Figure 4: Block diagram GW green hydrogen plant

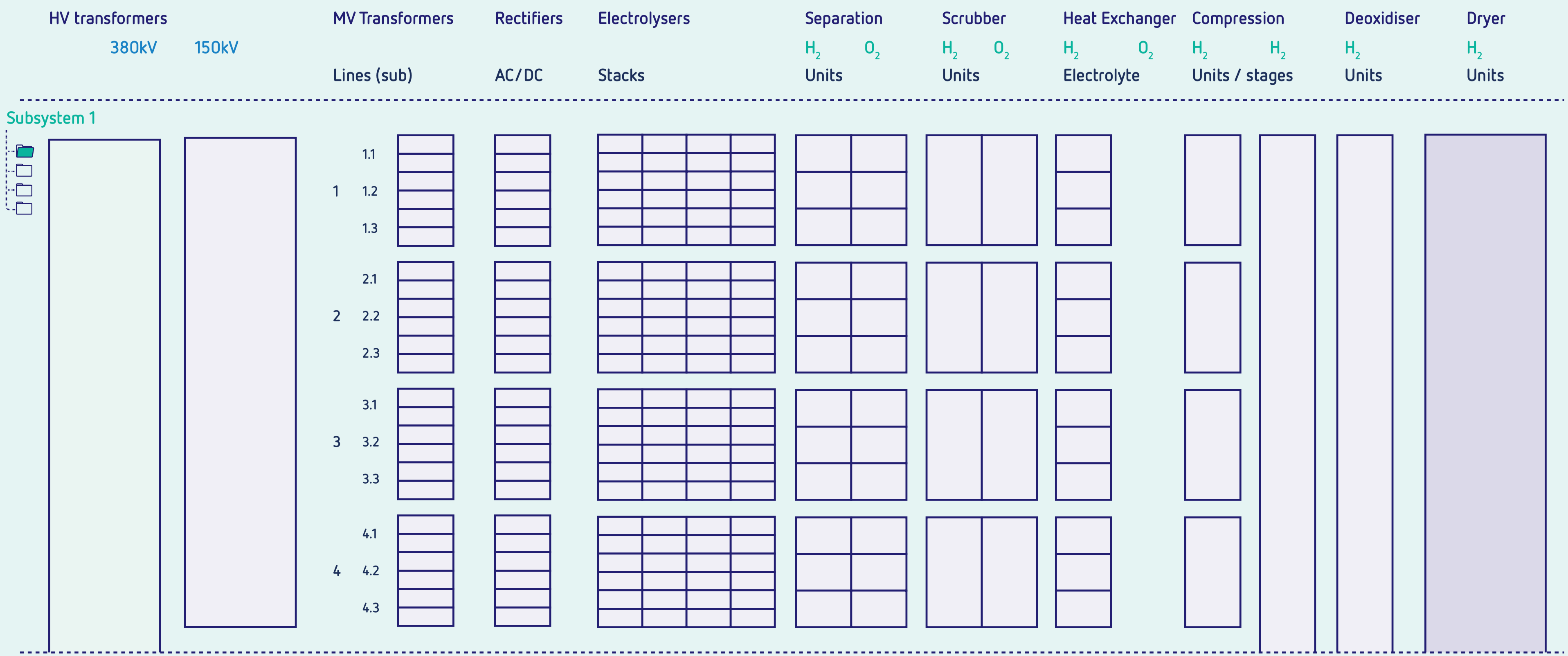


Illustration of typical modular design for Alkaline technology. One subsystem represents 25% of the full configuration.

Figure 6: Illustration of typical modular design for PEM technology. One subsystem represents 25% of the full configuration

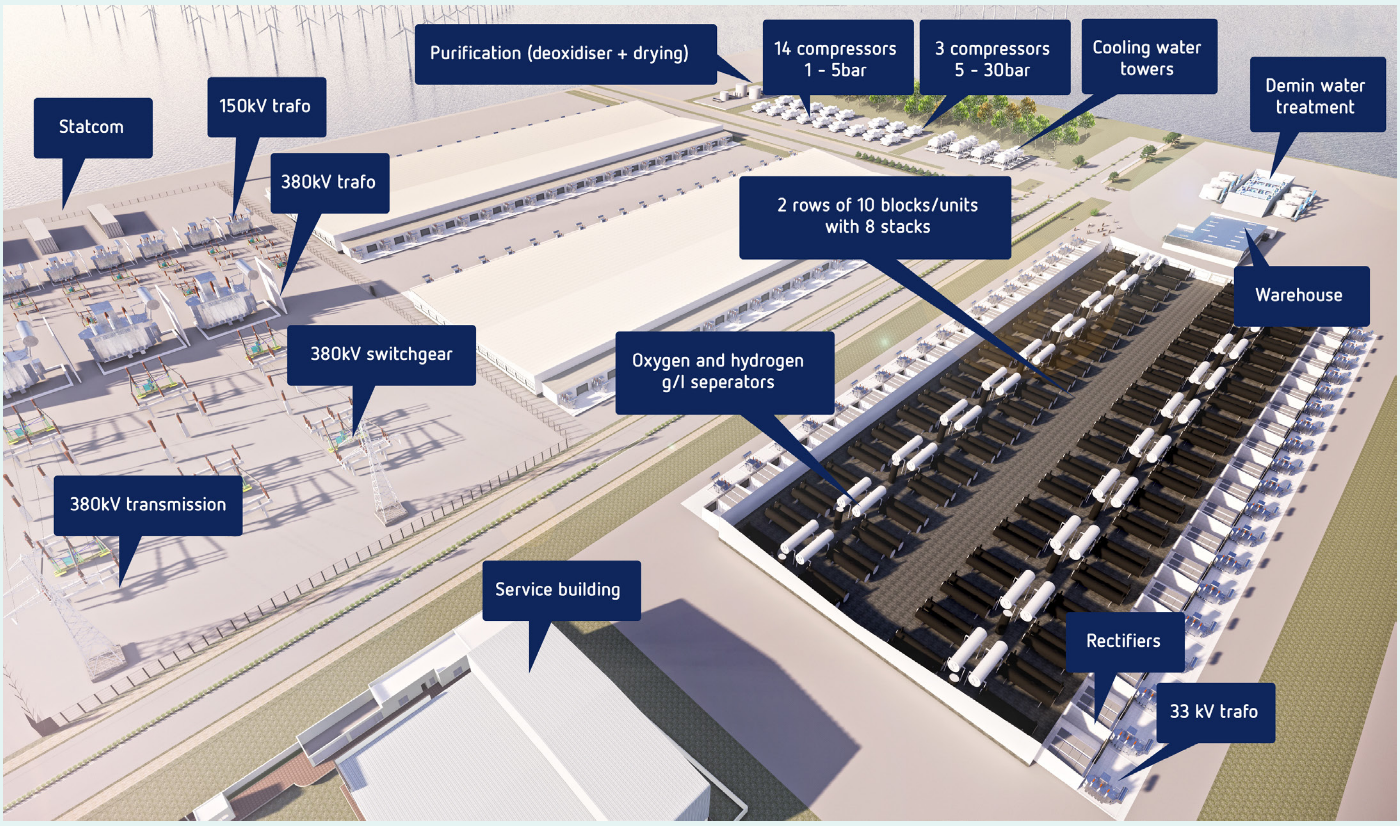


Figure 7: Artist impression of a state-of-the-art 1 GW green hydrogen plant based on Alkaline technology

State-of-the-art GW green hydrogen plant

The baseline design comprises the following areas, which are described here.

- **Electrical installations**
  Electrolyser stacks operate at low voltage and use direct current (DC). Connecting them to the national electricity grid of 380 kV thus requires high voltage power transformers and switchgear in three steps (380/150kV; 150kV/33kV and 33kV/1kV). Rectifiers are needed to convert the alternating current (AC) of the grid to direct current (DC) and to control the power quality. This is also called power electronics.

- **Electrolyser equipment**
  The Alkaline or PEM electrolysers split water electrochemically into hydrogen and oxygen. The stacks are connected to the DC supply and downstream gas-liquid separators. For Alkaline we need 432 stacks and for PEM this is 1485 stacks to meet 1GW capacity. Alkaline uses electrolyte, which is water/KOH solution, whereas PEM uses pure water.

- **Gas separation, compression and gas treatment (balance of plant)**
  These sections are often referred to as Balance of Plant. Gas-liquid separation units separate the hydrogen and respectively oxygen from the liquid, which is recirculated and cooled using heat exchangers. Compressors are needed to lift the hydrogen pressure to grid pressure. Gas treatment consists of deoxidisers to remove traces of oxygen from the hydrogen, and drying equipment to remove traces of water. The interconnecting piping between electrolysers and separators and piping to and between compression stations and purification is included here. We calculated 54 hydrogen gas-liquid separators and 54 oxygen gas-liquid separators for Alkaline. For PEM we counted 99 oxygen gas-liquid separators and equal number for hydrogen gas-liquid separators but these are much smaller in size.

- **Utilities**
  These ensure availability of consumables and auxiliaries that are necessary for continuous operation. This includes, amongst others, a demineralised water plant, cooling water towers, piping and connections for water intake and discharge, instrument air, nitrogen. Also interconnecting piping for utilities to other areas is included.

- **Process automation and safeguarding**
  These systems ensure a managed and safe operation and include equipment for process control and automation, safety management and ICT installations.

- **Buildings, foundations and underground infrastructure**
  Electrolysers, separators, heat exchangers, pumps, as well as rectifiers are installed indoors. Purification and compression equipment are installed outdoors. All necessary foundations, base plates, sewage/drainage and platforms and structural steel are part of this area. Also, a service building with the control room and warehousing is included.

Cost estimating principles

A bottom-up cost estimate for realising a 1GW green hydrogen plant has been prepared following common practices in the chemical industry. Each of the expert teams provided a design document defining the scope based on deliverables, like heat and material balance, drawings and sized equipment lists. Based on these specifications a cost estimate of the required capital expenditures for the equipment supply was made. Costs for installation, mounting and erection on site were added as well as indirect costs and contingency using multipliers. This leads to the estimate for the total installed costs, which is used for financial investment decisions. The breakdown is as follows:

- **Direct costs**
  This comprises all expenses for supply of equipment of the scope items mentioned earlier and installation, mounting and erection on site, including interconnecting piping and all materials and services from contractors and suppliers.

- **Indirect costs**
  These consist of, amongst others, expenses for engineering, project management, construction supervision and management, and commissioning costs. Also 10% allowances to cover (known) uncertainties, e.g. in amount of materials and prices, have been applied over direct costs.

- **Indirect owner costs**
  This refers to costs for owner project management, site supervisory teams, operator training, but also for example insurances, grid fees, electricity consumption and land lease during construction, commissioning and start-up. No price escalations are considered so the estimate is at a 2020 cost level.

- **Contingencies**
  In this feasibility phase, not all equipment, materials and installation is detailed in engineering deliverables, which means that the project definition is still at a rather low level. It is engineering practice to include contingency to cover risks (e.g. delays) and unknown scope, which lead to higher costs. Based on the achieved project definition in this study a percentage of 30% of the base estimate was applied.

Total Installed Costs

We estimate the **total installed costs of a GW green hydrogen plant** to be 1400 €/kW for a plant using Alkaline technology, and 1800 €/kW for a plant using PEM technology. When expressed in terms of hydrogen production the estimated total installation costs would be 3100 €/(kg/day) for Alkaline and 4400 €/(kg/day) for PEM technology. The use of the latter numbers is preferred, since it is based on the amount of hydrogen produced instead of the electricity input. In these numbers the difference between Alkaline and PEM is higher than the difference in capex due to the present higher efficiency of Alkaline technology.

Figures 8 and 9 provide a more detailed breakdown of the total installed costs. The figures show that, next to the stacks, the power supply and electronics and balance of plant significantly contribute to the direct costs. In the case of Alkaline technology, the capital expenditures required for each of these parts equal those for the electrolysis equipment. Also, utilities and civil costs contribute significantly. For PEM technology the contribution of electrolysis equipment is significantly larger due to the higher stack costs. Figure 10 represents the breakdown in total installed costs in case services and contingency are proportionally distributed over these parts.

Our analysis also demonstrates the relevance of incorporating indirect costs and owner cost, as these add up to approximately a quarter of the total costs. Also contingency is included to avoid unrealistic expectations in the development phase and reduce probability of overruns of project costs at execution phase.

Capex cost breakdown Alkaline technology (Million Euro)

Total Installed Costs 1400 Euro/kW

Direct costs 800 Euro/kW

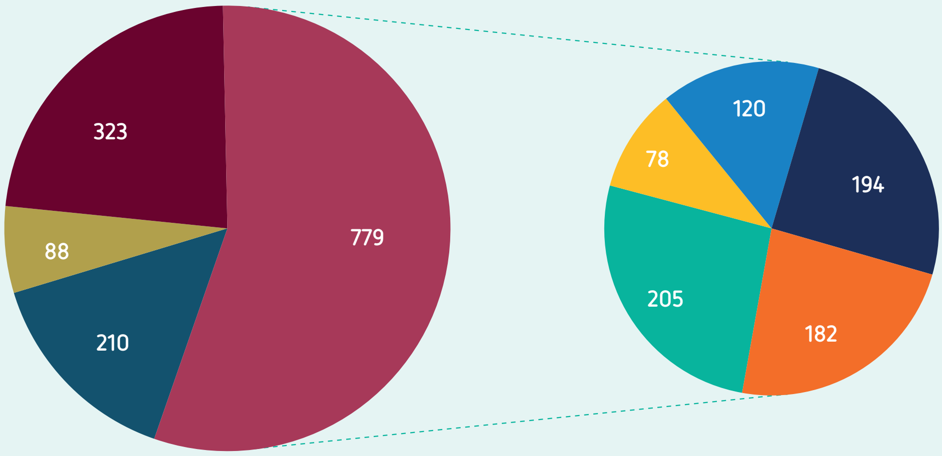


Figure 8: Breakdown of the total installed costs for 1 GW green hydrogen plant based on Alkaline technology (in Million Euro)

Capex cost breakdown PEM technology (Million Euro)

Total Installed Costs 1800 Euro/kW

Direct costs 1000 Euro/kW

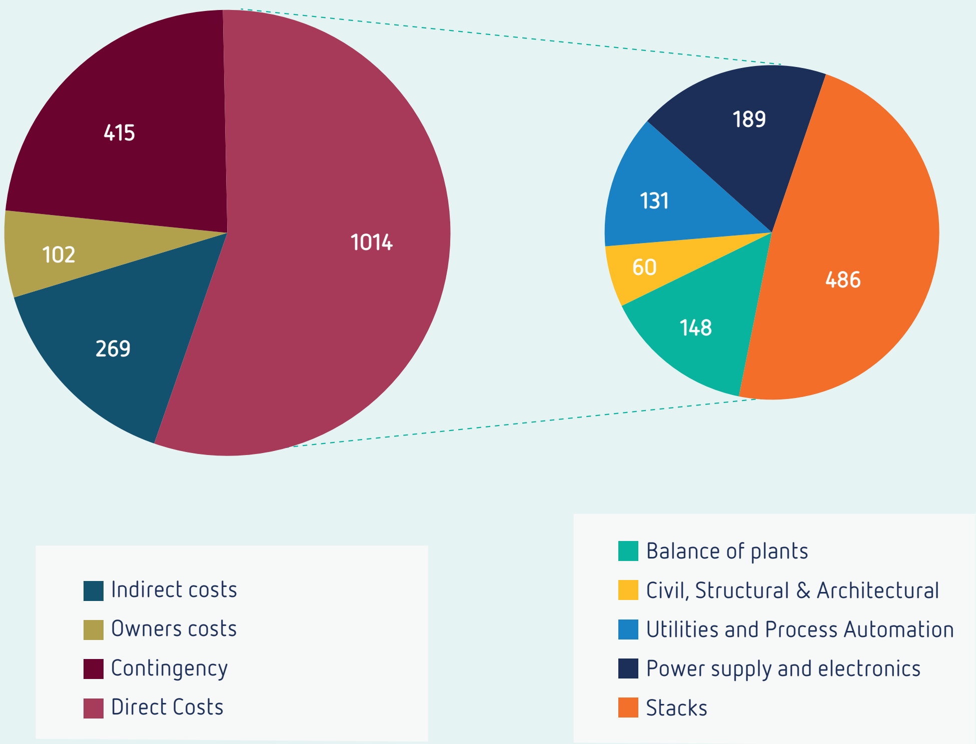


Figure 9: Breakdown of the total installed costs for 1 GW green hydrogen plant based on PEM technology (in Million Euro)

Total Installed Costs, including services and contingency

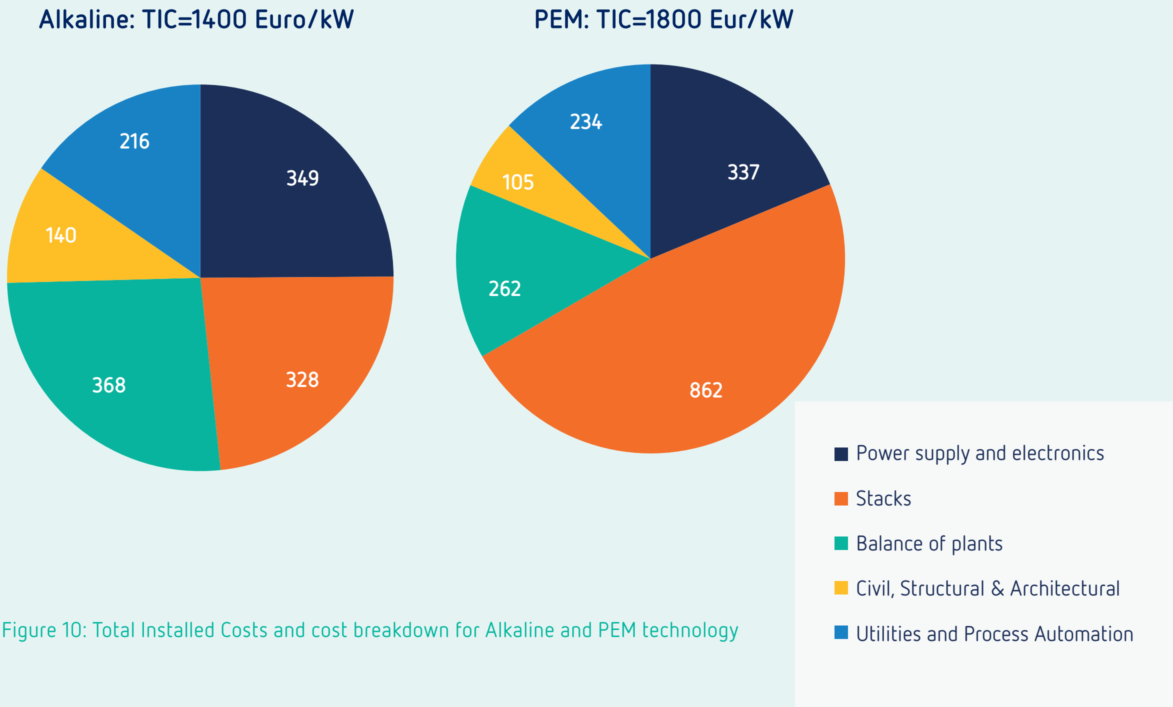


Figure 10: Total Installed Costs and cost breakdown for Alkaline and PEM technology

The accuracy of the total estimates is within a - 25% / + 40% range (complying with class IV level of the Association for the Advancement of Cost Engineering). This is primarily determined by the quality of deliverables and the level of project scope definition. The expert teams were able to calculate more than half of their equipment estimates on available figures (e.g. provided by suppliers and other sources). Where no hard data could be obtained, they took every effort to weigh and value the available information. For piping, installation, mounting and erection assumptions based on experiences have been made as is practice for this level of uncertainty.

In addition to this public report a more detailed report will be published in the course of this project providing more information and conclusions on this state-of-the-art design but also regarding advanced design of a future GW green hydrogen plant.

Other capex definitions and numbers

Besides total installed costs often other scope definitions are used for capital expenditures. This remains challenging since in many publications it is not entirely clear what is included and excluded. We are however able to put our results in perspective if we peel down our scope as follows:

- System supply: these costs comprise the supply part of direct costs and includes 33kV transformers and power electronics, electrolyser stacks and balance of plant modules. Our cost estimate is about 400-500 €/kW for Alkaline. This in the range of for example 300-600 €/kW as reported by others.[9]

- System supply and installation, these are direct costs but can still vary depending on size and scope. In our cost estimate, the numbers are about 600 €/kW for Alkaline technology and 900 €/kW for PEM technology in case civil and high voltage substations are excluded. Similar values have been reported. [10/11]

- EPC costs, these are direct and indirect costs but excluding owners costs and contingency, and which still can vary depending on size and scope. Our numbers for direct and indirect costs are 1000 resp. 1300 €/kW for Alkaline and PEM. No relevant references for EPC costs have been found.

Regarding system supply (and installation), the capex estimates of this study are in the ballpark with above reference numbers based on similar scope of supply. Concerning EPC, also civil, utilities and indirect costs need to be included. To these costs, owners costs and contingency should be added for total installed costs to cover all costs for the end-user or investor.

[9] https://www.hydrogeneurope.eu/sites/default/files/Hydrogen%20Europe_2x40%20GW%20Green%20H2%20Initative%20Paper.pdf

[10] RM01 - Electrolysis , Hydrogen Europe, June 2020.

[11] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_Hydrogen_from_renewable_power_2018.pdf

Conclusions

This study describes the total installed costs of a gigawatt green hydrogen plant. It provides a complete and realistic picture of the capital expenditures required for building such a plant, powered by wind energy, and ready to provide green hydrogen to industrial end-users.

For 2020, we estimate a total installed cost of 1400 €/kW for Alkaline electrolyser technology and 1800 €/kW for PEM technology. The study shows that the power supply and electronics, balance of plants, and civil and utilities contribute to the total installed costs in a comparable way as Alkaline electrolyser stacks. For PEM however, the electrolyser stack costs are higher than for Alkaline and equal the sum of mentioned other areas. Furthermore, we have demonstrated the importance of incorporating indirect costs, owner cost and contingency for end-users. These costs are often not reported but need to be taken into account from investment point of view. In case other (scope) definitions are used, like only direct costs for system supply and installation, our cost estimates are in line with reported values.

This baseline design and costs estimate provides the reference level for the next phase of this project to reduce capex and levelised costs of hydrogen.

Follow-up

A preliminary outlook on potential cost reduction was already made during engineering and compilation of cost estimates. This suggests that many incremental cost savings, see for example below, can add up potentially to a cost reduction with a factor 2. Further validation of this number is still needed. Yet even this factor 2 is unlikely to be sufficient to make green hydrogen competitive.

We also started investigating opex to improve levelised costs as the electricity costs are clearly an important cost driver too. Improvements can be achieved for example through optimising electricity costs through developing operating models but also co-siting opportunities and creating revenues (e.g. oxygen) and efficiency improvements.

Therefore, there is a need for breakthrough innovations, business models and technologies to further reduce levelized costs of hydrogen.

First ideas for capex reduction are:

- Minimizing the transformation steps, applying active control of rectifiers.
- Innovating electrolysers through increasing current densities, increasing efficiencies, lowering use of catalyst materials, using higher pressure and temperatures, scaling up unit sizes, reducing stack replacement costs.
- Considering different assembly and construction methods going for example to stick-built equipment instead of modules.
- Increase the number of stacks per gas-liquid separator.
- Developing a new range of high-volume hydrogen compressor units.

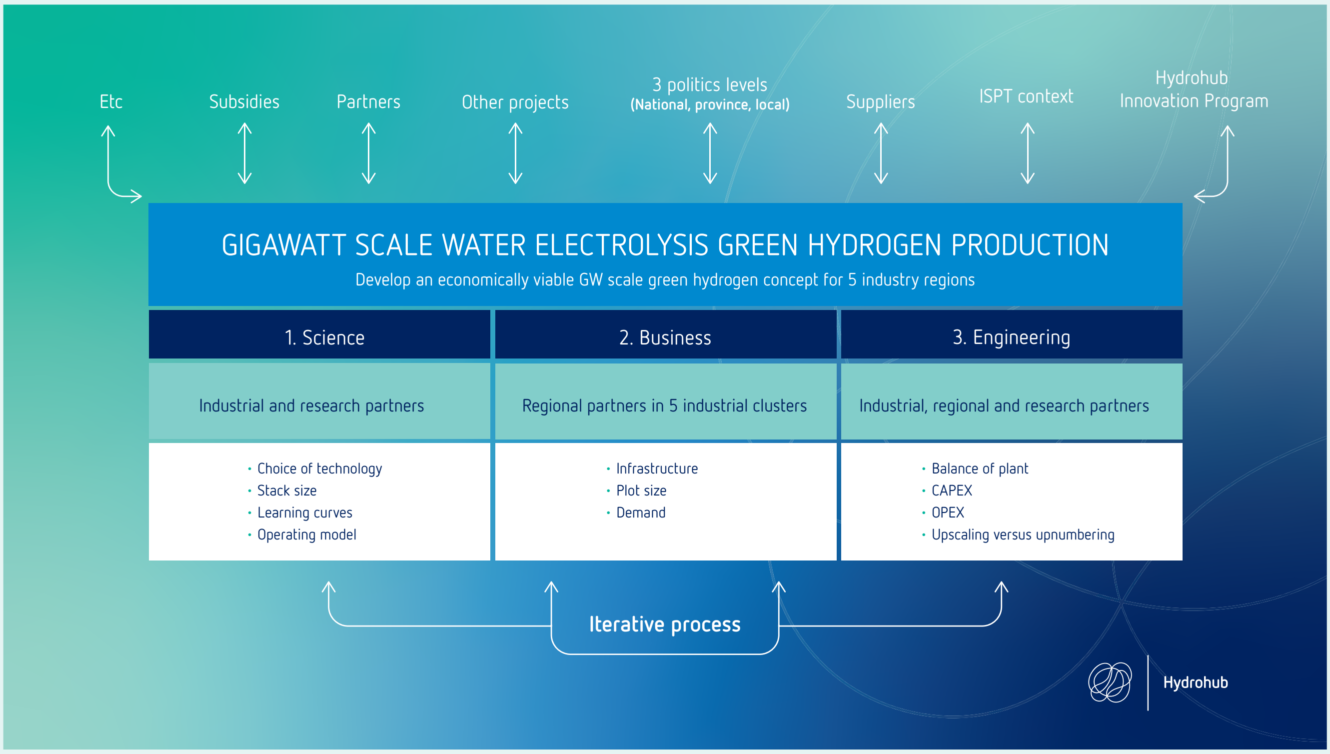
These and other ideas are being followed-up in the project with experts from industry, engineering and academia, but also require stakeholder involvement and especially input and feedback from suppliers. The results will be shared with you in a next public report in 2021.

The GigaWatt Scale Electrolyser project is part of the Hydrohub Innovation Program

The Institute for Sustainable Process Technology (www.ISPT.eu) is an open innovation network for the process technology community to support the development of sustainable processes. The GW electrolysis project is part of the **Hydrohub Innovation Program** aiming at supporting the development of green hydrogen at scale for industrial use.

The **Hydrohub GigaWatt Scale Electrolyser project** consists of 3 parts, see infographic below. This project focuses on the upscaling and upnumbering of electrolysers to a GW facility, and optimizing system design including electrical installations and balance of plant.

This study of the baseline economics is supporting the engineering part 3. Together with the results from the scientific part 1 and business part 2, its results will be used as input for further design development to an economically viable GW green hydrogen facilities in five industry regions.



Colophon

Title

Baseline design and total installed costs of a GW green hydrogen plant

Subtitle

State-of-the-art design and total installed capital costs

Publication date

October 26th, 2020

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Published by

Institute for Sustainable Process Technology (ISPT)

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About this report

This report was prepared by ISPT in close cooperation with partners. The study was performed by ISPT and partners. The Hydrohub GigaWatt Scale Electrolyser project is managed and coordinated by E4U Projects and Ekinetix on behalf of ISPT.

This report can be found online at https://ispt.eu/projects/hydrohub-gigawatt/

The Hydrohub GigaWatt Scale Electrolyser project

The Hydrohub GigaWatt Scale Electrolyser project is initiated by the Institute for Sustainable Process Technology (ISPT) and is part of the Hydrohub Innovation Program. The study has been done in close cooperation with partners:

- DOW
- Gasunie
- Nouryon
- OCI Nitrogen
- Ørsted
- Yara

and

- Imperial College London
- TNO
- Eindhoven University of Technology
- Utrecht University

PUBLIC FUNDING

This project is co-funded by TKI Energy and Industry with the supplementary grant 'TKI-Toeslag' for Topconsortia for Knowledge and Innovation (TKI's) of the Ministry of Economic Affairs and Climate Policy.

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