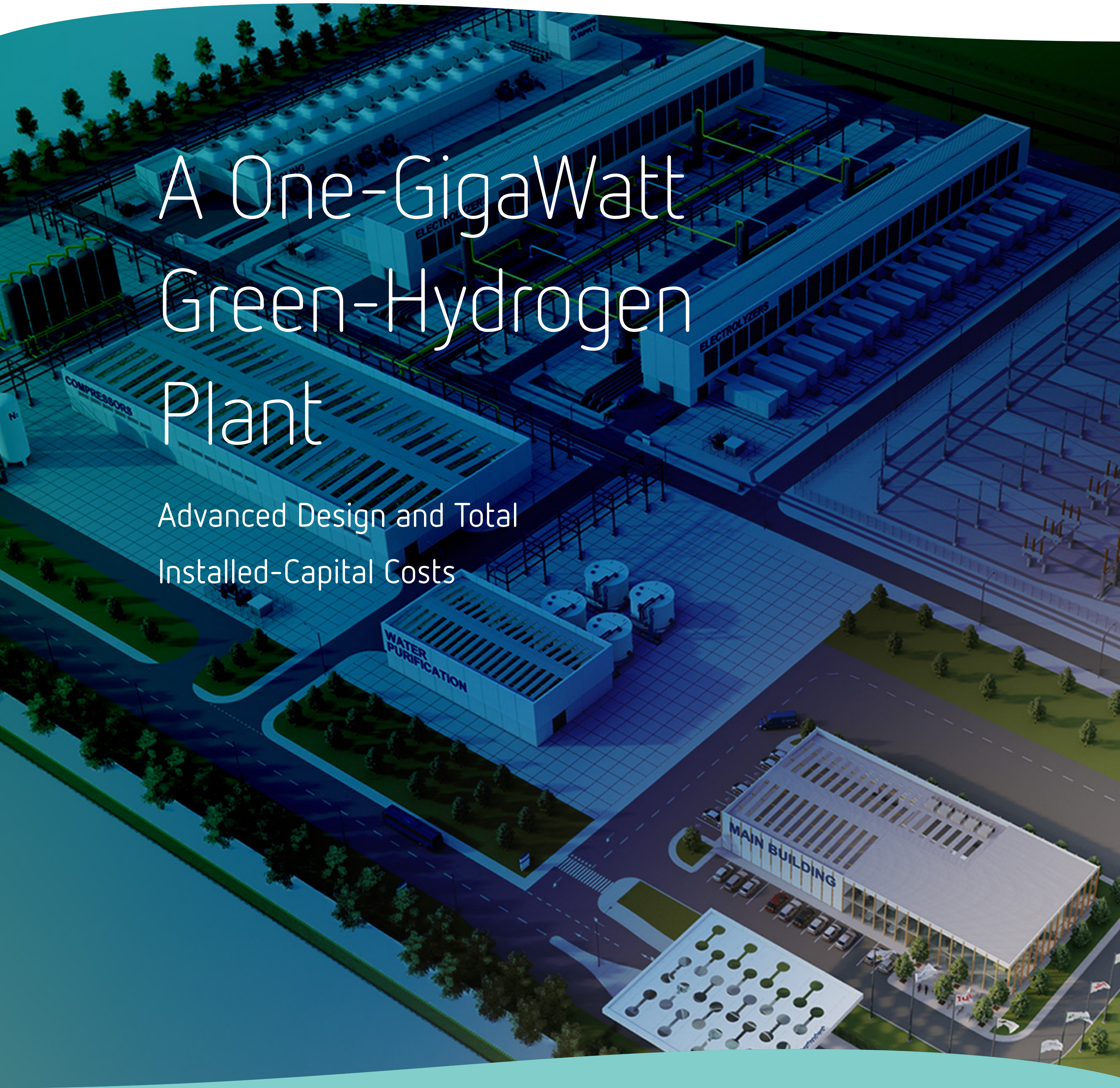
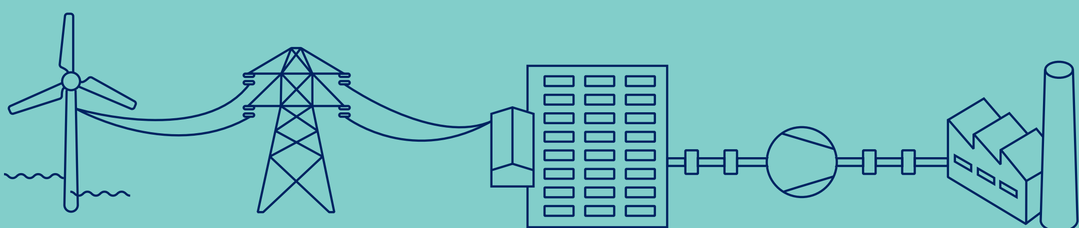
Public report

Hydrohub Innovation Program



A One-GigaWatt Green-Hydrogen Plant

Advanced Design and Total Installed-Capital Costs



Authors' acknowledgements

The execution of this advanced GW green-hydrogen project was a team effort, and it has taken us two years and a lot of virtual meetings to produce the present report. We would therefore like to express our special thanks to the following individuals from ISPT, and from our partner and stakeholder organizations, who have made such important contributions to the design, the results, and the benefits we have seen.

Contributors from our industrial partners are Dow Chemical (Kees Biesheuvel and Tom Dierickx); Frames (Eddy van Oort); Gasunie (Udo Huisman and Rienk Zwerver); Nobian (Michiel de Beer, Thijs de Groot, Paola Granados Mendoza, Karla Ribeiro da Costa, and Jan van de Wetering); OCI (Ruud Swarts); Ørsted (Steen Torpe Christoffersen, Katrine Andersen Elsøe, Nick van der Kolk, Thomas Herskind Olesen, and Sandor Schrameyer); and Yara (Dirk Blomme, Niek de Koster, Jacky de Letter, Bart Roman, and Johan Thoelen).

The universities and knowledge institutes we have partnered with are: Utrecht University (Anand Krishnan, Vinzenz Koning, and Gert Jan Kramer); Eindhoven University of Technology (TU/e) (Tamoor Ali, Pascal Etman, Gijs Herings, Xu Chen, and Yang Dongshen); Imperial College London (Nathanial Cooper, Nilay Shah, and Mahdi Sharifzadeh); and the Netherlands Organisation for Applied Scientific Research -TNO- (Arend de Groot and Stef Booij).

The team at ISPT was made up of Lia Bouma, Andreas ten Cate, Christa de Ruyter, and Carol Xiao.

We also would like to thank the following suppliers for their valuable input to the advanced design and the cost estimate: Alfa Laval, Baker Hughes, Burkhardt, Ekinetix, Exotech, GE Grid Solutions, Hamon, Howden Thomassen, Ingeteam, KAPP, KSB, MAN-ES, NEUMAN & ESSER, Richter Chemie-Technik, Siemens Energy, TenneT, SRI, and VDL.

Special thanks to Thijs de Groot for his inspiring input and support, and to Arend de Groot and Gert Jan Kramer for their help with drafting and other contributions.

– Hans van 't Noordende and Peter Ripson

Foreword by Nienke Homan GH2 (Green Hydrogen Organisation)

Seen in historical terms, it is not that long ago that humankind made the transition from using the energy that was readily available by chopping wood from trees to putting in a lot of effort to get coal, oil and gas from the ground.

We scaled up the use of energy. Having previously used firewood to warm ourselves and cook our food on a small scale, we started using coal, oil and gas to do the same thing for entire communities. Over the past century, we have learned to use oil and gas to create more prosperity for all. We have invested in infrastructure and machines, and have really got used to energy's being constantly available. Some of us still remember the times without a constant supply of energy, but most of us kind of panic even at the idea of not having energy available 24/7.

And now we are going to scale things up again. But this time we don't have a century for that change. Climate change is forcing us to move fast. Instead of a hundred years to organically grow and improve, we have just eight short years to dramatically turn the tide. EIGHT! But don't panic: We have infrastructure. We have the expertise and the know-how required.

And we have to deliver by 2030. There have been years when people doubted the feasibility of the energy transition, of a carbon-neutral economy, of the role of green hydrogen in the energy system. Several arguments were put on the table. But they did not stay there long.

The beauty of the energy transition, and in particular of green hydrogen, is that it has brought together sectors such as industry and knowledge institutes. And that's what makes things so different from a hundred years ago. This report is an example. It shows that we can scale up.

We can in fact meet the 2030 deadline—and meet it we will.

– Nienke Homan

Summary

Green hydrogen can replace natural gas as an energy carrier and industry feedstock to reduce CO_2 emissions. This transition requires economies of scale with the production of large volumes of green hydrogen in many large-scale water-electrolysis plants. These plants will be powered by large wind and solar parks that will have to be built within the next ten years. The goals here are really ambitious. The European Union (EU) aims to have 40-GW of electrolyzer capacity installed by 2030, while the ambition in the Netherlands is to have built green-hydrogen plants with a combined capacity of 3 to 4 GW by that date. The largest existing electrolyzers are at the 10-MW scale, whereas scaling up to GW scale is needed at acceptable cost levels.

The Hydrohub GigaWatt-Scale Electrolyzer project has produced an advanced design for such a 1-GW green-hydrogen plant, which would use alkaline water electrolysis (AWE) and polymer electrolyte membrane (PEM) water electrolysis, and which could start up in 2030. This advanced design builds on a previous state-of-the-art 2020 baseline design,[1] and foresees a considerable drop in investment costs (CAPEX). Consequently, the levelized cost of hydrogen (LCOH) is expected to come down in the lead-up to 2030, and to continue its decline thereafter. Still, more needs to be done to create a competitive green-hydrogen market.

We present **the technical design and the associated total investment costs of a greenfield 1-GW green-hydrogen plant** that would be built, and up and running, in a Dutch port area by 2030. This project shows that anticipated total investment cost levels of 730 €/kW or 1580 €/(kg/d) for AWE and 830 €/kW or 1770 €/(kg/d) for PEM are within reach. The CAPEX required will be about half of what would be required for the 2020 state-of-the-art design. To come to this cost reduction, several improvements have been made to the state-of-the-art 2020 design—see Figure 3. We incorporated innovations at the stack level, scaling up to larger stacks and modules, and came up with optimizations for, and other improvements to, the electrical installations, utilities, and balance of plants.

The scope of this technical design comprises all equipment and services required to connect to a 380-kV transport grid that will supply wind power from the North Sea and a pure hydrogen delivery point (30 Bara). The plant includes electrical installations for transformation and rectification, electrolysis (stacks), purification, and compression. The plant is designed to operate flexibly according to a wind profile, grid-balancing services, and end-user demand. Furthermore, the design complies with the grid code and health, safety, and environmental requirements.

The plant has the following technical specifications. A cost-effective electrical layout was prepared. It comprises 380 kV and 66 kV transformers and large semi-conductor active control (insulated-gate bipolar transistor, IGBT) rectifier units meeting (future) grid requirements. Each transformer-rectifier is delivered as self-contained e-houses, thereby ensuring a compact design.

Total Installed Costs AWE 730 €/kW **1580 €/(kg/d)**

Direct Costs 420 €/kW

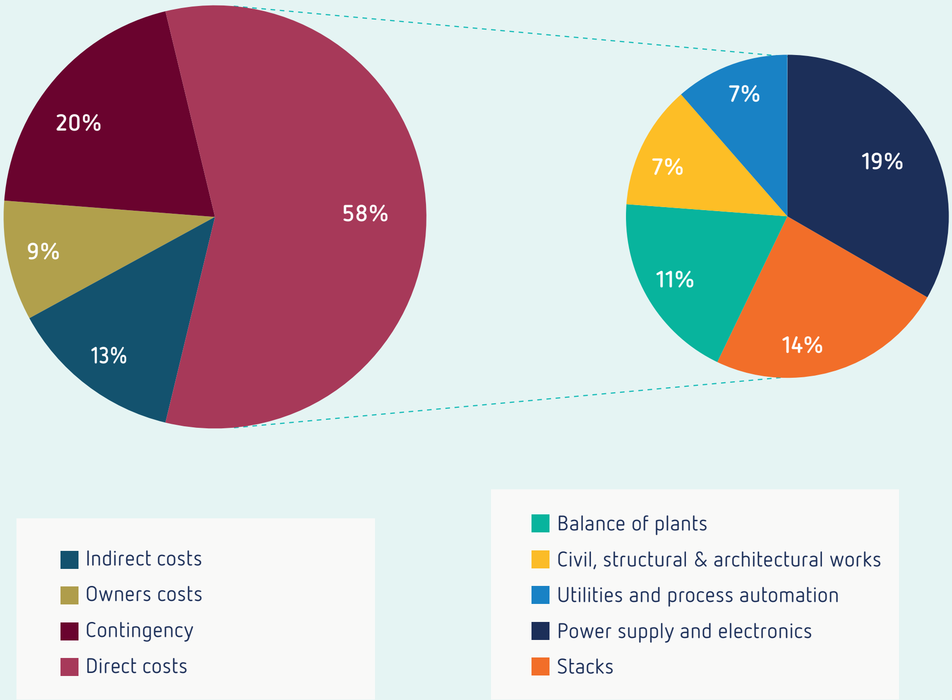


Figure 1: Breakdown of total installed and direct costs for AWE

Total installed costs PEM 830 €/kW **1770 €/(kg/d)**

Directs costs 450 €/kW

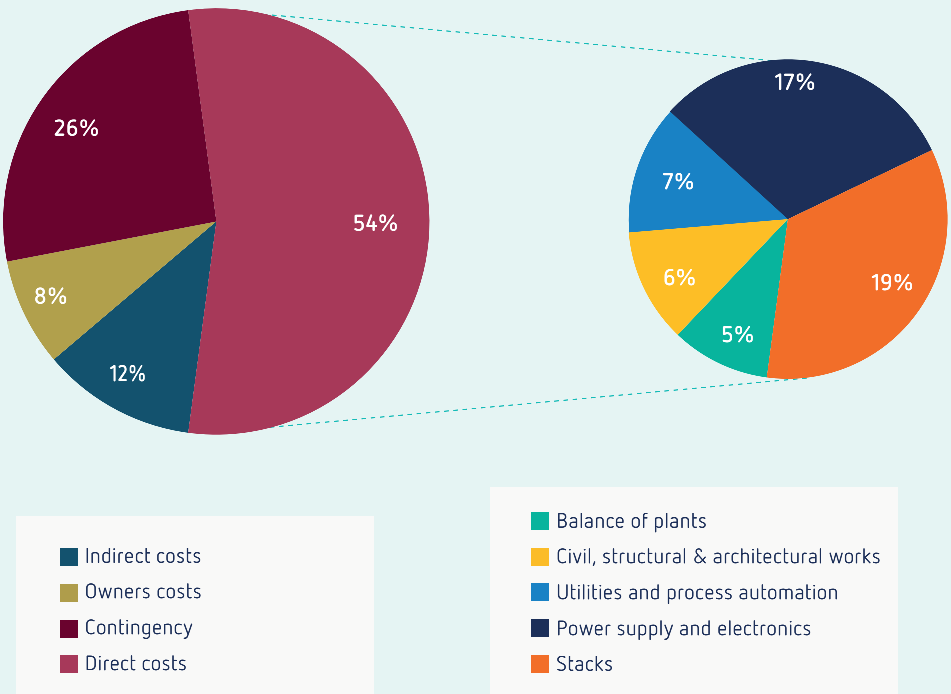


Figure 2: Breakdown of total installed and direct costs with PEM water electrolysis

The novel AWE electrolyzer stack is a large 20 MW stack with 335 cells. It operates at a high current density of 1.3 A cm^{-2}, and uses non-noble electrodes, at a temperature of 100° C. The novel PEM electrolyzer stack is a 10 MW stack with 310 cells. It has a current density of 3.5 A cm^{-2}, and uses improved membrane and electrode materials and low-iridium anodes. The stacks are electrically connected to rectifiers, and arranged in modules of 160 MW for AWE and 40MW for PEM, with improved gas-liquid separators. For AWE, the operating pressure is 5 Bara based on operational, safety, and economic considerations, and this requires mechanical compression to 30 Bara. As for the PEM technology, the hydrogen is already at 30 Bara, so no additional compression is needed. The efficiency of the system is thus slightly higher for PEM than for AWE, assuming 80% stack efficiency for both. The cooling water system design is heat recovery ready, meaning that large volumes of heat (> 130 MW at full load) can potentially be supplied to a district heating network. The plot size is about 10 ha for both technologies.

Substantial cost reductions can be achieved by incorporating the anticipated technology improvements. Many more R&D projects, pilots, and demonstration projects will be needed in order to make this happen. However, time is short. The required technologies must be commercially available in 2026 in order for a financial investment decision (FID) to be made in 2028 and for commercial operations to begin in 2030. This means that the development cycle that must bring the proposed innovations to a mature level can be longer than four years.

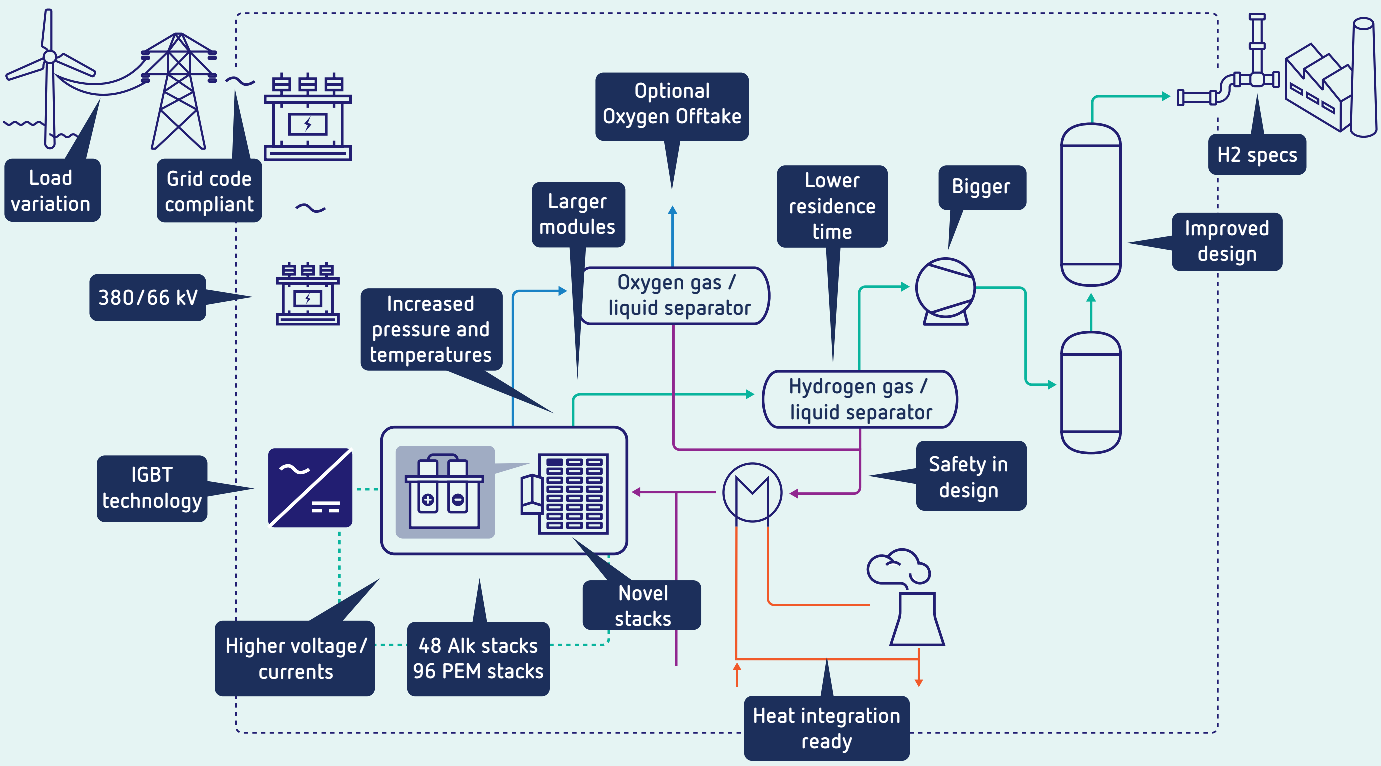


Figure 3: Main optimizations for the advanced design of a 1-GW green-hydrogen plant based on AWE technology

Table of content

Introduction

There is a great sense of urgency around the need to scale up green hydrogen as a renewable feedstock and energy carrier. The aim of the European Commission is to reach 40GW of installed electrolyzer capacity in the EU by 2030. But green hydrogen is still too expensive to be a feasible alternative, and will be for quite some time. We need to reduce the investment costs in the lead-up to 2030 by coming up with and carrying out innovations, and by scaling up the hydrogen production plants. In this report, ISPT presents the facts and figures regarding reducing the potential CAPEX required for a 1-GW green-hydrogen plant that would be commissioned in 2030.

Green hydrogen can replace natural gas as feedstock for the industry and energy carrier to reduce CO_2 emissions. This transition requires large volumes of green hydrogen produced by many GW-scale water electrolysis plants powered by wind and solar power. The Fit-for-55 package[2] from the European Commission calls for the creation of 40 GW of installed electrolyzer capacity by 2030. In the Netherlands, the ambition is to have built 3 or 4 GW of green-hydrogen plant capacity by 2030. But in fact, that number needs to be doubled to meet the EU's ambitious Fit-for-55 goals.[3,4,5] The Dutch and European goals are really ambitious, but green hydrogen is still too expensive at the moment to be a feasible alternative, and will be for quite some time.

These ambitions are not simply "political" or aspirational. In recent years an increasing number of activities have been undertaken to develop the hydrogen economy. Initiatives have been announced to realize 100 MW (or larger) green-hydrogen projects to make the ammonia, steel, and jet-fuel industries more sustainable. These projects are expected to be operational in 2024.[6,7,8] The national gas grid operator Gasunie is working on the creation of a hydrogen infrastructure backbone for transport services. This backbone will connect five Dutch industrial clusters (Rotterdam-Moerdijk, Chemelot, Northern Netherlands, North Sea Canal Area, Zeeland) with each other—see below—with storage facilities in the Netherlands. The backbone will also connect the Netherlands to Germany and Belgium.[9]

ISPT initiated the Hydrohub GigaWatt Scale Electrolyzer project in 2018. Everyone was keen to understand what it would take to produce green hydrogen on an industrial scale. The routes by which the technology could be scaled up, and the potential involved, were unknown, and a solid cost basis was not available. The ISPT led the development and execution of the project with industrial partners Dow Chemical, Gasunie, Nobian, OCI, Ørsted, and Yara, and knowledge institutes TNO, Imperial College London, TU/e, and Utrecht University.

The project started in 2019 with regional system-integration studies of the potential for 1-GW green-hydrogen production plants in five industrial clusters in the Netherlands—see Figure 4.[10] This was followed in October 2020 by a baseline report for a 1-GW green-hydrogen plant based on state-of-the-art technology.[11] Cost estimates were given for a 1-GW plant based on AWE technology, and for another based on PEM technology. The baseline estimates assumed that one of these plants would be commissioned in 2020 as the first of its kind at that scale. The total installed costs were estimated at 1400 €/kW for AWE technology, and 1800 €/kW for PEM technology.

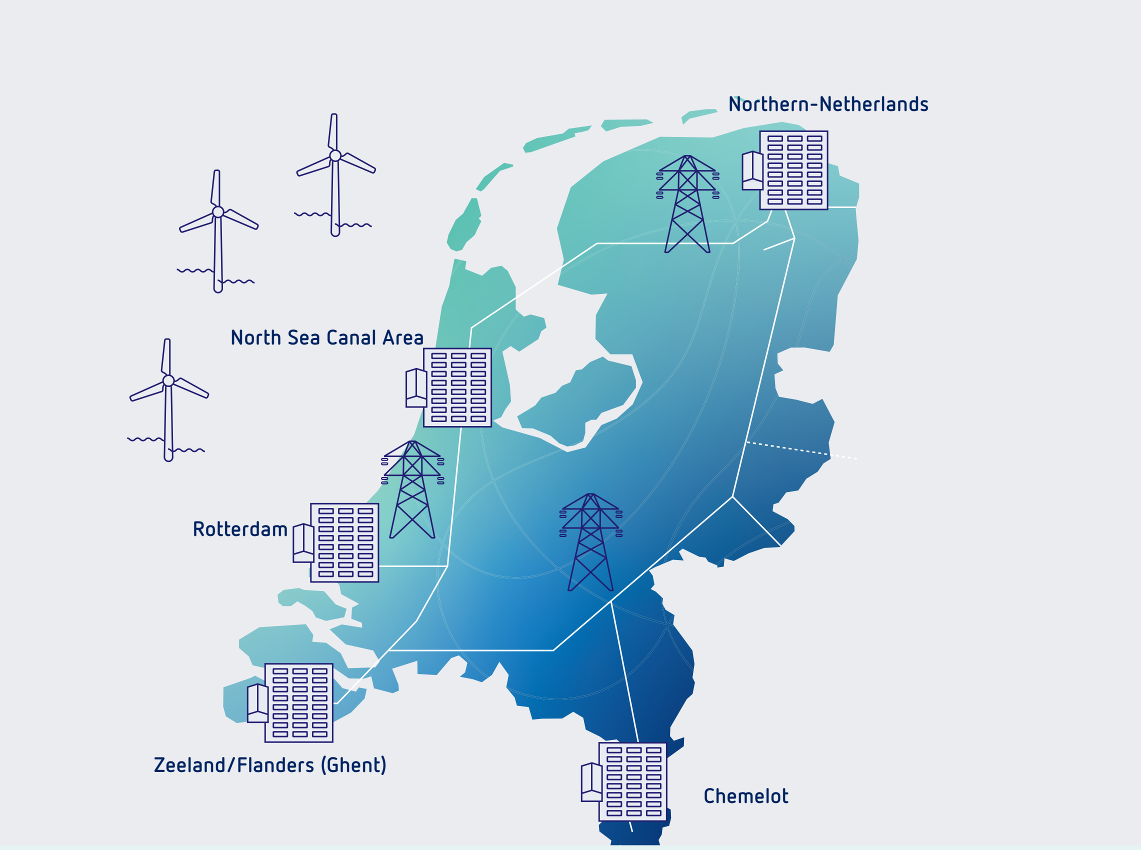


Figure 4: Potential locations for the 1-GW green-hydrogen plants in five industrial clusters in the Netherlands

The current research builds on the findings of the aforementioned baseline report and is contributing to the development of an advanced design for a 1-GW green-hydrogen plant to be commissioned in 2030. The design incorporates innovations and economies of scale through which the CAPEX and the LCOH[12] can be expected to come down in the lead-up to 2030. The design is optimized for electrical installations, electrolyzer stacks, gas treatment, and system integration. In this report we present the results with facts and figures for potential investors and stakeholders. The anticipated total investment costs are 730 €/kW for AWE and 830 €/kW for PEM. The CAPEX required will be about half of what would be required for the 2020 state-of-the-art design.

In the following sections the key assumptions informing the project, the scope of the project, the modular design for it, and the cost estimates associated with it are presented and discussed, based on a scenario in which an advanced 1-GW green-hydrogen plant is operational by 2030.

Key assumptions informing the advanced design

The advanced design is for a greenfield 1-GW green-hydrogen plant that will be built in 2030. We have defined the requirements for the design and the key assumptions informing it. The plant will be connected to a 380kV transport grid that is expected to supply wind power from the North Sea. It will operate according to typical wind patterns. It will be connected to a hydrogen backbone, to which it will deliver high-purity hydrogen to be used by customers in the process industry. Its design will include the electrolyzers with electrical installations and process units, as well as all piping, process automation, civil works, utilities, and a service building to enable stand-alone operation. For the advanced design, we took a modular approach. We subdivided the 1-GW green-hydrogen plant into smaller parts called electrical power blocks (Figure 7) and process modules (Figure 8).

The advanced design is for a greenfield 1-GW green-hydrogen plant to be built in 2030. The scope of the project with connections to a 380kV transport grid and to hydrogen infrastructure is depicted in Figures 5 and 6 for AWE and PEM technology, respectively. The scope includes the electrolyzers with electrical installations and process units as well as all piping, process automation, civil-works, utilities and a service building to enable stand-alone operation.

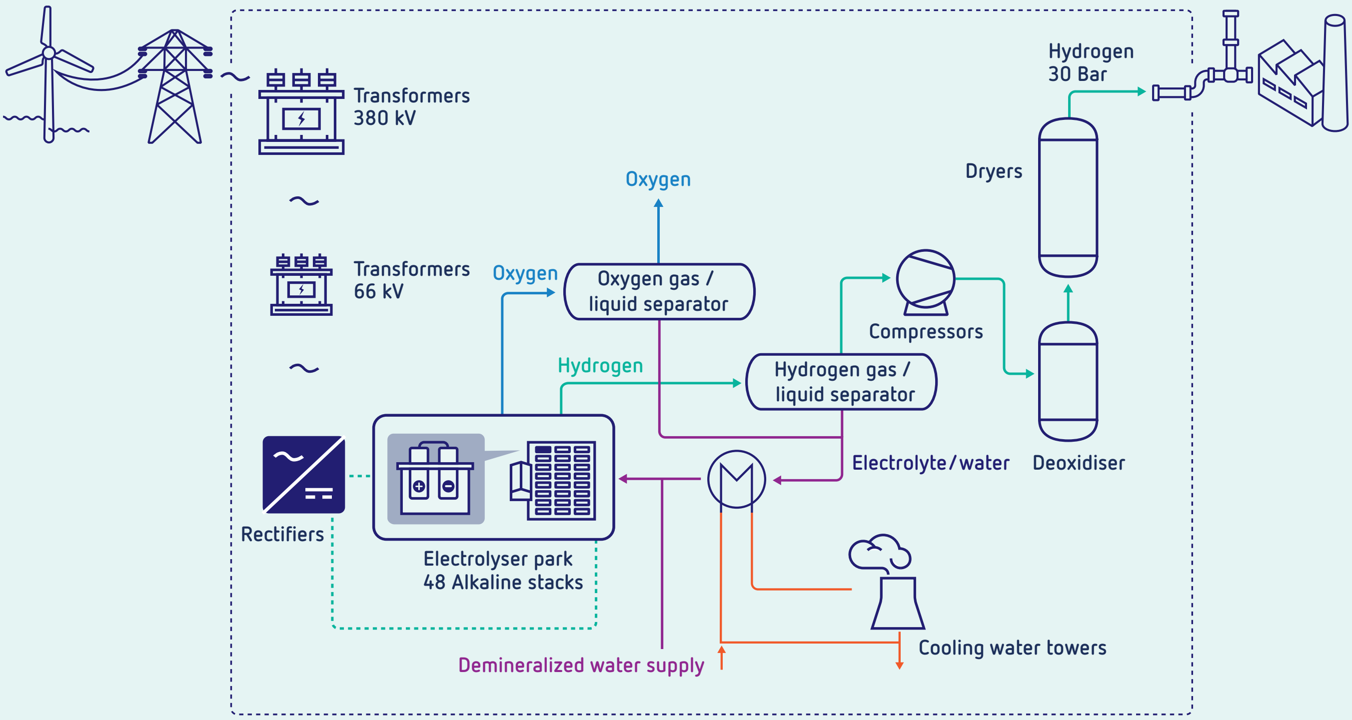


Figure 5: Scope of a greenfield 1-GW green-hydrogen plant based on AWE technology

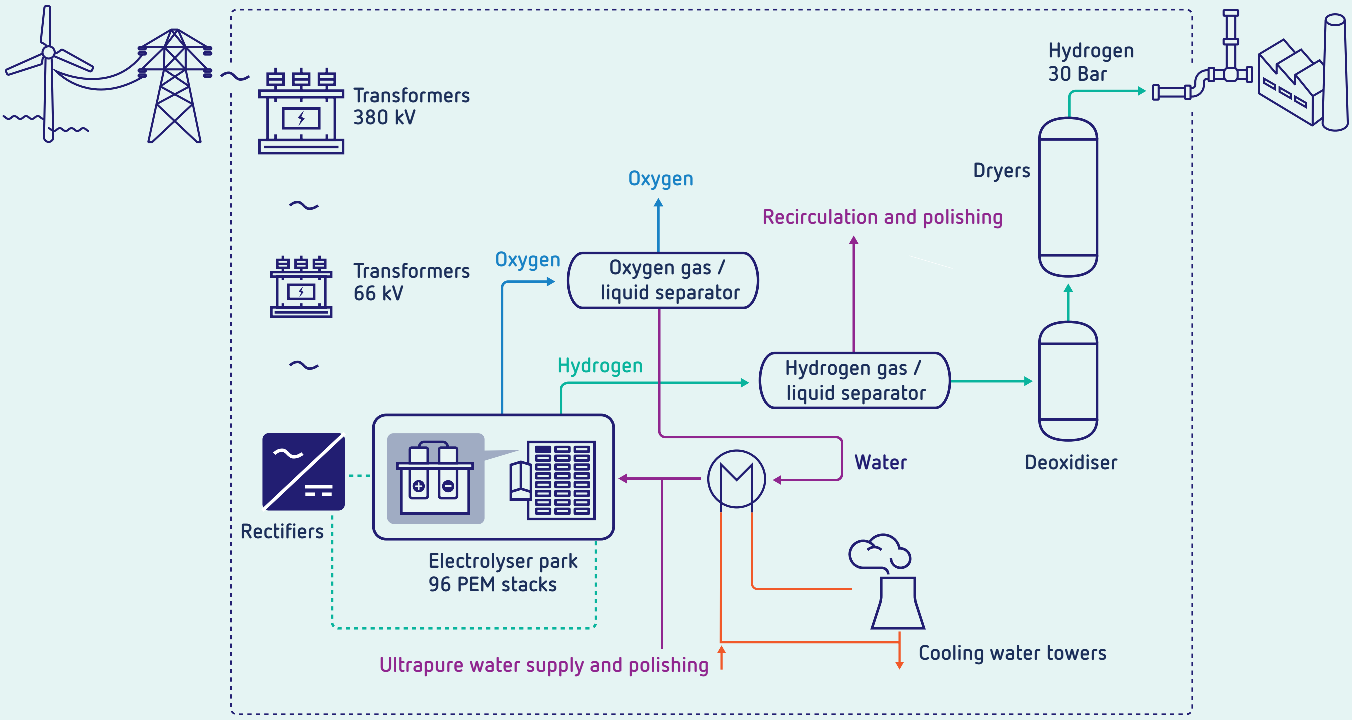
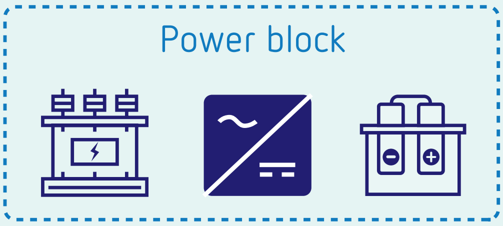


Figure 6: Scope of a greenfield 1-GW green-hydrogen plant based on PEM technology

We defined the following requirements and assumptions as starting points for the design:

- The location that has been envisaged for a 1-GW green-hydrogen plant is a heavy-industry port area in the Netherlands.
- The design complies with the grid code and with health, safety, and environmental requirements. This includes cooling water intake and discharge, heat recovery, noise, NOx, ATEX, and process, personal, and external safety.[13]
- The plant will use offshore wind power delivered at a 380 kV connection point with 1 GW of capacity, including auxiliary power consumption and electrical losses. Operating mode will be intermittent, following variations, in accordance with the typical wind profile for a wind park in the North Sea.[14] The green-hydrogen plant will be capable of taking part in frequency-balancing reserve[15] and congestion management.
- The hydrogen will be delivered to customers either directly or through a regional or other backbone, potentially including storage to accommodate base load demand from end users. The nominal hydrogen output capacity will be 19 tonnes per hour (210,000 Nm3/hr). The hydrogen will be delivered at 30 Bara pressure and 99.99% purity with a maximum of 5 ppm, by volume, of both water and oxygen.

- All oxygen produced will be vented (oxygen offtake will be optional).
- A heat-integration-ready concept will be adopted to enable heat recovery for district-heating purposes.
- Advanced AWE and PEM electrolyzer stacks will be used for electrolysis. These new-generation stacks are expected to be mature before 2030, but are not yet on the market. They have a higher power rating, because they have high-performance electrodes and components made from fewer materials, including those that are scarce.
- An approach for an inherently safety design will be needed. Process safety scenarios will be identified and assessed. Safety distances will be considered in the plan for the site, and ATEX zoning will be applied.
- Demineralized water will be produced in reverse-osmosis units based on pre-treated fresh surface water. For PEM, ultrapure water is needed with a continuous and centralized polishing of recirculated water over electrolyzers.
- The design of the 1-GW green-hydrogen plants for AWE and PEM technology is modular. We divided the plant into repetitive units for electrical installations (power block) and process installations (module). Each power block consists of transformer-rectifiers and stacks, while each module consists of stacks, gas-liquid separators, and associated equipment. See Figures 7 and 8.



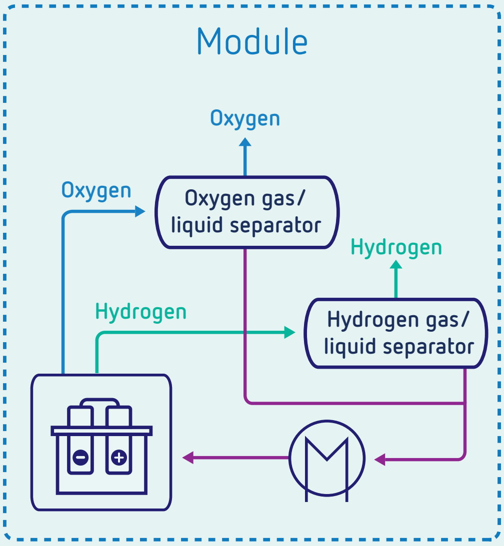


Figure 7 and 8: Power block and module

Optimisation, improvements, and innovations

In this section, we present the technical design of the 1-GW green-hydrogen plant. We show the potential cost reductions from innovations at the stack level, from optimizations in the electrical system and the balance of plant, and from scaling up to large modules.

This design is based on the state-of-the-art design of how a plant could theoretically have been built in 2020. While we were making the state-of-the-art design, it became clear to us that the main cost drivers for building a 1-GW green-hydrogen plant are not only in the electrolyzer part of the AWE and PEM technology, but also in the electrical, civil-works, and process parts of the plant. On the basis of the state-of-the-art design, we propose several innovation, optimizations, and other improvements. These developments are indicated in Figure 9 and summarized in Table 1.

Through upscaling and innovation, the number of stacks is reduced by a factor of 15 for PEM technology, and of 9 for AWE technology. The annual production rate is about 72 ktonne/a (800 M Nm^3/a) for this advanced design for both technologies. This is based on available operating hours following the wind pattern (4,000 full load h/a), required availability of 94%, and the achievement of system efficiency.

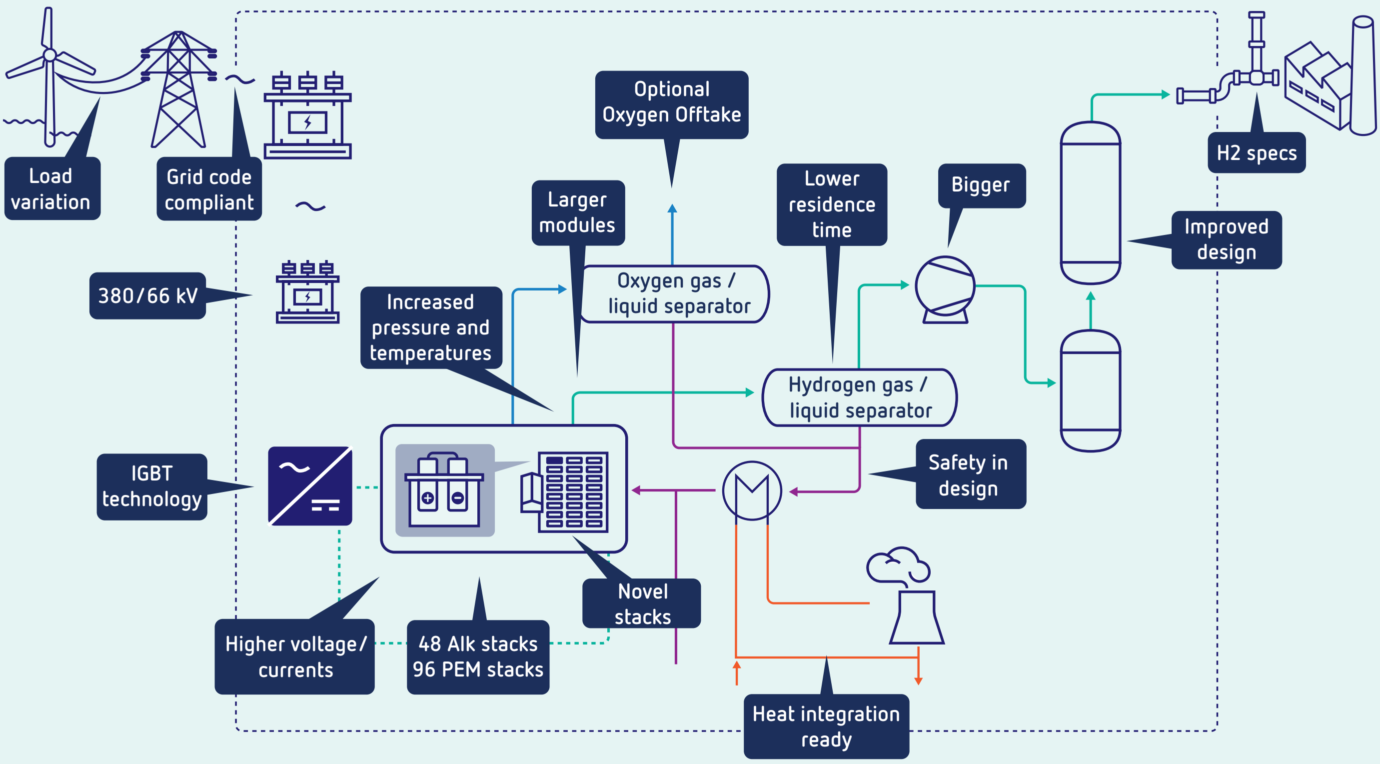


Figure 9: Main optimizations for the advanced design of a 1-GW green-hydrogen plant based on AWE technology

	Advanced Design (2030)	Baseline Design (2020)
Connection to grid	Grid code-compliant (future)	Included
Electrical system	380kV/66kV	380 kV/150 kV/33 kV
Rectifier technology	IGBT	Thyristor
Water electrolysis stack generation	Novel stack	Available stacks
Current density of AWE	1.3 A cm^{-2}	0.2 A cm^{-2}
Number of stacks of AWE	48	432
Current density AWE	3.5 A cm^{-2}	2 A cm^{-2}
Number of stacks PEM	96	1,485
Pressure electrolysis (AWE/PEM)	5/30 Bara	Atmospheric/20 Bara
Nr of modules (AWE/PEM)	6/24	54/99
Compression for AWE	3*50% reciprocating compressors	7+1 reciprocating compressors
Balance of plants (separation and purification)	Outdoors, improved, flexible, compact	Indoors, systems available on the market
Safety in design	Inherently safe design	Included
Plot size	10ha	17ha (AWE) and 14ha (PEM)

Table 1: Main proposed innovations, optimizations and improvements

Electrical system

The electrical system is important, because it converts the electricity from the grid (380 kV, AC) to the needs of the electrolyzer stacks (1,200 V, DC). Electrical installations transform voltage from high to medium to low (HV/MV/LV) by means of transformers, and convert alternating current (AC) to direct current (DC) by rectifiers. The electrical-system layout (single-line design) is similar for AWE and PEM technologies and is optimized with respect to:

- meeting grid requirements
- frequency reserve support
- minimizing electrical losses
- reducing CAPEX

Meeting grid requirements

TenneT provided the grid requirements for a virtual 380kV point of connection (in 2030) in Borssele, Zeeland, near existing power plants and industrial facilities. These requirements anticipate future electricity generation and demand, they are based on the transition system operator grid code and they are in accordance with present compliance procedures. The grid requirements impose specifications for electrical design, including for specific and total harmonic emissions limits, the prevention of voltage dips and outages, and a minimum power factor of 0.9, which ensures sufficient transport capacity. The emission limits are for operating conditions of the (disturbing) installation of the connected party and the system (Dutch grid). This is a particular a challenge given the prevailing load variations. The electrical installations and the electrolyzers are particularly suitable for restoring the frequency of the grid, because of their fast response and their large scale, so that there is less of a need to impose disturbances on the grid.

Transformers and rectifiers

For the HV electrical system, four state-of-the-art 380/66kV 300MVA transformers with open-air switchgear are selected in order to minimize costs. Transformer rectifiers are needed, to transform MV to LV and AC to DC, and so that current can flow to the stacks, depending on the load setpoint. These 66/1.5kV transformers are equipped with gas-insulated switchgear. In the case of AWE technology, two stacks in series will be electrically connected to a rectifier, whereas for PEM, two parallel series of two stacks each will be connected. This combination of transformer-rectifier and stacks is defined as a power block, which is 40MW for both PEM and AWE. The voltage that goes to the stacks is around 1,200V DC, due to a higher number of cells in the innovative stacks (see stack section below), which lowers the number of connections to the stacks. This voltage is higher than that usually used in the electrolyzer industry, but it is still in accordance with the Low Voltage Directive,[16] thus avoiding costs for special MV equipment.

In addition to aiming for lower CAPEX, the conceptual design of the electrical infrastructure also aimed to minimize electrical losses by optimizing the net electricity supply to the electrolyzers for hydrogen production. At full load, the expected efficiency is nearly 98%.

In principle, two main topologies are possible for rectifiers: thyristor-based solutions[17] and IGBT power electronics.[18] IGBT is expected to be cost-competitive with thyristor-based solutions at a system level because, unlike Thyristors, IGBT technology uses active control and does not require harmonic filters and power-control devices (Statcom) to meet emissions limits and provide reactive power compensation.

The advanced design anticipates the development of IGBT units that have larger power ratings than the currently available 3MW. Despite this development, multiple IGBT units are needed for one power block because of the limited unit size. This is caused in turn by the properties of the high-switching semi-conductors, which lead to heat dissipation. Each transformer-rectifier is delivered as a self-contained e-house with a dedicated cooling unit. Thanks to this compact design, the expected footprint of a power block with IGBT is comparable to the footprint you need with Thyristors today. The proposed transformers are part of the assembly, and use an ester type of oil, preferably vegetable-based. They thus meet fire safety standards and simplify fire-prevention requirements. Given the high currents involved, multiple DC busbars with large cores are needed to connect the rectifiers to the stacks. The scope of the electrical system includes an auxiliary power supply, a motor-control center, HV/MV cables, and LV cables to consumers, as well as about 15km of DC (aluminum) busbars of 3,000 mm^2 to the stacks.

Water electrolysis stacks

Advanced AWE stack

This is an electrolyzer stack that operates at a high current density of 1.3 A cm^{-2}, thus resulting in a hydrogen output (4460 Nm^3/h) and single-stack power (19.6 MW) that is significantly higher than what is available from stacks currently on the market. A schematic representation of the advanced AWE stack inspired by patent literature is shown in Figure 10.[19] From the outside, it looks like a classic AWE electrolyzer, although it is a bit shorter because its cells are not as thick, despite the fact that there are more of them. Internally, the most important aspect is the zero-gap cell design, which is enabled by nickel matrasses that gently push the electrode meshes onto the diaphragm.

The key difference from present-day electrolyzers lies in the operating conditions listed in Table 2. The temperature of 100 °C, in combination with the zero-gap configuration and the use of a thin diaphragm, enables efficient operation (1.8 V) at the current density of 1.3 A cm^{-2}. This in turn results in a nominal stack power of 19.6 MW and a hydrogen production rate of 4,460 Nm^3/h, which is significantly higher than what is possible with currently available electrolyzers. The pressure is 5 Bara, which is a trade-off between the advantages of atmospheric and pressurized electrolysis. This pressure has the advantage over atmospheric electrolysis that the gas hold-up is lower, thus allowing for thinner cells and higher ramp rates. Compared to electrolysis at elevated pressures, typically carried out at 15 to 30 bar, the lower pressure level results in less gas crossover. This in turn makes it possible to use a thin diaphragm, and enables a lower minimum load for the electrolyzer. The main operating conditions and performance characteristic are given in Table 2.

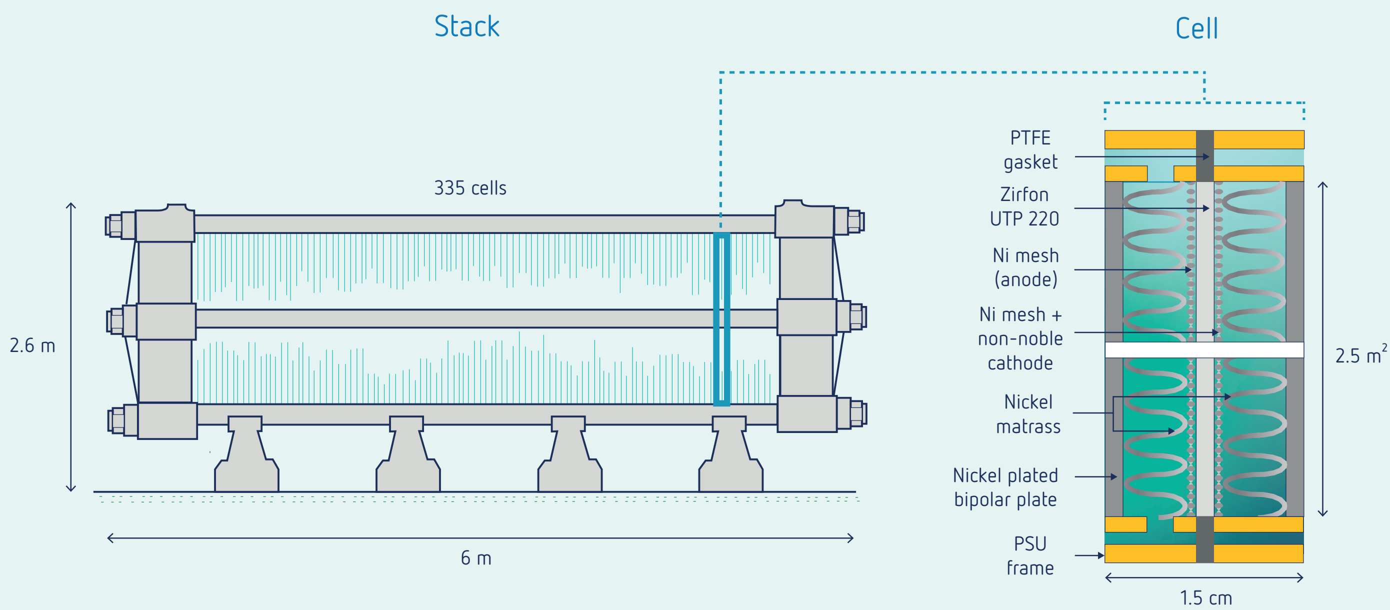


Figure 10: Schematic representation of the advanced AWE stack

Operating temperature	100 °C
Operating pressure	5 Bara
Nominal current density	1.3 A cm^{-2}
Cell potential @ nominal load (at start)	1.8 V
Nominal stack power	19.6 MW
Current efficiency	98%
Nominal stack hydrogen output	4,460 Nm^3 h^{-1}
Minimal load	15%
H_2 in O_2 (nominal load/minimum load)	0.3/1.6%[20]
Degradation rate	1% per year

Table 2: Operating conditions and performance of the advanced AWE stack

The advanced AWE electrolyzer design is still a preliminary design, which needs to be further developed in the coming years and validated through pilots and demonstrations. This design combines technologies at an overall technical readiness level (TRL) of 4 to 9.[21] One important developmental aspect is the validation of the ability to operate at high current densities with non-noble cathode coatings (e.g., Raney Nickel or Ni-oxides). These coatings have a long history in the chlor-alkali industry, where they have shown their durability at current densities of up to 0.6 A cm^{-2}.[22] There are no fundamental electrochemical limitations that would make these coatings unsuitable for operation at higher current densities, but there will likely be a negative impact on their lifetime. If the lifetime turned out to be insufficient, more-advanced coatings based on noble metals can be used as an alternative. For these coatings, high current densities of up to 1.2 A cm^{-2} have already been achieved.[23] Another key developmental aspect is the durability of the stack components at an operating temperature of 100 °C, which is higher than that of present-day systems.[24] Therefore, the durability will need to be validated and, where needed, components with insufficient durability will be replaced by more-advanced materials.

Advanced PEM stack

It is expected that substantial technological progress will be made on the novel PEM stack in the next 5 to 10 years. The stack is currently at at TRL of 3 to 7.[25] This development will lead to future stack designs that outperform the-state-of-the-art stacks substantially with a current density of 3.5 A cm^{-2} at a stack efficiency of nearly 80%. There is a need to reduce costs and minimize the use of scarce materials, while at the same time increasing demand and improving the lifetime of stacks and, in particular, of electrodes. Part of the technical potential will thus be sacrificed to achieve a balanced set of objectives.

Specifically, we anticipate the development of better functional materials and cell design, which will lead to lower cell potential at a high current density, with the use of fewer scarce materials.[26]

The performance would be largely in line with targets, e.g., from the Fuel Cells and Hydrogen Joint Undertaking (FCH JU).[27] Iridium loadings in electrodes will be driven down to levels as low as 0,1 mg cm^{-2}. Advances in materials will lead to more-effective components, such as high-performance polymers for membranes, thus resulting in thinner membranes and lower ohmic losses. Furthermore, advanced electrode designs will aim for higher catalyst utilization and reduced transport losses in electrodes and catalytic layers. Abundant materials for the coating of bipolar plates and electrodes will be used, thus minimizing the use of platina and gold.

Substantial cost reductions can also be achieved by scaling up the cell area and the number of cells in a stack. However, the uniformity of flows and of compression forces becomes more critical as the cell area and the height of the stack increase. Based on calculations of flow velocities, heat distribution, and the weight of the stack, the dimensions specified in Table 3 are considered a reasonable estimate for stacks operational in 2030. The stack design that has been used for the calculation of cost and performance is illustrated in Figure 11. This is a 10 MW stack based on an active area of 0.5 m^2 per cell and a hydrogen production rate of 2,250 Nm^3/h, which is much higher than what is possible with current PEM electrolyzers. The main operating conditions and performance characteristic are given in Table 3.

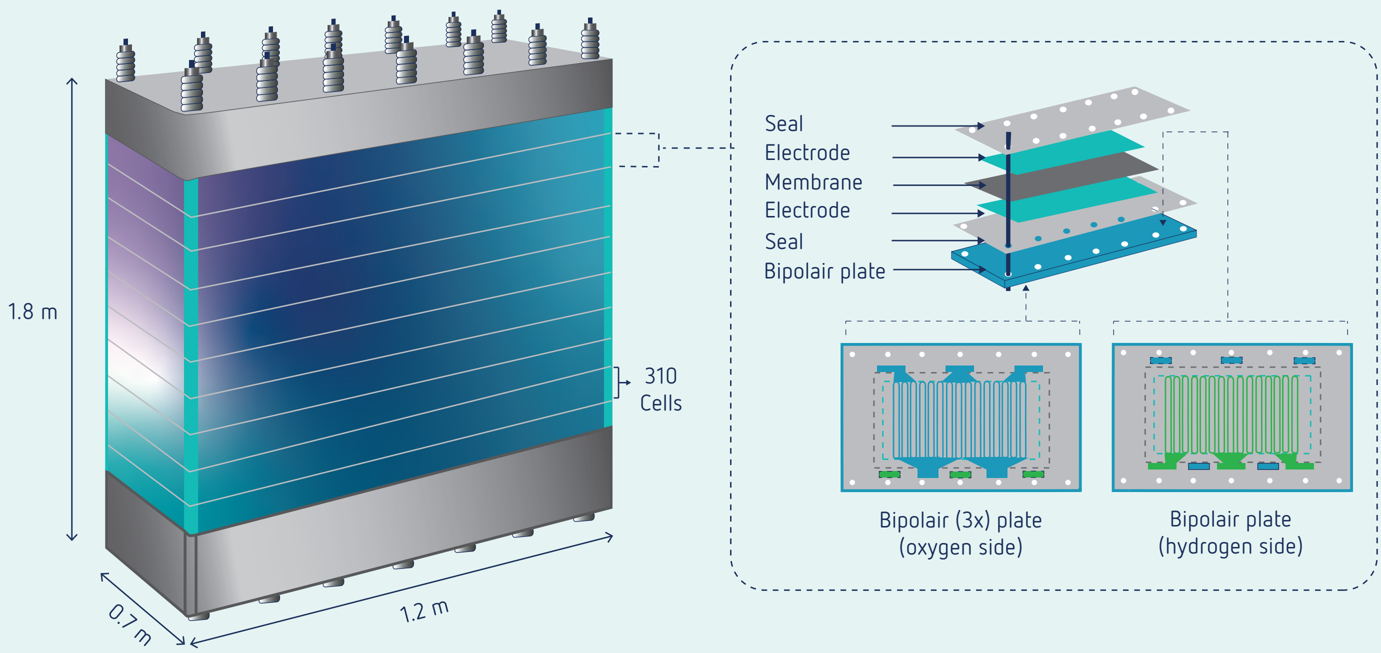


Figure 11: Schematic representation of the advanced PEM stack

Operating temperature nominal load	70 °C
Minimuml load	10%
Operating pressure (cathode)	30 Bara
Operating pressure (anode)	4 Bara
Nominal current density	3.5 A cm^{-2}
Cell potential @ nominal load (at start)	1.83 V
Number of cells	310
Effective cell area	0.50 m^2
Total cell area	0.84 m^2
Nominal stack power	10 MW
Nominal stack hydrogen output	2,250 Nm3 h^{-1}
Minimum load	10%

Table 3: Operating conditions and performance of the advanced PEM stack

Performance of the advanced design is assessed through electrochemical modelling for this project, based on specific assumptions regarding improvements in properties of the functional components (membranes, catalysts, and electrodes) and the interactions between and among these. A model-based approach is theoretical, and uncertainties remain about what actual progress in technological developments is possible in the timeframe required. Therefore, a sensitivity analysis was carried out to identify and analyze assumptions. The following main challenges emerged:

- The iridium loading needs to be reduced by a factor of between 10 and 100, not only because of cost, but because current loadings are a barrier to large-scale application. This target requires a much more efficient use of the catalyst than is possible with current state-of-the-art electrolyzers. Although the literature shows good performance with ultra-low loadings, such performance has yet to be demonstrated in actual systems over several years of operation with a variable load.

- Thinner membranes will be needed to reduce ohmic losses. At the same time, the membrane needs improved mechanical stability because of the higher difference in pressure and the bigger cell area (less-uniform compression). An additional challenge is the gas cross-over, which increases as the membrane thickness decreases. Improvements are needed in the barrier properties of the material, but also in the electrode architecture and effectivity of recombination catalysts.

- A higher temperature has a strong impact on performance but also on degradation. Operating the electrolyzer at 70 °C therefore requires more-robust materials. As degradation mechanisms are highly complex and interactive, it also assumes that the design of future cells and stacks will change considerably to prevent degradation and negative interactions between and among functional components.

Many solutions that have been considered for the advanced design are currently being tried out on a small scale in laboratories. The uncertainty about the performance of the advanced design therefore lies mainly in the scaling up of these solutions and the demonstration of their robustness.

Balance of plants

The balance of plants consists of separators with recirculation circuits, pumps and heat exchangers, compression (for AWE), and a purification system.

For this 2030-based design, the size of the separators will be optimized, thus minimizing gas volume while achieving good bubble and droplet separation. The resulting liquid residence time in the separators is less than 2 minutes, both for AWE and PEM. For PEM we have chosen only for process water flow at the anode side, and for two gas-liquid separators (oxygen and hydrogen) per module. For AWE, dedicated electrolyte (30% KOH) recirculation systems for anode and cathode were chosen, thus enabling a lower minimum load because of reduced hydrogen transport to the oxygen side.

The suggested optimum operating pressure for the AWE electrolyzers is 5 Bara, which is a balance between the total costs of ownership (TCO)[28], stack design and operational and safety aspects. The step from 1 Bara (state-of-the-art 2020 design) to 5 Bara (current design) eliminates the first and costliest stage of hydrogen compression. Higher pressures are not favorable for the stack design and operation, as explained in the stack section. From a safety point of view, lower pressures are preferred, as lower quantities of hydrogen are present in the contained system with stacks and separators. The equipment, other than the stacks, is located outdoors, so that natural ventilation can be used and to save on building costs.

For PEM, there is no need for compression, but for the AWE system, the hydrogen produced at 5 Bara in the stack needs to be compressed to 30 Bara. A specification for both reciprocating and turbo compressors has been made and discussed with suppliers. The reciprocating compressors are available on the market, whereas turbo compressors are not yet mature enough for this hydrogen application and would need a lower pressure ratio and higher volumes. Therefore, two reciprocating compressors were chosen with one installed spare to attain plant availability of 94%.

For the purification of the hydrogen that is produced, catalytic deoxidation and dryers with electrical heaters (and where the adsorbent is silica gel) and coolers are used. Two vessels for deoxidation and six vessels, including two in regeneration mode, are needed to meet the turn-down ratio. Recirculation of dried gas is foreseen to meet product specs specification also at low flow. No recompression is needed for the regeneration of dryers, losses in pressure are kept to a minimum.

For the AWE electrolysis modules, the selection of materials is critical, because of the operating temperature of 100°C and the higher corrosion rates and risk of stress corrosion cracking that result. The material selected for parts that are in contact with electrolytes and oxygen is nickel for piping and coolers, and cladded nickel (3 mm) for separators. For parts in contact with electrolytes and hydrogen, duplex can be used. For parts operating at lower temperatures, stainless steel 316 (SS316) is sufficient. For the downstream processing of hydrogen, in the absence of potassium hydroxide and oxygen, carbon steel is used. Embrittlement is not observed for these services. Regarding PEM modules, SS316 is selected. The total length of piping in modules (typically from DN200 to DN700) and in interconnecting piping for gases and cooling water, is about 15km.

Overall system efficiency at full load is 77% and 75.8% for PEM and AWE, respectively. The system efficiency includes stack efficiency, auxiliary power consumption, stack energy losses, and electrical losses in the electrical installations—see Figure 12. The stack efficiency for both novel electrolyzer technologies is 80% (HHV). The net electricity supply to electrolyzers is 963MW (a 3.7% loss) and 948MW (a 5.2% loss) for PEM and for AWE, respectively. The difference is mainly because of mechanical compression losses—19MW at full load. These efficiency levels are calculated for new stacks at the start of commercial operations. During operations, however, efficiency will drop because of the aging and degradation of stacks, thus leading to more electricity consumption per unit of hydrogen. Usually, the lifetime of a stack, including in economic terms, is typically limited to a 10% decline in stack efficiency because of the increasing operating costs of electricity and the recurring costs involved in the replacement of stacks.

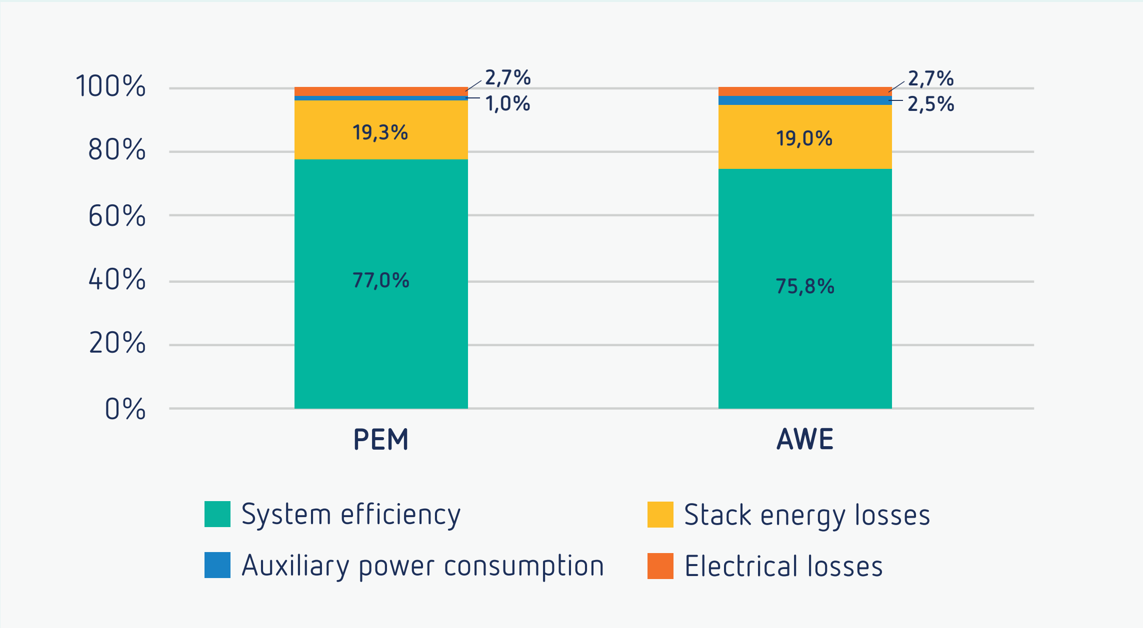


Figure 12: System efficiency

Utilities

There is a separate cooling-water system for the heat exchangers in the recirculation loop of the electrolyzers. This will make it possible to recover heat and supply it to district heating networks. The coolers are designed in such a way that, at full load, they can cool the stacks at end-of-life conditions (higher cooling demand). And the coolers are optimized for heat recovery at high temperatures. In the case of new stacks, the cooling demand is around 40% lower. The cooling demand and the heat supply grow over time from 140MW to 230MW for AWE, and from 160MW to 265MW for PEM (full load).

For the purification section, another cooling water system is installed at lower operating temperatures with a cooling duty of around 35MW for maximum gas flow.

For AWE, demineralized water is sufficient as process water, whereas for PEM we need ultrapure water. The demineralization plant can produce is 230 m^3 of demineralized water per hour. The ultrapure water is produced from demineralized water by a reverse-osmosis plant with post-treatment. In the case of PEM, the polishing of ultra-pure water through ion-exchange resins is required to avoid the inactivation due to impurities in the ultrapure water, which in turn result from leached metal ions from SS316 materials. The estimated polishing capacity is about 500m^3/h, which is double the ultrapure capacity, but which constitutes approximately 1% of the recirculation flow.

Modular design and layout

To design the plant, we used the modular-design method. First, the sizes of the different components in the system (transformer-rectifiers, electrolyzer stacks, and the balance of plants) were optimized. Consequently, they are not the same size and how many of them there are in the system varies. The components are grouped into independently operating modules or blocks. This method has several advantages:

- **It creates flexibility in terms of phased development, with easy adaptation to newer technology generations.**
- **It enables the combination of PEM and AWE plants with potentially different stack generations.**
- **It enables standardization, which saves costs.**

We also looked into the layout of the plant (Figure 15). Taking account of the space that would be required for the components, for roads, for safety distances, and for other factors, we estimated that roughly 10 ha would be required in the case of both PEM and AWE.

Modular design

The electrolyzer stacks are grouped with shared transformer-rectifiers, separators, and other balance-of-plants equipment. One 40 MW transformer-rectifier power block is connected to four 10 MW stacks for PEM, and to two 20 MW stacks for AWE. The power blocks for AWE and PEM are the same, whereas modularity for the balance of plants is different in each case. Each 40 MW PEM module has one hydrogen gas-liquid separator and oxygen gas-liquid separator. The AWE module is bigger, with eight stacks connected to the separators, so a 160 MW module.

This modular design enables phased development and deployment, and facilitates adaptation to newer generations of technology. Standardization, which yields cost savings, could also mean that the design can accommodate a combination of PEM and AWE technology and, potentially, different generations of stacks within the same plant.

Figures 13 and 14 show, in schematic form, the modular designs for AWE and PEM plant configurations with repetitive modules and power blocks. The figures illustrate an economy of scale, dividing the 1-GW configuration into 2 (480MW), 3 (320MW), or 4 (240MW) subsystems at the plant level, for a total of 6*160 MW AWE modules or 24*40 MW PEM modules.

Figure 13: AWE modular design

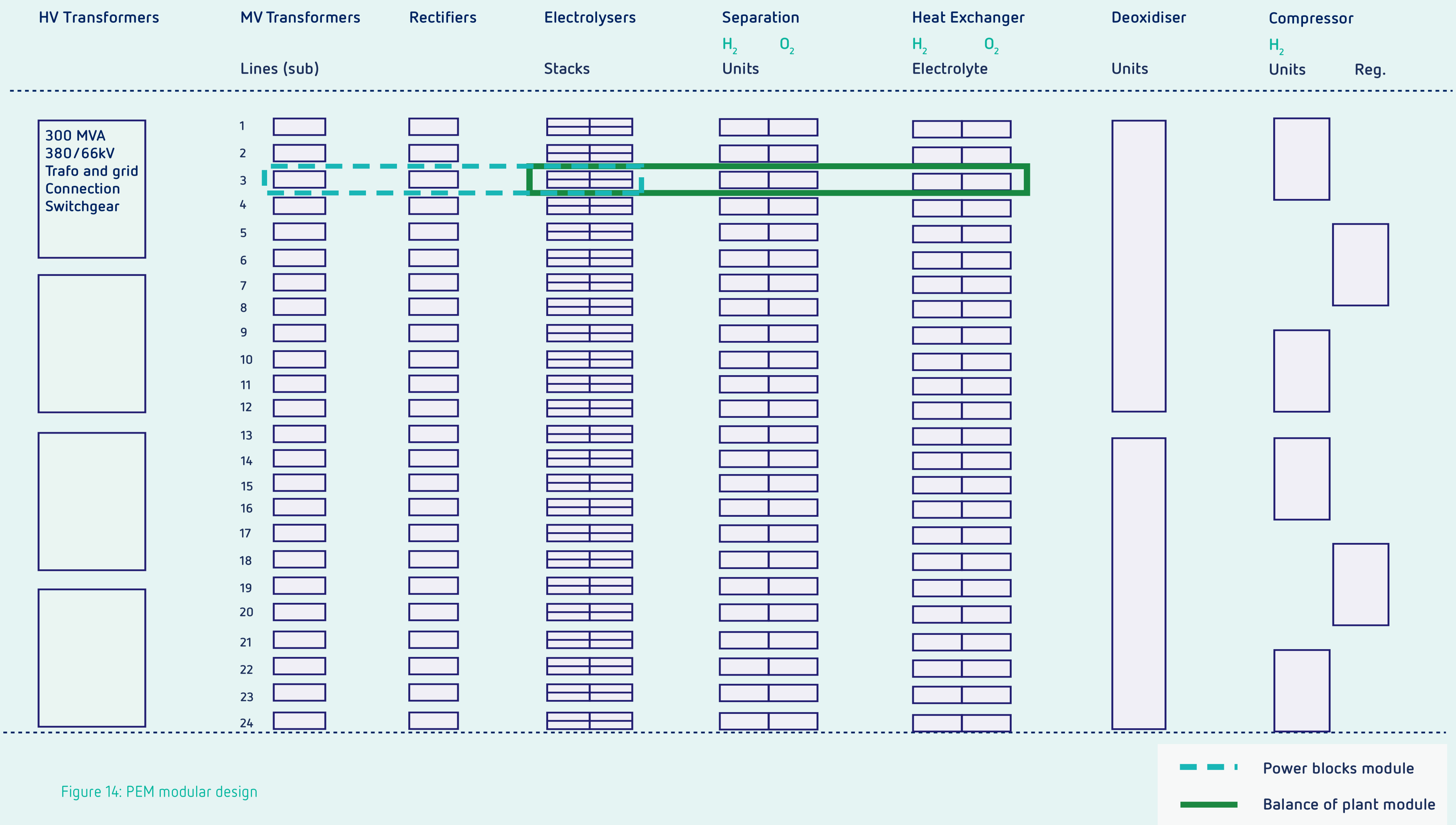


Figure 14: PEM modular design

Layout

Figures 15 and 16 show the layout of the AWE and PEM plants, respectively. The HV transformers and switchgear are in a restricted area and occupy about one-fifth of the total plot. The MV/LV transformer-rectifiers are close to the electrolyzer building to minimize the distances for electrical connections. The electrolyzer stacks are installed in two separate buildings, each roughly 100 meters long. The separators, pumps, and coolers for each module are located outside, between the buildings. And that is also where a pipe rack has been installed for hydrogen, oxygen, demineralized water, and cooling water piping. The compressors, for AWE, are installed in a shed near the outdoor purification system. The service building and the utilities with cooling water towers and a water-treatment building are on the periphery. There is enough space for roads, access, maintenance, and pipe and cable routing. Internal safety distances, and distances to plot boundaries, have been taken into consideration. The required plot space is roughly 10 ha in the case of both PEM and AWE.

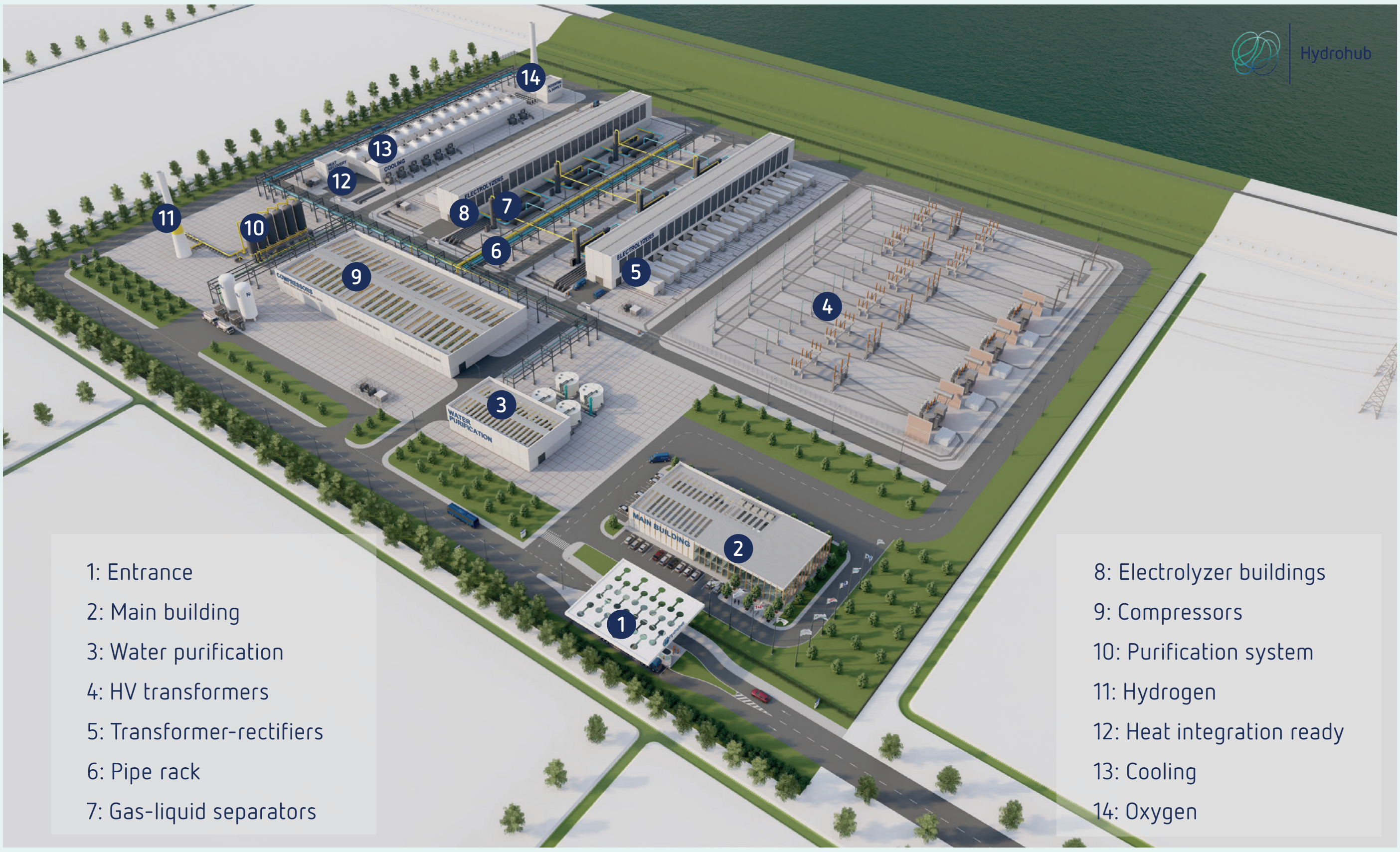


Figure 15: Artist's impression of an advanced AWE 1-GW green-hydrogen plant

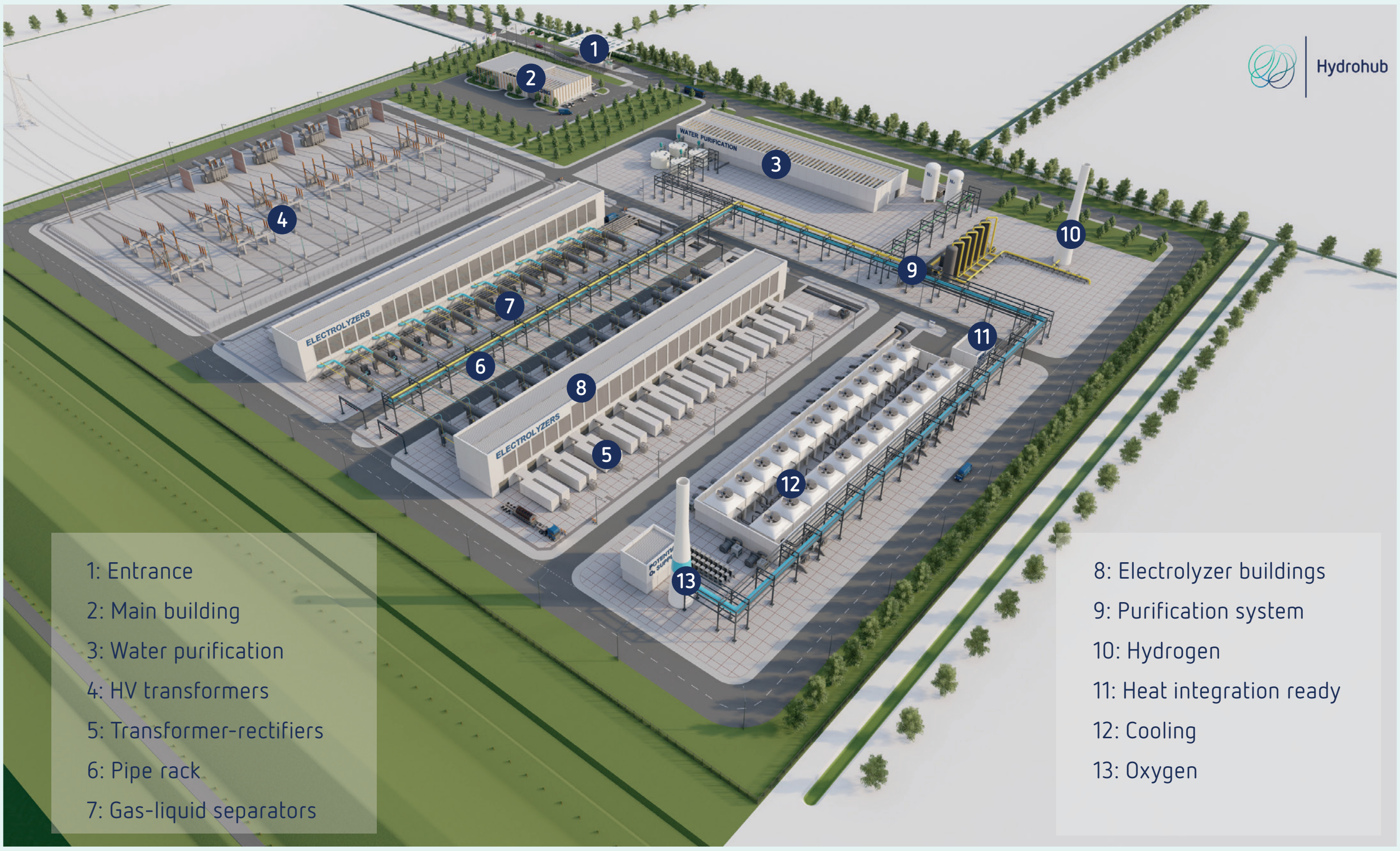


Figure 16: Artist's impression of an advanced PEM 1-GW green-hydrogen plant

Cost-estimating principles

The cost estimate is determined from an investor's point of view, and incorporates direct costs, indirect costs, owner costs, and contingency.

- **The direct costs were estimated based on supplier quotes for equipment, and on unit rates for bulk materials. That approach was not possible for innovative electrolyzer stacks. The costs in that case were estimated and validated based on expected material costs and on costs for manufacturing, labor, overhead, and margin.**
- **Indirect costs consist of engineering, procurement, and project and construction management (EPCm).**
- **Owner costs are those that are allocated to the owner/operator.**
- **Contingency is added to the direct and indirect costs in order to prevent unrealistic expectations in the development phase and to reduce the probability of cost overruns in the execution phase. The difference in terms of the level of innovation, and therefore of the technology risks associated with PEM and AWE, is reflected in a different contingency rate.**

A cost estimate for realizing a 1-GW green-hydrogen plant has been prepared in accordance with engineering practices in the chemical industry. A specialized team of experts broke down the scope into various engineering deliverables. Based on these specifications, suppliers of balance-of-plant equipment were asked for feedback and information on technological developments and quotations. For costs related to piping, and to civil-works and electrical installations, bills of materials were prepared. That in turn made it possible to come up with cost estimates for bulk materials, based on unit rates from industry partners' databases.

For the estimation of novel stack costs, the team combined a bottom-up approach for material costs with a top-down approach for manufacturing, overhead, and margin.[29] The team prepared a breakdown at the component level in order to determine the material costs of each part of a stack. The AWE stack cost estimate was validated with input from partners and a manufacturing company. As a result, the accuracy of the direct-cost estimates in the case of AWE technology is thought to be somewhere between +30% and -15%. In the case of the PEM technology, that figure is thought to be somewhere between +40% and -25%.

The total installed costs are defined as direct and indirect costs, with allowances and contingency. Direct costs include those for the supply of equipment, on-site construction and services from contractors and suppliers, and allowances for uncertainties, both known and unknown—e.g., both in terms of the quantities of materials required and of specific prices. Indirect costs consist of EPCm, and costs allocated to the owner/operator.[30]

Contingency is added to the direct and indirect costs in order to prevent unrealistic expectations in the development phase and reduce the probability of overruns of project costs in the execution phase. The contingency is empirically and statistically determined.[31] The novel PEM stacks are deemed to be more innovative (lower TRL) than the novel AWE stacks. A higher contingency is thus taken to cover the associated technology risks. For PEM the contingency is put at 35% on top of the direct and indirect costs. For AWE stacks, the contingency is set at 25%.

The estimate of total installed costs is based on October 2021 cost levels. This can be translated to 2030 cost levels with two corrections. First, indexation should be applied, to take account of volatile material and energy costs and of higher labor costs. Second, cost reductions enabled by increased market incentives and growth in demand are expected to bring more mass fabrication and automation to bear on the manufacturing of stacks. Several suppliers of electrolyzers are building, or have recently announced investments in, a stack production capacity of one or more GW per year. The extent to which this will reduce costs has not been assessed.

Total installed costs

The estimated total installed costs for an advanced 1-GW green-hydrogen plant are about 50% of the cost estimate of the forementioned 2020 baseline design: 730 €/kW or 1580 €/(kg/day) for AWE technology, and 830 €/kW or 1770 €/(kg/day) for PEM technology. The electrical costs are just as important as the stack costs.

The total installed costs of a 1-GW green-hydrogen plant are estimated at EUR 730 million (730 €/kW installed capacity) for a plant using AWE technology, and at EUR 830 million (830 €/kW installed capacity) for a plant using PEM technology. When expressed in terms of hydrogen production, the estimated total installation costs would be 1580 €/(kg/day) for AWE technology and 1770 €/(kg/day) for PEM technology. The use of the latter numbers is preferred, since they are based on the amount of hydrogen produced instead of the electricity input, thus taking account of efficiency. The total installed costs are about half of what would be required for the 2020 the state-of-the-art design. This reduction is achieved through scaling up and innovations at stack level as well as optimizations in the electrical system and in the balance of plants.

Figures 17 and 18 provide a more detailed breakdown of the total installed costs, showing separately the direct costs and total installed costs, which include indirect costs, owner costs, and contingency. The figures show that, in addition to the stacks, the power supply is important. In addition, the balance of plants—including piping, utilities, and civil-works—contributes significantly to direct costs. Direct costs for PEM and are comparable to those for AWE, although the cost breakdown is different, with higher stack costs for PEM and lower costs for the balance of plants. Indirect costs and owner's costs make up a substantial part of the total installed costs. The indirect costs, owner's costs, and contingency costs are-added as a percentage on top of the direct costs. As we have seen, different contingency rates are applied for PEM and AWE, and that explains why the total installed costs for PEM are 100 €/kW higher.

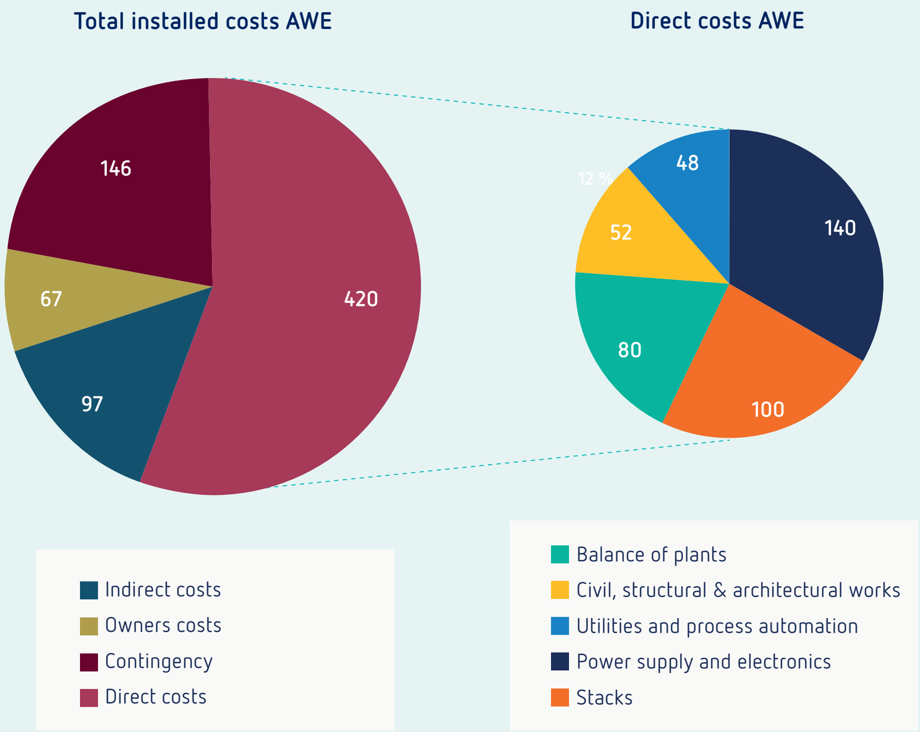


Figure 17: Breakdown of total installed and direct costs for AWE, in €/kW

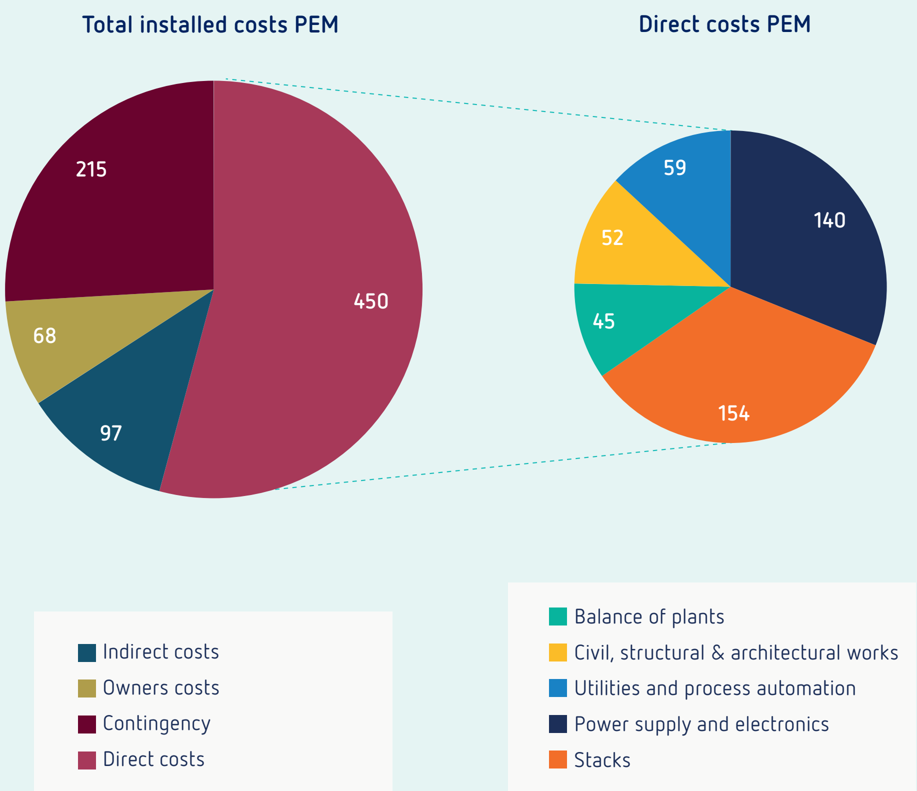


Figure 18: Breakdown of total installed and direct costs for PEM, in €/kW

Discussion of results

The estimated cost reduction of 50% in the advanced design relative to baseline state-of-the-art design will come from substantial savings on stack costs for PEM, and from larger and fewer modules for both technologies. The costs for the advanced design are lower than the targets set by the FCH JU. To achieve these reductions, developments in the relevant technologies and in manufacturing for both AWE and PEM should be accelerated significantly. The potential for both technologies is promising, but it needs to be proven by real-life projects. On top of that, further efforts are necessary to create a mature green hydrogen market.

Comparison of results

Our analysis shows that it is possible to halve the costs for an advanced 1-GW green-hydrogen plant, as measured against the 2020 baseline design, by the end of this decade—see Figures 19 and 20. Cost reductions can be found in practically all parts of the cost estimate. With the PEM technology, substantial savings in stack costs have been achieved that originate primarily from the advanced cell design with high-performance materials, innovative electrodes, and a large cell surface area. In the case of AWE, the cost savings on stacks are smaller because the technology is more mature. Most savings in AWE stack costs originate from the increased current density, while the costs of improved electrodes per m^2 are higher. As a result, the number of stacks is reduced by a factor of 15 for PEM and by a factor of 9 for AWE technology, compared with the baseline design.

Electrical, civil, mechanical (balance of plants), and utility costs also went down mainly due to upscaling to larger modules, more compact design, and design optimizations. The compact design, for instance, leads to a 10ha plot size—4ha (PEM) or 7ha (AWE) less than needed in the baseline design for a 1GW green-hydrogen plant. As the indirect costs and contingency costs are in fact a percentage added to the direct costs, the latter go down accordingly.

When comparing the results to other public references, it appears that these sources do not report total installed costs, but usually refer to system (supply) costs with smaller nameplate capacity (e.g. 100 MW) and a different scope.[32] We need to adjust the scope to make comparison with the FCH JU possible. Not counting HV electrical, civil-works, and site installation, the direct costs for AWE and PEM are around 300 €/kW—less than the 400 and 500 €/kW FCH JU 2030 targets for AWE and PEM, respectively.

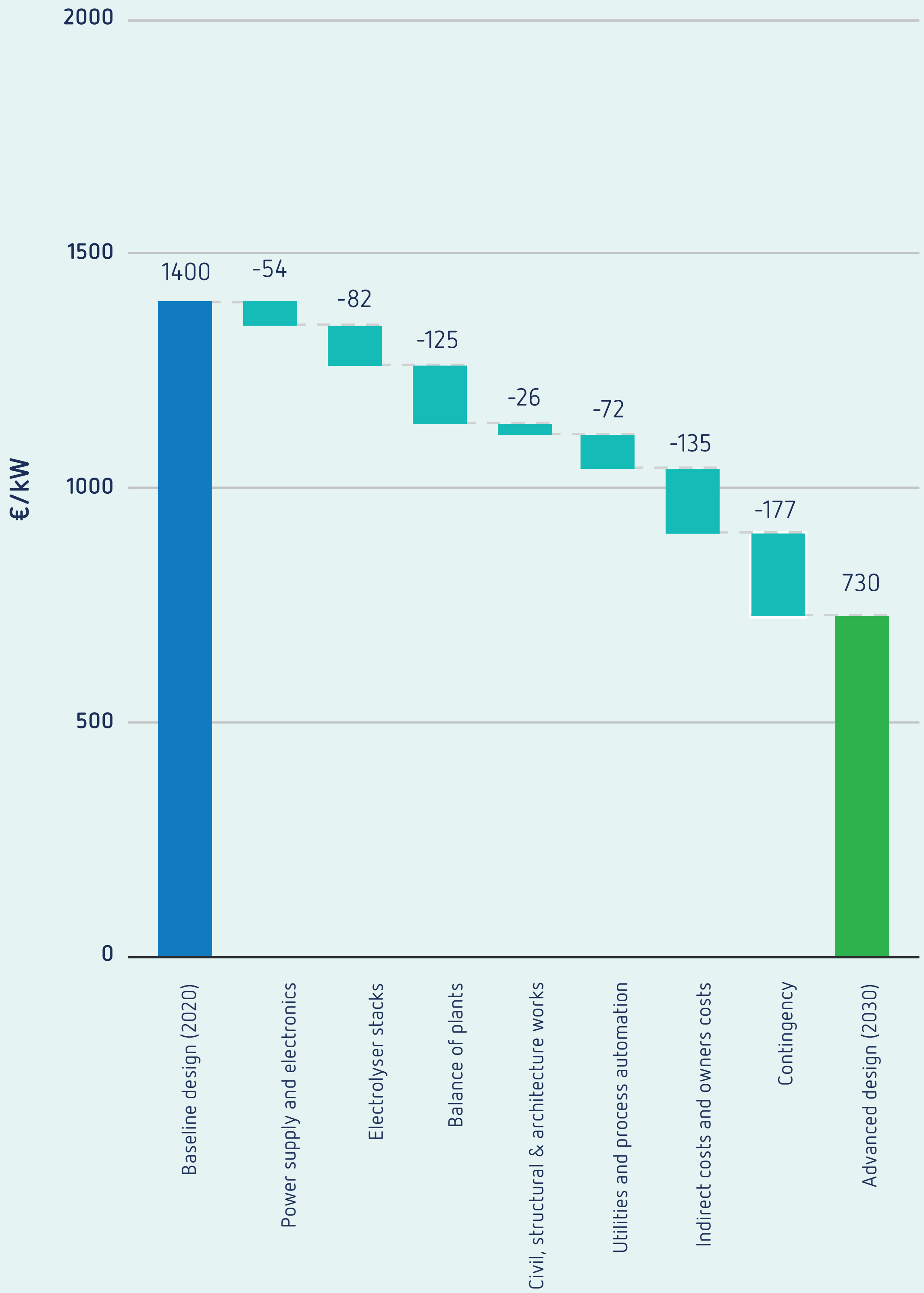


Figure 19: Cost reductions for the advanced-design AWE plant, as measured against the 2020 design

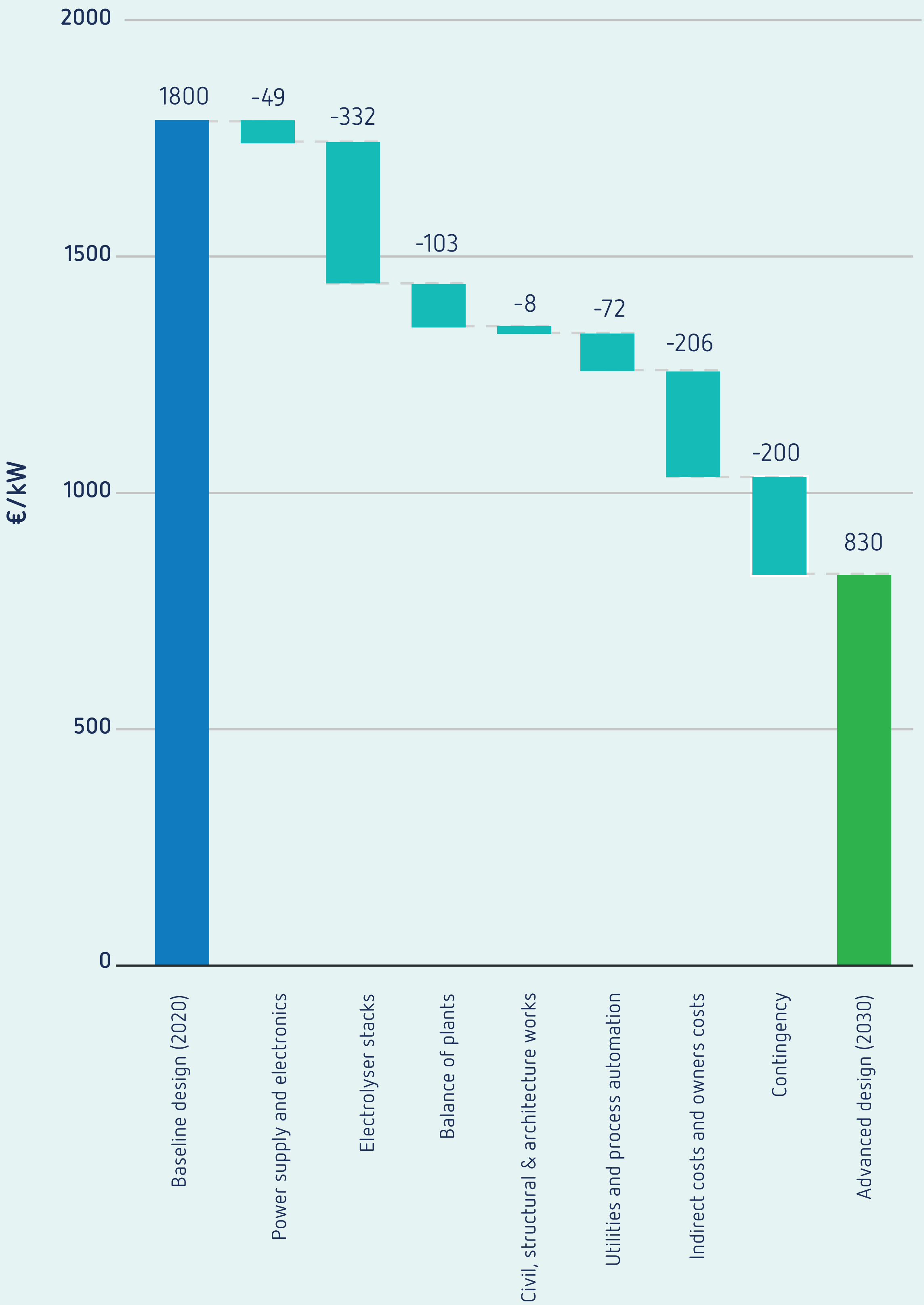


Figure 20: Cost reductions for the advanced-design PEM plant, as measured against the 2020 design

Innovation and upscaling in design

The main drivers of lower costs in the advanced design are innovation, scaling up, and optimization. The present TRL in the novel stacks has been assessed at the component level. For novel PEM-stack technologies, the anticipated innovations are at a TRL of between 3 and 7, while for AWE the TRL is between 4 and 9. As noted in the sections on stack design, this innovative design involves a technological risk. Therefore, the innovations should be developed, tested, and validated with real-life pilots and demonstration projects before being implemented at full scale.

The modular approach enables adaptability and risk mitigation through the addition of more modules. Space, tie-ins, and provisions for the future extension of the plant can already be considered in the initial design. In the case of an extra module with corresponding power blocks, the cost of one AWE 160MW module is roughly EUR 100 million extra, while for PEM it is about EUR 30 million extra for one 40MW module. A hybrid solution is possible with PEM and AWE modules next to one another, both connected to the same power block in the operating plant.

Costs and availability of materials

In the cost estimate, we assume that all materials are available on time and in sufficient qualities for the project. Examples include iridium and other scarce materials for PEM; nickel for AWE stacks, piping and equipment; copper and aluminum for electrical installations; and semi-conductors for power electronics. However, it can be expected that besides the impact of volatility on material costs, the availability of materials and manpower can become an issue, especially for long delivery items (e.g. semi-conductors), thus leading to delays or even snarling supplies and hampering the execution of the project. In the advanced design, this risk is addressed for stacks by minimizing the use of materials, including those that are scarce, by using thinner coatings and non-noble electrodes. For equipment, it is addressed by using a modular design and by scaling up to larger modules.

Development of equipment to be used

Product development with respect to power electronics, compressors, and other equipment is taking place on the premises of original equipment manufacturers. This poses a challenge for system integrators, suppliers, contractors, and end users—everyone that is working along the entire supply chain to come to the smartest and most cost-effective system design. The advanced design is the first iterative system design, and should be further improved and aligned with the field in the next period. For example, the power-electronics market is currently dynamic. It faces growth in the demand for installations that can handle renewables. This translates to enormous potential for technological improvement in relation to larger power ratings and improved topologies.

Way forward

There is a 4-year window of opportunity for accelerated innovation that is necessary to deliver the advanced design in 2030. To do this, a final investment decision (FID) must be taken at the latest in 2028. This requires at least 2 years of project preparation before FID, meaning that the technologies that are envisaged in this report must be commercially available by 2026. Considerable efforts will thus be required in this connection.

The overall system should be up and running by the end of this decade. Elements of the system will include connections to offshore wind farms and/or solar parks, hydrogen pipelines and storage, as well as integration into the production plants for variable offtake. Oxygen offtake, and getting heat supplies to district heating networks, are opportunities whose realization will depend on local needs, demand, and flexibility. Stakeholder interests should be addressed in order to create the economic, technical, and regulatory conditions that will in turn make it possible to meet these objectives.

Although green hydrogen has been produced for over a century already, the process safety of electrolysis-based hydrogen operations remains an important topic. Suppliers of electrolyzer systems, authorities, and industrial end users have limited knowledge of and experience with specific hazard scenarios related to the presence of hydrogen and oxygen inside the same equipment, separated by a thin membrane. Therefore, it is essential to gather and develop further knowledge, guidelines, and experimental data in order to ensure the safety of large-scale green hydrogen.[33]

The 730-830 €/kW total installed cost of the advanced conceptual design is not yet at the level expected for a mature green hydrogen economy.[34] Considerable efforts will be required to make green hydrogen more competitive, not only in terms of CAPEX, but also as regards the cost of electricity and the optimal operation mode of the green-hydrogen plant. The optimal operation mode refers to the question of whether a plant will operate in accordance with electricity supply of the wind parks, or batteries will be used to guarantee a more stable energy supply to the plant, or other operation modes.

Based on learning-curve analysis that has been done within the project, we estimate that something on the order of €100 billion in project-based subsidies will be needed to create a global electrolyzer industry that can deliver a cost-competitive large-scale green-hydrogen plant.[35] One could compare this to what was required to make wind and solar parks the commercially viable businesses they are today.

Follow-up

This report has presented the facts and figures related to a 1-GW green-hydrogen plant. If this plant is to be up and running in 2030, faster innovation will be needed. Pursuant to the findings in "The way forward," the key areas for further innovations are:

- Accelerate research and development related to advanced materials in order to extend stack lifetime (degradation of performance) and improve scaling-up and stack performance, and then to test these developments through pilots and demonstrations of advanced AWE and PEM stacks.

- Explore, develop, and demonstrate advanced rectifier-stack-separator concepts for optimized large-scale electrolyzer modules.

- Investigate and optimize rectifier-stack interfacing to understand DC ripples and the impact of these developments on lifetime and efficiency under industrial conditions and given dynamic operations.

Virtual representation

Artist's impression of the entrance of an advanced 1-GW green-hydrogen plant

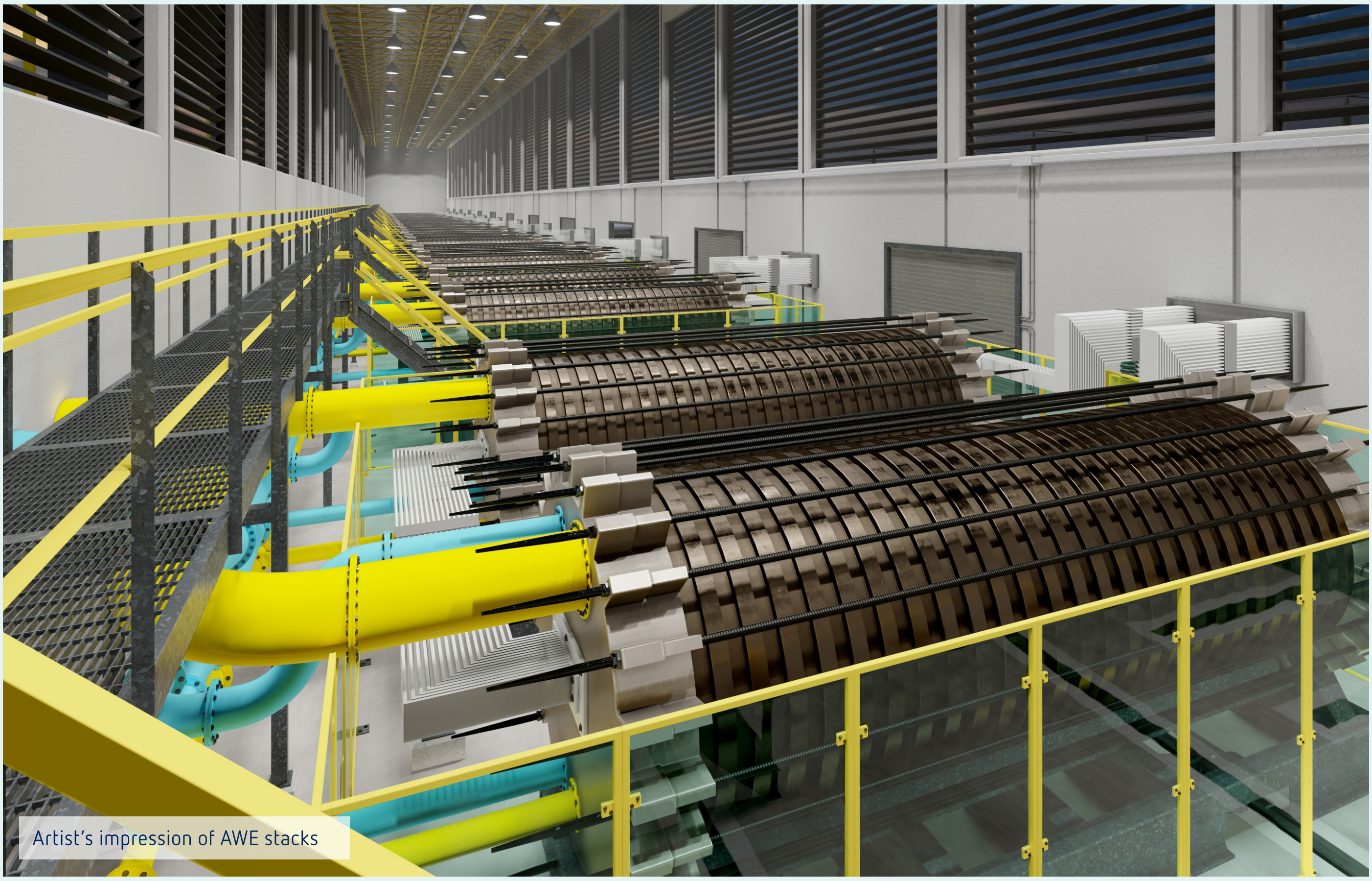
Take the virtual tour

3D environment:

https://gigawatt-hydrohub.expo.royalhaskoningdhv.com/

Short movie:

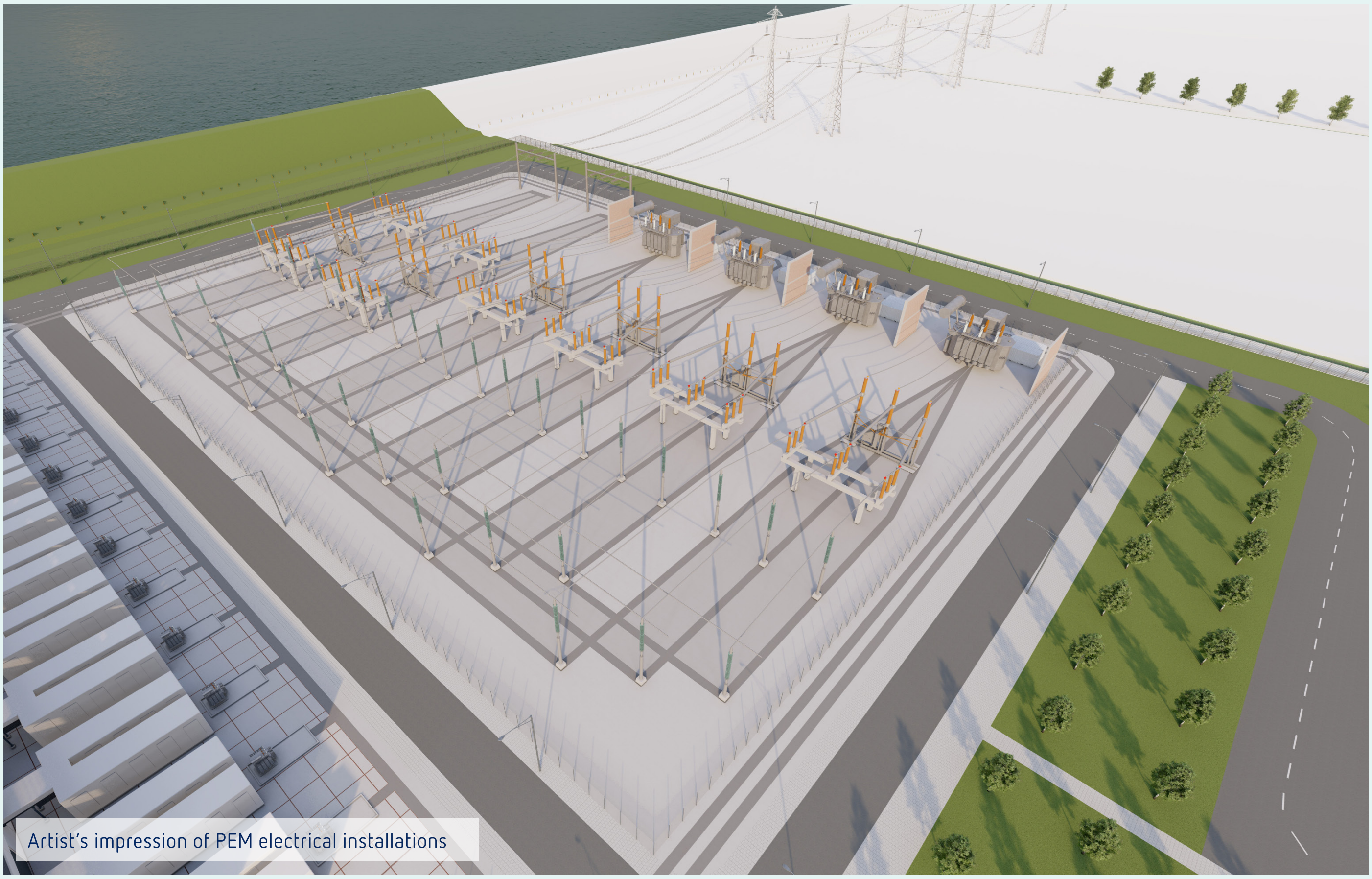
https://youtu.be/fw5zPUbPo1Q



Artist's impression of AWE stacks

Artist's impression of PEM stacks

Artist's impression of AWE pipe rack


Artist's impression of PEM electrical installations

References

[1] https://ispt.eu/media/ISPT-public-report-gigawatt-green-hydrogen-plant.pdf
[2] Fit for 55 | Legislative train schedule | European Parliament (europa.eu).
[3] https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/national-climate-agreement-the-netherlands.
[4] Nederland Fit for 55? | PBL Planbureau voor de Leefomgeving.
[5] National RD programme GroenvermogenNL 2021, www.groenvermogenNL.org.
[6] Ørsted and Yara seek to develop groundbreaking green ammonia project in the Netherlands (orsted.com)
[7] Hydrogen Hub Amsterdam, North Sea Canal Area (Hydrogen Hub NZKG_uk_v06_LR 05-10.pdf, portofamsterdam.com).
[8] Ongoing projects, Port of Rotterdam.
[9] Gasunie, 2021, HyWay27.
[10] Public report Gigawatt green-hydrogen plant, ISPT, October 2020 Publications – ISPT.
[11] Public summary Integration of gigawatt scale electrolyses in 5 industrial clusters, ISPT, July 2020 Publications – ISPT and overview of locations (arcgis.com).
[12] Levelized costs of hydrogen refers to the total of the discounted CAPEX and OPEX divided by annual hydrogen production, and is expressed in Euro/kg H2.
[13] For a 1-GW green-hydrogen facility, the SEVESO III Directive 2012/18/EU is not applicable, because the \ quantity of H2 involved is below the threshold of 5,000 kg.
[14] Ørsted, Actual Generation Offshore Wind North Sea, capacity 957 MW, with a load factor of 0.42, 2018.
[15] Short-term frequency support such as frequency containment reserve, formerly known as primary frequency control, and mid-term frequency support such as automatic frequency restoration reserve, which is secondary frequency control.
[16] Low Voltage Directive 2014/35/EU.
[17] Thyristor is a semiconductor low-frequency switching device that can operate like a rectifying diode once it is "ON".
[18] IGBT is a semi-conductor high-frequency output switch for controlling and converting AC/DC and DC/AC. It can be full-bridge or half-bridge, and is also available as a diode-IGBT chopper.
[19] US 6,554,978, high-pressure electrolyzer module.
[20] 30% of the lower explosion limit.
[21] TRL 4 mean tested at the lab scale, while TRL 9 means full-scale readiness.
[22] T.F. O'Brien et al., Handbook of Chlor-Alkali Technology, Springer, 2005.
[23] De Nora electrodic package for AWE water electrolysis, https://denora.com/products/applications/energy-storage/alkaline-water-electrolysis.html.
[24] Currently, the highest temperature is 95 °C for Chinese AWE electrolyzer systems.
[25] TRL 3 means proof-of-concept tested, while TRL 7 refers to prototype demonstration in operations.
[26] Green hydrogen cost reduction (irena.org).
[27] FCH JU (2018). Multi-annual work plan, updated version. Brussels: Fuel Cells and Hydrogen Joint Undertaking
[28] TCO is calculated with electricity costs for compression (40 €/MWh and 4000h/a) and CAPEX for compressors, stacks, and equipment.
[29] Krishnan Subramani, University of Utrecht, 2021.
[30] Public report Gigawatt green-hydrogen plant, ISPT, October 2020 Publications – ISPT.
[31] Source: Cost Contingency as the Standard Deviation of the Cost Estimate for Cost Engineering, Article · January 2004, Geoffrey Rothwell, Organisation for Economic Co-operation and Development.
[32] FCH JU (2018). Multi-annual work plan, updated version. Brussels: Fuel Cells and Hydrogen Joint Undertaking
[33] A new project by ISPT on green hydrogen safety is starting in 2022.
[34] Green hydrogen cost reduction (irena.org).
[35] Gert Jan Kramer, University of Utrecht, presentation at Frontiers conference Nobian, autumn 2021.

Colophon

Title

A One-GigaWatt Green-Hydrogen Plant

Subtitle

Advanced Design and Total Installed-Capital Costs

Publication date

January 20, 2022

Authors

Hans van 't Noordende (E4U Projects), Peter Ripson (Ekinetix)

Editor

Christa de Ruyter

Copyediting

Ciarán Ó Faolain, www.textabulous.com

Graphic design

Hella Hekkelman, www.hellagooddesign.com

Virtual renders 1-GW green-hydrogen plant

Royal Haskoning DHV, https://global.royalhaskoningdhv.com

Published by

Institute for Sustainable Process Technology (ISPT)

Address

Groen van Prinstererlaan 37, 3818 JN Amersfoort, The Netherlands

Telephone number

+31 (0)33 700 97 97

E-mail

info@ispt.eu

Website

www.ispt.eu

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
- Nobian
- 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.

Consortium partners

Groen van Prinstererlaan 37
3818 JN Amersfoort
The Netherlands
t. +31 (0)33 700 97 97
info@ispt.eu

Join us!

WWW.ISPT.EU

Andres ten Cate
Program Director
andreas.tencate@ispt.eu
t. +31 (0)6 158 74 702

Carol Xiao
Program Manager
carol.xiao@ispt.eu
t. +31 (0)6 284 94 183