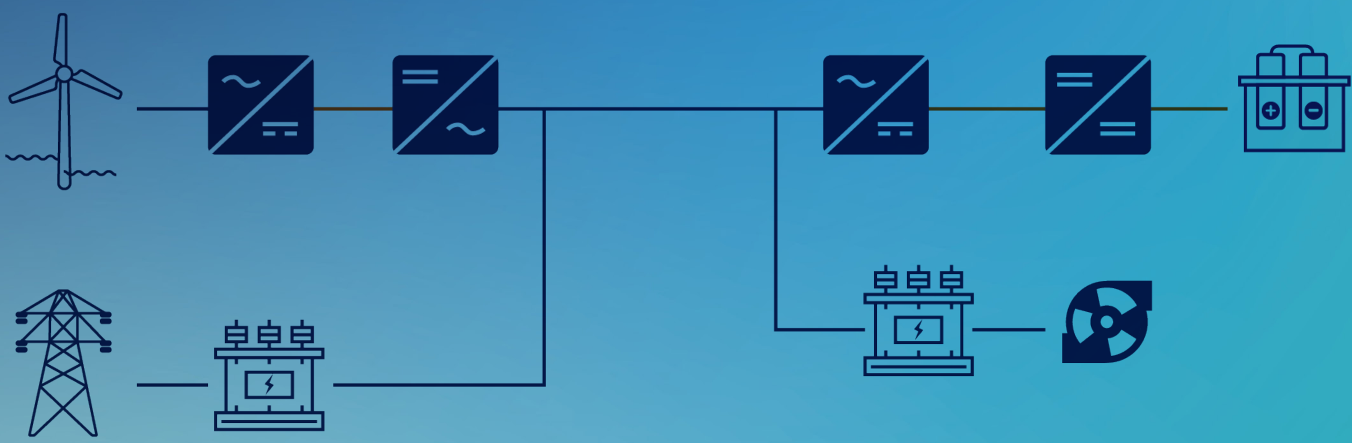
Institute for Sustainable Process Technology

DC | New electrical layout and converters for GW green hydrogen plant



HyCC

equinor

Port of Rotterdam

Ørsted

YARA

Hitachi Energy

Institute for Sustainable Process Technology

Acknowledgement

We are delighted to share this report with you to increase awareness and knowledge of large-scale green hydrogen production and renewable energy systems. This report is the result of an interactive and iterative cooperation in an open innovation project. The development and execution of this feasibility study was a real team effort of experts from ISPT, the innovation platform for the process industry, Hitachi Energy as a leading technology provider, and the Partners from large industrial owner-operators. We held about twenty Teams biweekly meetings and workshops and exchanged knowledge and experience to drive innovation in alternating current (AC) and direct current (DC) solutions. The aim was to develop an alternative electrical layout and converter topology for connection of renewable electricity to large scale electrolysers for green hydrogen production.

This report is based on the following (internal) reports drafted by the project team from Hitachi Energy and Partners from Industry:

- 50241001 User Requirement Specification ISPT DC-DC GW scale green hydrogen production Final
- 50241002 Power Converter concept design for Large Scale Electrolysers

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Please join us.

The authors

Executive Summary

As the development of large, distant offshore wind farms continues to increase, High Voltage Direct Current (HVDC) is used to transmit direct current (DC) electricity from these sites to the mainland. This electricity has the potential to power large-scale green hydrogen plants. For example, the Dogger Bank Wind Farm in the United Kingdom, already partly constructed, will use HVDC lines to deliver offshore wind energy to the UK grid, where it will be converted to High Voltage Alternating Current (HVAC) for onshore distribution. Similarly, in The Netherlands, 2GW HVDC transmission lines will connect offshore wind farms to onshore HVAC power grids through interconnectors with power inverters (DC/AC) in 2030. Hence, electricity can be transmitted to the grid and to large-scale electrolysers, like a hydrogen conversion park in Rotterdam (see Figure S1). Medium and Low Voltage (MV/LV) DC solutions could make sense as the water electrolysis process also uses DC at a low voltage level. However, the required converters are not yet mature for this purpose and still need to be developed.

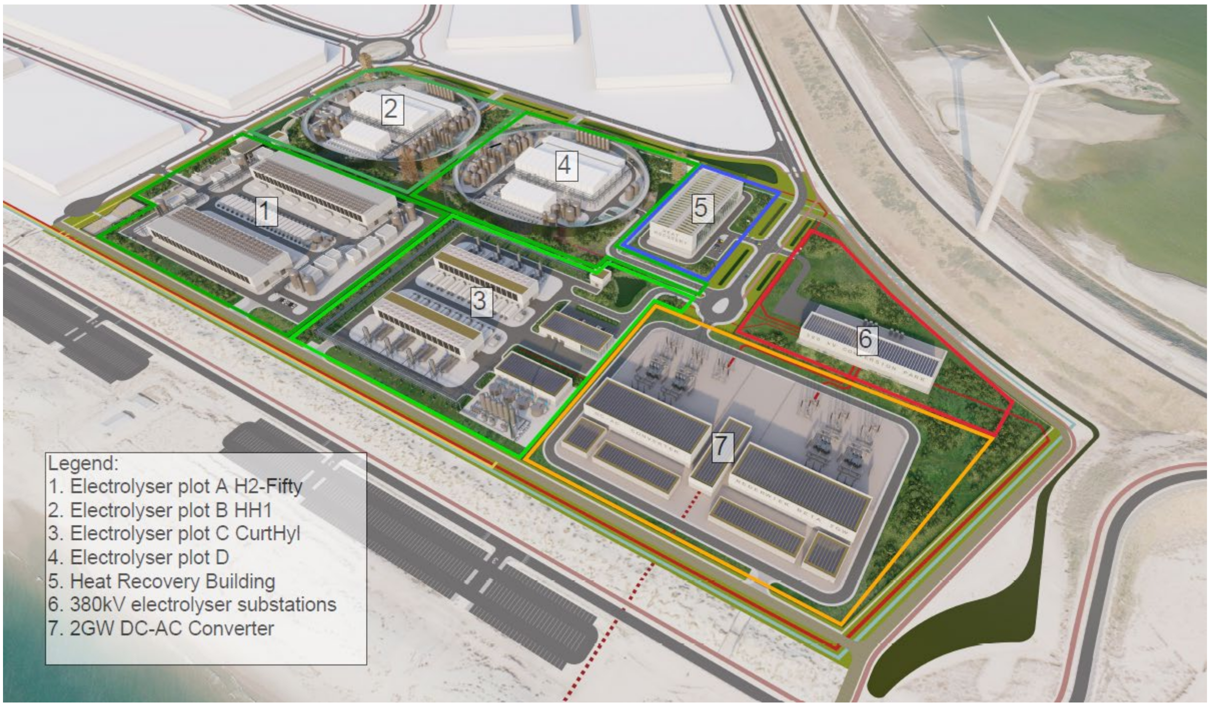


Figure S1. Artistic impression of power supply and green hydrogen production at a Conversion Park, Rotterdam Maasvlakte

The Institute for Sustainable Process Technology (ISPT), in cooperation with Hitachi Energy and consortium partners Equinor, HyCC, Ørsted, Port of Rotterdam, and Yara, has completed a feasibility study to explore (hybrid) electrical layout, incorporating DC and AC connections, and to develop optimised power conversion schemes for a GW scale water electrolysis plant.

The objective is to prepare a conceptual design for a converter topology that enables the integration of this new electrical layout, highlighting both its benefits and limitations. Based on this design, a comparison has been made between a new electrical layout, which utilises novel converters, and a typical GW green hydrogen plant that employs transformers and rectifiers (see Figure S2). This comparison is carried out by detailed modelling using simulation software, evaluating the electrical performance of the entire plant - from the point of common coupling to the electrolysers. The analysis includes all transformers, switchgear, converters, cabling, busbars, and electricity consumers. The aim is to illustrate potential efficiency gains, power losses, harmonic emissions, grid requirements, and costs (CAPEX and OPEX).

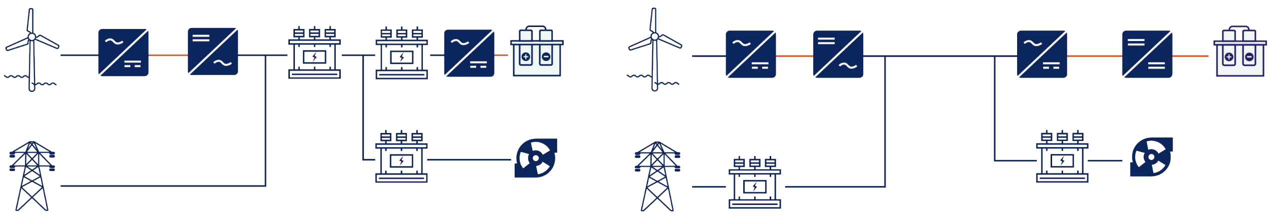


Figure S2. Hybrid electrical layouts with existing grid connection (left) and future connection with innovative converters (right) for a large scale green hydrogen plant with electrolysers and e-consumers

The proposed layout, as illustrated in Figure S3, has been selected as the most promising power converter scheme due to its relatively high maturity level, the suggested higher efficiency, the potential lowest complexity, costs, and footprint. This design utilises a power conversion topology that divides the medium voltage to a level suitable for the electrolyser module. Although other electrical layouts and power converter schemes were also identified, they were ultimately rejected in favour of this scheme.

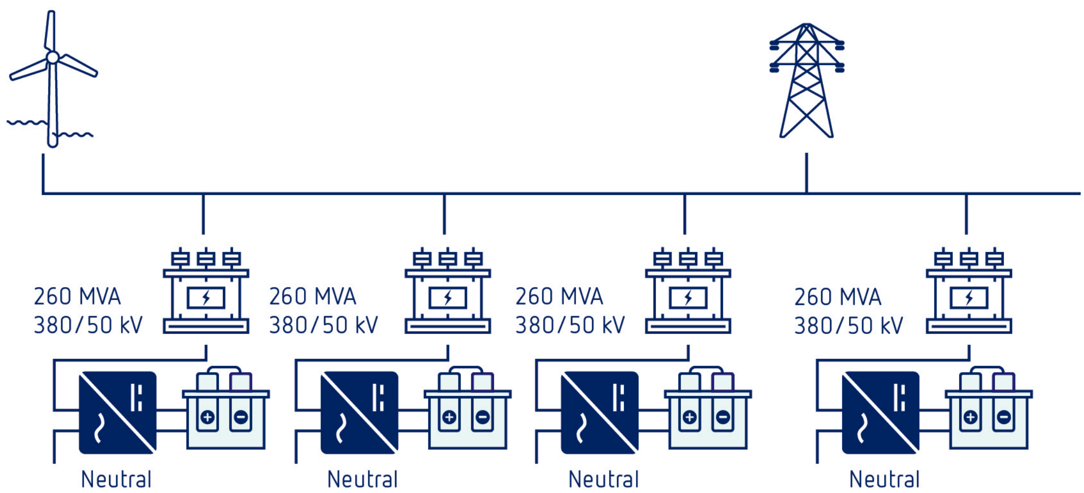


Figure S3. New electrical layout with proposed power converter scheme for a large-scale green hydrogen plant

The electrical performance analysis has been conducted for both the existing and the new layout The main findings of this feasibility study, for the coupling of a GW green hydrogen plant to an offshore wind farm and the HVAC grid, based on the new innovative converter design on medium voltage level, are as follows:

- The modelling suggests that the proposed solution could result in higher electricity efficiency utilisation, mainly through avoiding one conversion step.
- Power factor compensation and harmonic emissions are also improved. In the new design, no additional compensation, such as STATCOM, was used in the power flow. The reactive power consumption and power factor obtained are due to the existing electrical equipment, mainly transformers and cables.
- The footprint of the proposed electrical layout is difficult to estimate as there are many unknowns in the power ratings and sizing of the converters. It should be noted that the electrical systems would account for approximately 25% of the total area of a typical large-scale green hydrogen plant. It would be expected that the proposed layout would result in a smaller footprint.
- CAPEX is expected to be slightly higher and OPEX slightly lower (due to efficiencies). Maturity is low and uncertainty level is high, so it is too early to draw conclusions on the economics.

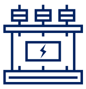
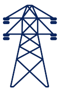
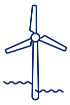
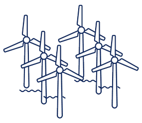
The proposed innovative power converter is not available in the short term and will require further development in both hardware and software. Special attention is required to galvanic isolation due to the medium voltage connection with different (grounding) potentials. It is recommended to further investigate the proposed innovative converters, optimizing the techno-economic size and feasibility, enhancing power quality, the galvanic isolation, and improving interfaces with the electrolysers.

Abbreviations

Abbreviation	Description
A	Ampere
AC	Alternating Current
AWE	Alkaline Water Electrolysis
BOL	Beginning-of-Life condition stacks
BoP	Balance of Plant
DC	Direct Current
EB	Electrolyser banks
EL	Electrolyser
EoL	End-of-Life condition stacks
H_2	Hydrogen
HVAC	High Voltage Alternating Current
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
IMVC	Innovative Medium Voltage Converter (IMVC)
kV	kilo Voltage
HVDC	High Voltage Direct Current
LV	Low Voltage
LVDC	Low Voltage Direct Current
MOSFET	Metal Oxide Semiconductor Field-Effect Transistor
MV	Medium Voltage
MVA	Mega Volt Ampères
Mvar	Mega volt ampères as reactive power
MVAC	Medium Voltage Alternating Current
MVDC	Medium Voltage Direct Current
MW	Mega Watt
OLTC	On Load Tap Changer
ONAN	Oil Natural Air Natural
P	Active Power
PCC	Point of Common Coupling
PEM	Proton Exchange Membrane
POI	Point Of Interconnection
Q	Reactive Power

RFNBO	Renewable Fuels of Non-Biological Origin
SiC	Silicon Carbide
SST	Solid State Transformers
TR	Transformer/Rectifier
TRL	Technology Readiness Level
TSO	Transmission System Operator
VDC	Voltage at Direct Current
WE	Water Electrolysis

Legend

	Converter: converting one level of DC to another level of DC
	Inverter: converting DC to AC to another current level
	Rectifier: converting AC to DC to another current level
	Transformer
	AC-grid
	Electrolyser
	Pumps and compressors
	AC Electricity supply
	Wind turbine
	Wind farm (renewable electricity)

Contents

1. Introduction

Since the "War of the Currents" at the end of the 19th century, the electricity grid, devices and machineries have predominantly been based around Alternating Current (AC) technology. Water electrolysis, the electrochemical process of splitting water into hydrogen and oxygen, however, requires Direct Current (DC). The common way is to supply renewable electricity for production of green hydrogen via AC-grid and to convert to DC at utilizable voltage for electrolysers, which for bigger plants requires a large number of medium voltage transformers and rectifiers. A distribution design in DC can potentially provide advantages in a GW scale hydrogen plant. It is therefore of interest to investigate more optimised power conversion schemes for large-scale green hydrogen plants.

As HVDC connected renewable energy assets and interconnectors are becoming more common, in the future direct connection of HVDC infrastructure with converters to medium voltage (MV) and to low voltage (LV) could make sense to feed large-scale electrolysers operating at LVDC. For instance, in United Kingdom the Dogger Bank Wind Farm which is already partly constructed will supply offshore wind energy to the UK grid by 320 kV HVDC lines and converted to 400 kV AC grid onshore.[1] In The Netherlands, 2GW 525kV HVDC transmission lines will connect offshore wind farms to onshore 380kV HVAC power grids through interconnectors with power inverters (DC/AC) in 2030.[2] Hence, electricity can be transmitted to large scale electrolysers, like a hydrogen conversion park in Rotterdam, see Figure 1. The HVDC to MVDC and MVDC to LVDC converters are not yet mature for this purpose and still need to be developed.

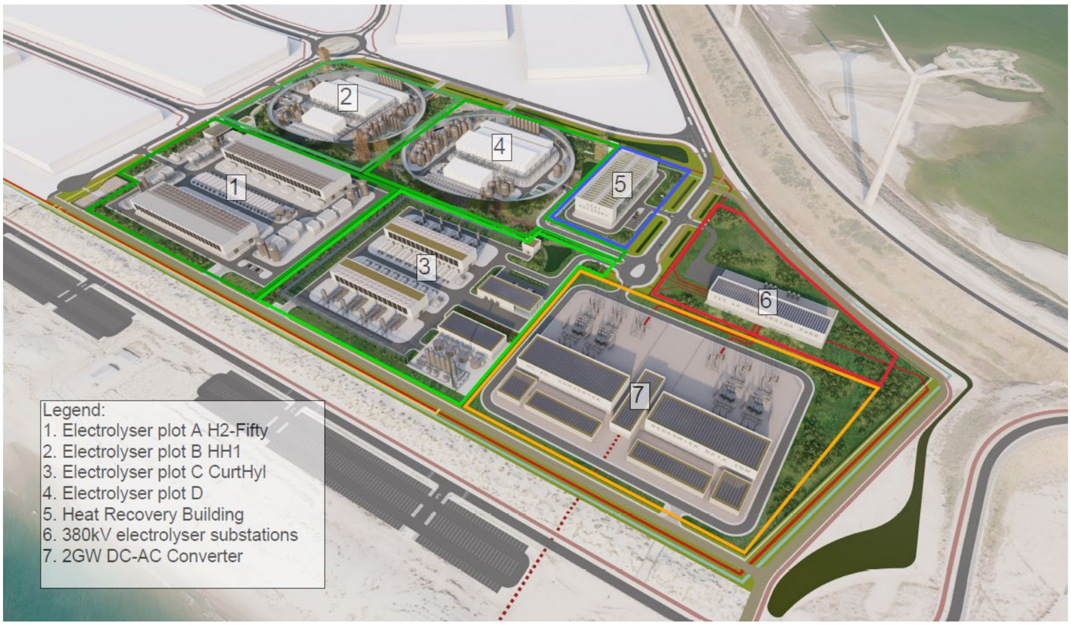


Figure 1. Artistic impression of power supply and green hydrogen production at a Conversion Park, Rotterdam Maasvlakte [3]

[1] Wind Farm Construction - Dogger Bank Wind Farm
[2] TenneT accelerates grid expansion and energy transition
[3] Picture courtesy from Port of Rotterdam

2. The consortium

The Institute for Sustainable Process Technology (ISPT), Hitachi Energy and consortium partners form industry have completed a feasibility study to investigate a new electrical layout with DC connection to a GW scale green hydrogen plant. In this feasibility study, Hitachi Energy was responsible for exploring a new electrical layout and a novel power converter design for this application. The design was prepared in cooperation with consortium partners Equinor, Hitachi Energy, HyCC, Ørsted, Port of Rotterdam, and Yara. ISPT, the leading institute for open innovation in the process industry in the Netherlands, was managing this one-year project, which was finished in May 2024. This project is a follow-up of the ISPT Gigawatt (GW) scale electrolyser project, which delivered an advanced 2030 design for a (virtual) one GW green hydrogen plant connected to a 380kV AC grid with AC/DC rectifiers, see Figure 2. [4]

Figure 2. Illustration of layout for advanced GW green hydrogen plant 2030

3. Goal

The goal of this feasibility study is to assess new AC and DC solutions for connecting large scale green hydrogen plant to renewable electricity systems like offshore wind farms in a time horizon to 2030. More specifically, the objective is to prepare a conceptual design for a converter topology, to make this possible and to show the benefits and constraints. Based on this design a comparison has been made between a new electrical layout using novel converters and a typical GW green hydrogen plant. The aim is to model and illustrate the gains in efficiency, power losses, harmonic emissions, grid requirements, and costs.

[4] Hydrohub GigaWatt Scale Electrolyser project

The converter topologies consist of specific arrangements of electrical components. A converter is often referred as a group name of electrical devices to change currents, comprising inverters, rectifiers and DC/DC converters. The converter topologies use semiconductors (e.g. Silicon or silicon-carbide-SiC) to convert, switch and control voltage and current. The electrical components include diodes, thyristors, transistors, and power electronics to control. Power electronics topologies used for high power and high voltage/ current applications are usually based on thyristors converting between AC and DC . More advanced topologies use high frequency active front-end switches like insulated-gate bipolar transistor (IGBT) and metal oxide semiconductor field-effect transistor (MOSFET) solutions. These topologies reduce harmonic emission distortion at different frequencies and load variations, meeting grid requirements. In case of an arrangement of advanced voltage source converters harmonic filtering equipment could be further reduced or eliminated. Moreover, an innovative medium voltage converter (IMVC) is applicable to a wide range of medium and high-voltage applications.

There are three types of converters:

Inverter: converting DC to AC to another current level

Rectifier: converting AC to DC to another current level

Converter: converting one level of DC to another level of DC

Another electrical device is a transformer, converting one voltage level of AC to another voltage level of AC. Unlike conventional transformers with copper windings and oil cooling, advanced solid state transformers (SST) use semiconductors and power electronics, which can adjust voltage levels rapidly and precisely, and control power factor.

4. Scope

The project scope is indicated in Figure 3 showing a high-level block diagram for representing a general idea for off-grid operation of electrolysers as well as auxiliary power supply from the MVAC grid to other electricity consumers. It is suggested to include both HVDC and HVAC/MVAC electricity supply to the electrolyser stacks (allowing for minimum load power supply to stacks, as well as potentially grid balancing and frequency restoration). In the operation condition, all the power used to generate the hydrogen is coming from a renewable source in accordance with RFNBO delegated act. [5]

The feasibility study comprises the complete electrical infrastructure and electrical equipment for an onshore large-scale green hydrogen plant with alkaline water electrolysis (AWE) technology. The total capacity of the green hydrogen plant is 1 GW at End-Of-Life conditions. [6] This includes the HV cable to the substation and interconnector, transformers, switchgear, converters, filters, busbars, and associated infrastructure needed for their proper installation and operation, i.e., auxiliary transformers, civil costs, cooling systems, control systems.

The battery limits are at the Point of Common Coupling (PCC) to the grid and at the terminals of the electrolyser stacks. There are two PCC's, one to feed the BoP and utility consumers from the MVAC grid and one to feed the electrolysers from the HVDC or HVAC grid. The offshore connection to the wind farms and HVDC lines are not included.

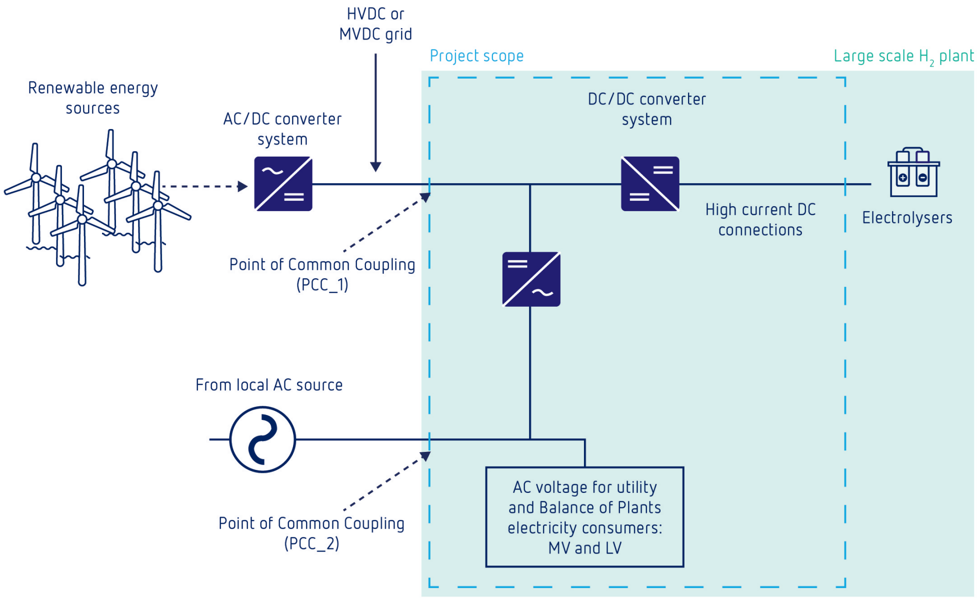


Figure 3. Off-grid and grid connection of a large-scale green hydrogen plant

[5] Delegated regulation - 2023/1184 - EN - EUR-Lex (europa.eu)
[6] Electrolyser stack end-of life (EOL) condition is typically defined at 10% voltage increase compared with Beginning-of-life (BOL).

5. Conventional electrical layout

A large-scale hydrogen plant can be connected to a HVAC grid and an offshore wind park through an interconnector, see Figure 4 for a typical electrical layout. Also, the connection to the BoP electrical consumers is indicated (pump symbol). In the existing situation, the plant is connected to the grid by 380 kV (usually underground) cables at a substation. Today, the power from an offshore windfarm is also grid connected, so through HVAC. Power supply to the electrolysers is through transformers and transformer-rectifiers.

As benchmark for the conventional situation the state-of-the -art ISPT Gigawatt (GW) scale electrolyser project is considered, which resembles this layout. [7] The power supply is 380/33 kV with thyristor-based rectifiers. The power rating of the stacks connected to the power electronics is assumed at 5MW. [8] The other electricity consumers are pumps, compressors, ventilation, etc, which are part of the Balance of Plant (BoP), and utilities, like cooling water pumps. Compressors are included going from atmospheric electrolysis to 30 bara at battery limit to feed hydrogen into a hydrogen pipeline. The assumed distance between the PCC and the hydrogen plant substation is 3.5 km and between the substation and the HV transformers about 1km, total HV cables is estimated at 13km. [9]

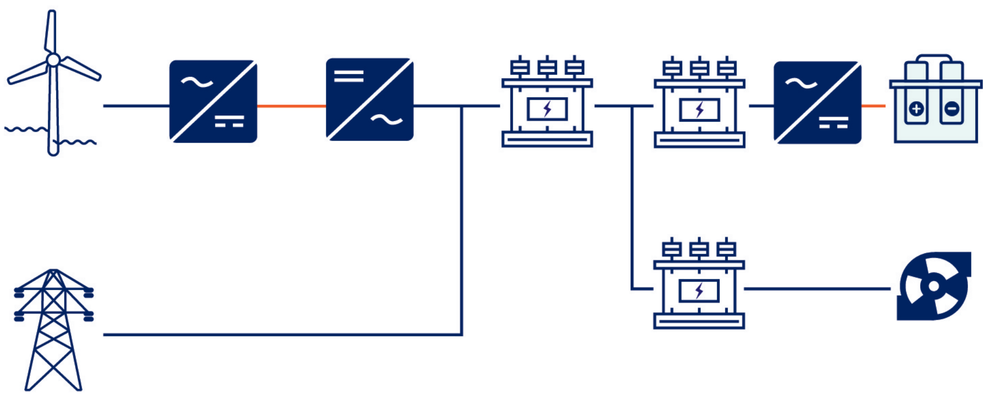


Figure 4. Electrical layout with grid connection for a large scale green hydrogen plant

[7] Hydrohub GigaWatt Scale: building an electrolysis plant (ispt.eu)
[8] In the model no distinction is made between alkaline electrolyser make and technology.
[9] Port of Rotterdam, conversion park Maasvlakte, distances between the PCC and the hydrogen plant substation are up to 5-6 km and between the substation and the HV transformers about 0.5 to 0.8km.

6. New electrical layouts

In this study, different layouts and power converter schemes have been identified and evaluated to feed the electrolysers directly connected to the external renewable power source through HVDC or MVDC. Hybrid solutions with both HVDC and HVAC grid connection are considered. Four options have been developed with the focus to feed the electrolysers with as few transformation steps as possible. In Figure 5 an illustration is provided of the options with high level electrical layouts.

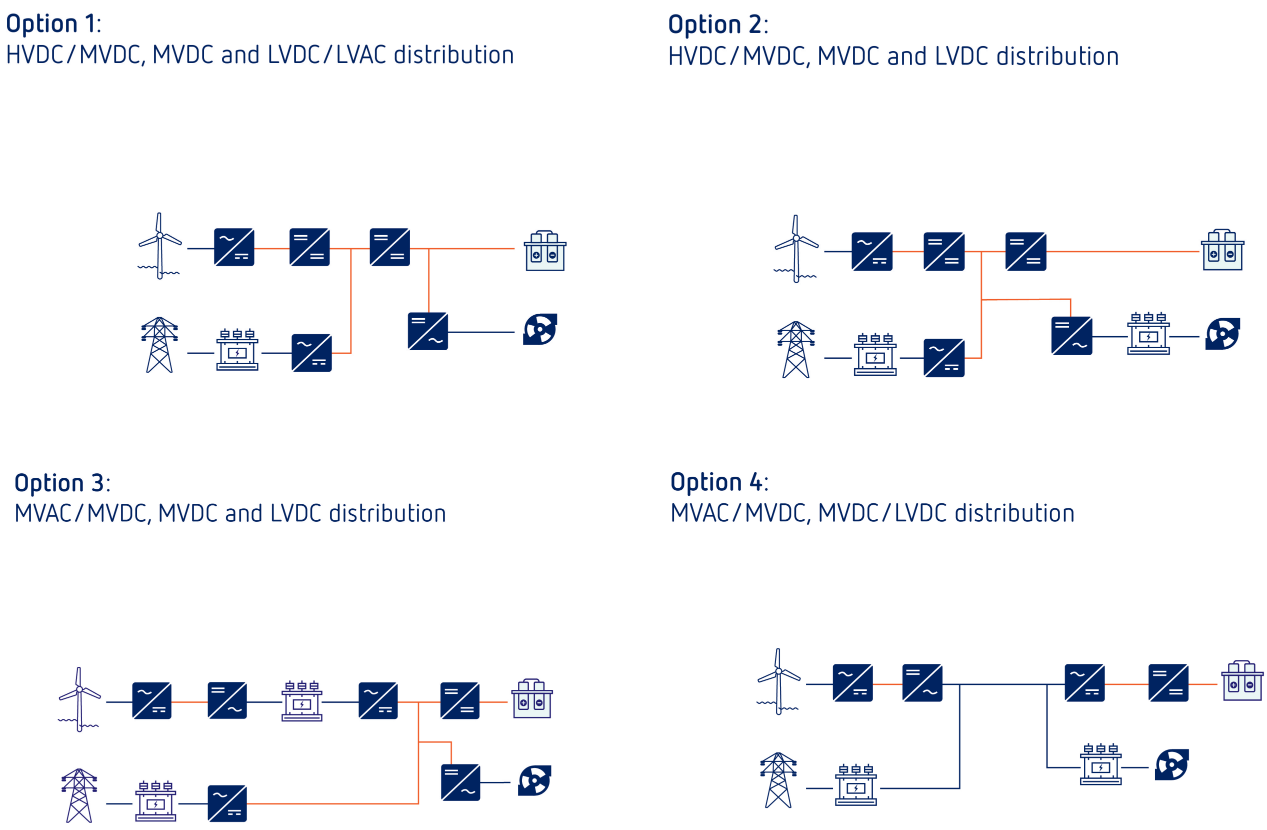


Figure 5. Different hybrid options for electrical layout of a large scale green hydrogen plant

Today, the 525 kV connection with the offshore wind farm is considered to use HVDC with AC interface in the substation. HVDC is a mature technology and available at this stage and widely used in the future connection with offshore wind farms in the short and midterm, in contrast with HVDC/MVDC converter technology which is not available at this stage.

The options 1 and 2 are similar using these newly to be developed HVDC/MVDC/LVDC converters to feed the stacks directly through HVDC with renewable electricity and through inverters from the 380 kV AC-grid. The main difference between option 1 and 2 is the inverter voltage level (medium resp. low) to supply power to the balance of plant equipment.

The option 3 and 4 are based on HVAC power supply from renewables (with power being transferred from the long distance through HVDC) and connected as well to the grid. The option 3 uses MVAC transformers-rectifiers, and MV/LV DC-DC converters. The option 4 layout consists of an innovative concept distributing MVAC directly to LVDC in the stack.

7. Assessment criteria and electrical modelling

A preliminary assessment has been made to screen the options with power converter schemes based on several criteria agreed upon at the start of the study. Hence, one option has been selected for the concept development of the power converter technology and modelling of the electrical system. Using these criteria, the selected option is compared with a typical electrical layout for a GW green hydrogen plant.

The criteria are:

- Maturity of the converter technology: expectation to have this available on the market in 2030 and assuming that a competitive product can be developed [10]
- Efficiency: losses in the cables/busbars, transformers and converters
- Reliability: failure rates, simplification of the layout and components
- Footprint: surface area required for the electrical system
- Harmonics emissions: Power electronics or need for filters [11] to meet grid requirements THD<0,4% [12]
- Power factor 0.9
- Personal safety: galvanic isolation
- Cost CAPEX: high level qualitative assessment relative to a HVAC green hydrogen plant
- Cost OPEX: indication of benefits based on efficiency gain

Power system analysis software is used predominantly to determine the improvement in efficiency, calculate reactive power, and reduce the harmonics emissions between the conventional and new electrical layout. Modelling of the system is done in DIgSILENT Power Factory 2022 SP4. The following information was provided to create the electrical model of the plant.

- Transformers: Nominal power (Sn), nominal voltages, short-circuit impedance (Zcc), load losses (Pw), magnetizing current (Xu) and no-load losses (Po), connection group type, earthing type and value, tap changer and number of taps and tap rate, type of voltage regulation.

[10] The maturity is usually expressed as Technical Readiness Level (TRL) but is here done in a more qualitatively way to compare technology maturity between the options.
[11] By way of comparison, AC harmonic filters of typical line-commutated converter stations can cover nearly half of the converter station area.
[12] The grid requirements as provided by TenneT for the ISPT Hydrohub GigaWatt Scale Electrolyser project have been used. These harmonic emissions and reactive power requirements have been determined for a virtual 2030 situation at PCC Substation Vlissingen The Netherlands. No rights can be made for future usage in actual projects.

- Cables and busbars from PCC to transformers, converters and electrolysers: type, material, length, section, AC resistance/reactance/susceptance/conductance, type of grounding connection at each side of the cable.
- Technical data for the motors: type (induction, synchronous, fed with VSD), rated voltage and power, impedances. All the MV motors are modelled individually while the LV motors are represented as equivalent aggregated model (as per the existing model to be provided to consulting). Detailed characteristics for the load; type of load and distribution.
- Apart from the electrolyser banks, only the BoP equipment that have an impact on the electrical studies, such as compressors and pumps, is explicitly modelled, while the rest of auxiliary equipment is represented as a lump load.
- Software model for the electrolyser is not available, so it was considered like a static load with the equivalent consumption, based on a typical I/V curve.

8. Converter topologies

The indicative maturity level of the different converter technologies for each option is presented in Table 1. The layouts and converter topologies for each option are more elaborated in Figures 6 to 9. The different converters are numbered in these figures which correspond to the Table 1.

Table 1. Maturity level (TRL) of the different converter technologies

Nr.	Electrical layout	Option 1	Option 2	Option 3	Option 4
#	Converter type	HVDC/MVDC. MVDC and LVDC distribution	HVDC/MVDC. MVDC and LVAC distribution	MVAC/MVDC. MVDC and LVAC distribution	MVAC/MVDC. MVDC-LVDC distribution
1	HVDC/MVDC	-	-	NA	NA
2	MVDC/LVDC	0	0	0	NA
3	LVDC/LVAC	0	NA	NA	NA
4	MVAC/MVDC	0	0	0	NA
5	MVDC/LVAC	NA	0	0	NA
6	MVAC/MVDC	NA	NA	0	0
7	HVDC/HVAC/MVAC	NA	NA	+	+

+	Available and proven technology.
0	Not available yet, possible development in mid-term <2030
-	Not expected available in mid-term <2030, possible development >2030
NA	Not applicable

The suggested converters in the opted layout configuration with DC/DC-connection show relatively low technology maturity levels. Especially the HVDC/MVDC converter #1 in option 1 and 2 is not expected on the market at least in mid-term and depending on the development from the market whereas the other MV and LV converters as indicated in all options could be potentially developed within a foreseeable time horizon. Moreover, the DC/DC converters #1 and #2 require that a transformer is necessary to provide the voltage adaptation and galvanic isolation. Several designs for the converters #1 and #2 are already proposed in academic publications[13], but power isolated converter for direct translation of HVDC to MVDC presents yet challenges to solve. The HVDC/HVAC interconnectors #7 are already available on the market, which are needed for the option 3 and 4.

Summarising, MV converter technology is still low on maturity. This is partly due to the operation in “islanded mode” directly connected to the offshore wind farm, which is not feasible right now since the grid forming functionality is not available at the existing wind turbines. Whether it is interesting nonetheless to invest in the development of new topology with DC/DC converters or other solutions depends also on the other criteria.

Option 1: HVDC / MVDC, MVDC and LVDC / LVAC distribution

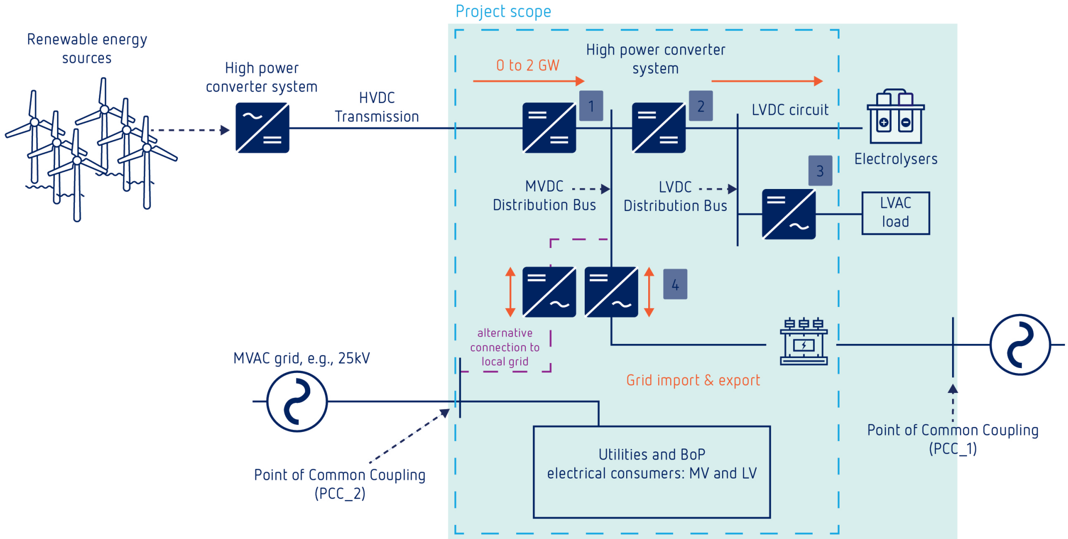


Figure 6. Electrical layout hybrid. Option 1. HVDC / MVDC, MVDC and LVDC / LVAC distribution

[13] http://www.resonantlinktechnology.com/renewables/

Option 2: HVDC/MVDC, MVDC and LVDC distribution

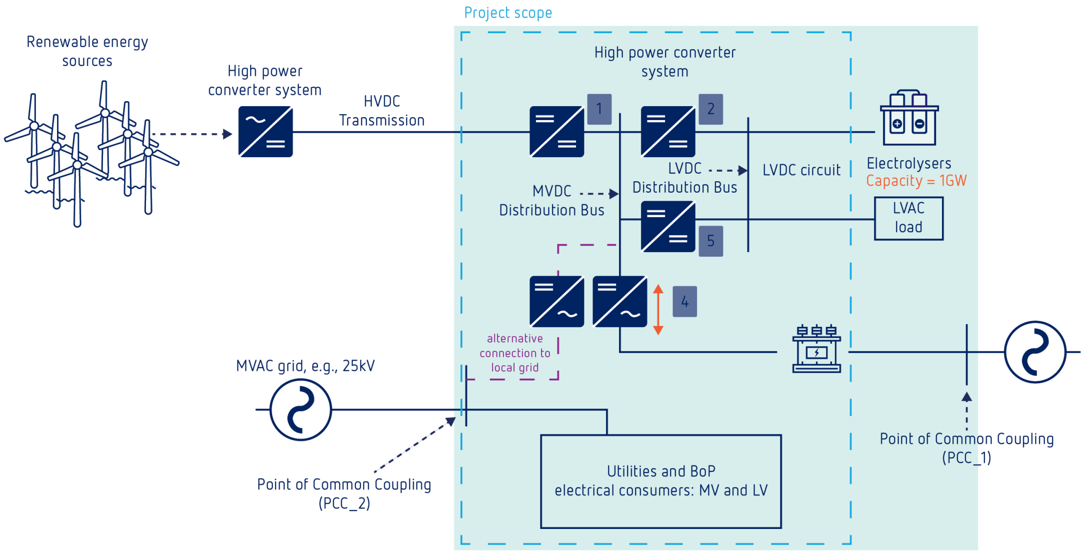


Figure 7. Electrical layout hybrid. Option 2 HVDC/MVDC, MVDC and LVDC distribution

Option 3: MVAC/MVDC, MVDC and LVDC distribution

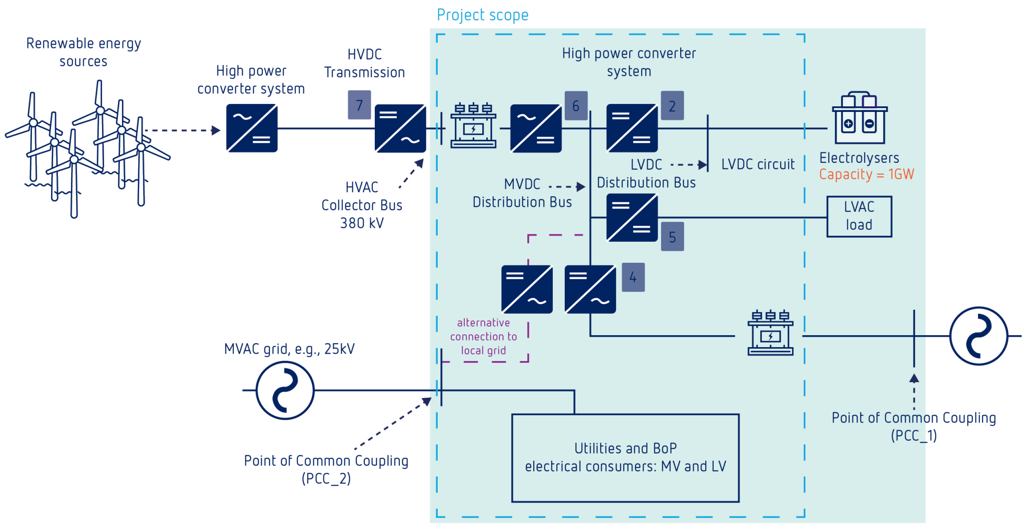


Figure 8. Electrical layout Hybrid. Option 3. MVAC/MVDC, MVDC and LVDC distribution

Option 4: MVAC / MVDC, MVDC / LVDC distribution

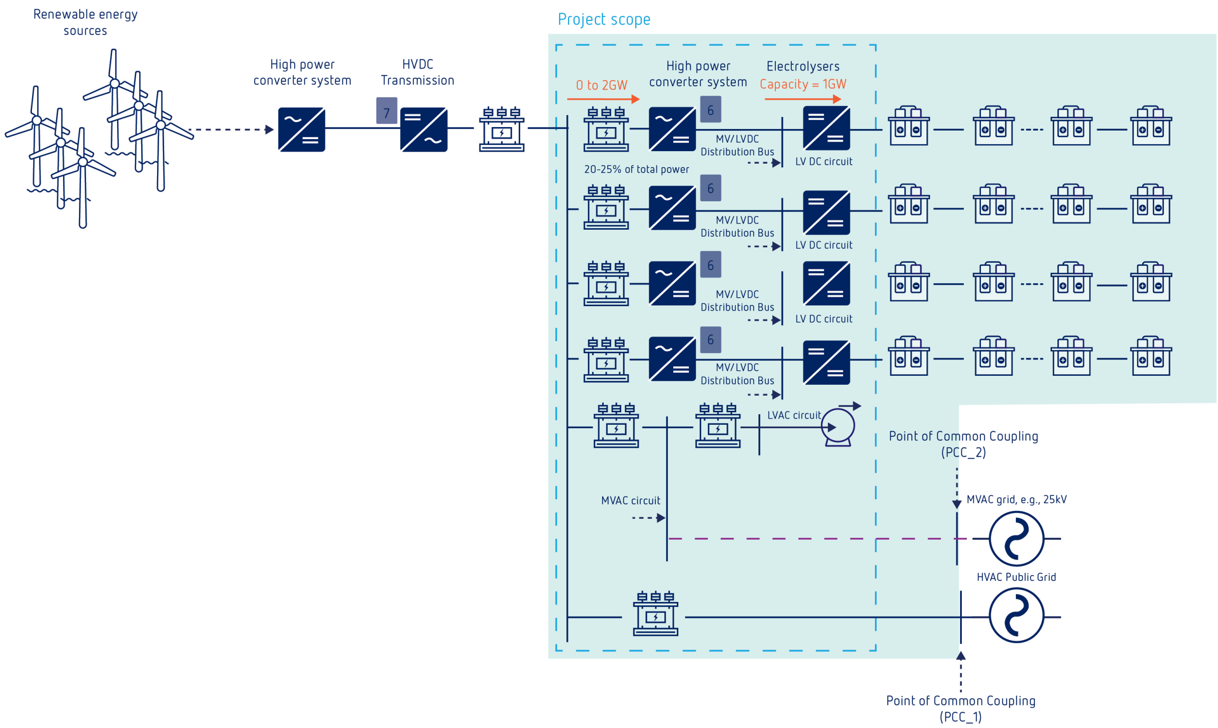


Figure 9. Electrical layout Hybrid. Option 4. MVAC / MVDC and MVDC / LVDC distribution

The results of the other criteria, including Table 1 summarised, are given in Table 2. Regarding efficiency, option 4 suggests a higher efficiency due to the reduced complexity of the layout and components. Option 1 and 2 would bring lower efficiencies due to the additional converters to connect the external grids and with the LV loads in the plant. Also, efficiency at different load is slightly lower in transformer and HVDC. Option 3 has the lowest efficiency due to the additional converter #6. The reliability shows a similar pattern, with option 4 having the highest reliability due to the reduced complexity of the layout. The reliability of option 1 and 2 have a lower efficiency due to more components and lower maturity levels.

The footprint of the proposed electrical layout is difficult to estimate as there are a lot of unknowns with the converter power ratings and sizing. One should bear in mind that the electrical systems would make around 25% of the total area of the green hydrogen plant. Nevertheless, it could be expected that the option 4 would result in the lowest footprint.

In all options, harmonic filters would be needed at DC side of the converter and possible in the connection with HVAC and MVAC public grid. Possible additional filters due to converter MVAC/MV/LVDC (#6) are needed for option 3 and 4. More calculations are needed to determine the harmonic emission limits, e.g. total harmonic distortion (THD), and therefore filters to meet the grid requirements.

The personal safety should be according to the relevant IEC standards; this shall be part of the design.

The Total Costs of Ownership comprises the weighted average lifetime costs including CAPEX and OPEX. Options 4 is expected to have the lowest TCO. As a rough estimation the CAPEX for option 3 and 4 would be considered lower both compared with the high number of components which are needed for the converters in the options 1 and 2. Also, the uncertainty level for option 4 is lower than for the other options with lower TRL. The OPEX are depending on the efficiency and reliability, so maintenance costs and replacement of components, which are probably less favourable for the options 1 and 2.

Based on this assessment option 4 has been selected as most promising power converter scheme due to the relatively high maturity level, the suggested higher efficiency, the potential lowest complexity, costs and footprint.

Table 21. Qualitative assessment of the options with electrical layout and converter topologies

Electrical layout	Option 1	Option 2	Option 3	Option 4
Maturity (Table 1)	-	-	0	0
Evaluation criteria	HVDC/MVDC. MVDC and LVDC distribution	. HVDC/MVDC. MVDC and LVAC distribution	MVAC/MVDC. MVDC and LVAC distribution	MVAC/MVDC. MVAC and LVAC distribution
Efficiency	0	0	-	+
Reliability	0	0	-	+
Footprint	0	0	-	+
Harmonics & filtering	0	0	0	0
Personal safety	0	0	0	0
Total Costs of Ownership	-	-	0	+

+ Higher performance

0 Neutral

- Lower performance

9. New electrical layout and converter design

The new electrical layout is depicted in Figure 10 and based on option 4 as shown in Figure 9. The proposed power converter scheme uses medium voltage converter topologies to directly supply electrolysers in the secondary side of the electronic block. The power supply system requires a substation from HVAC to MVAC, comprising only one step-down transformer and circuit breakers. The transformer feeds the MVAC power converter, which through the power electronic convert the alternate voltage to LVDC adapted to the requirements of the electrolyser. The power conversion from AC to DC feeding the electrolyser uses an innovative topology, connected to MVAC and stepping down to LVDC, connecting each electrolyser to a sub-module branch, on each medium converter arm, dividing the voltage to a potential suited for the electrolyser module. The power converters provide the direct current supply to the electrolyser itself.

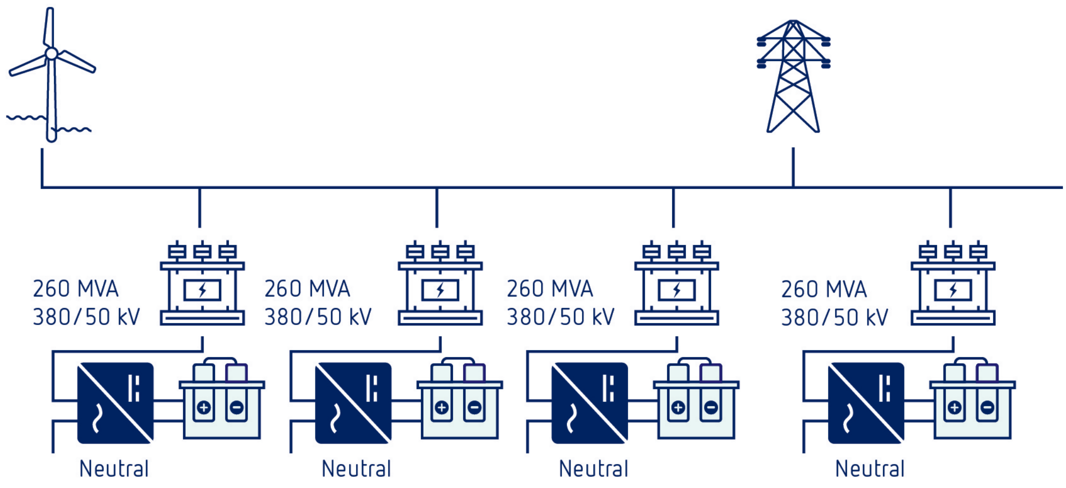


Figure 10. New electrical layout with proposed power converter scheme for a large-scale green hydrogen plant

The new layout for a GW green hydrogen plant would therefore comprise:

- 260 MVA power transformers, total 4*260 MVA=1040 MVA.
- Each transformer and converter are dedicated to one electrolyser bank.
- There is no common MV busbar as in the state-of-the-art design.
- A bus duct connects each power module from the converter to the electrolyser.
- 4 sets of converters rated totally 240 MW to feed the electrolysers
- The total rated power of the converter is 4*240= 960 MW, but it is considered for the analysis and simulations performed that the converter could provide that additional 40 MW.

The proposed new layout in Figure 10 compared with the conventional layout in Figure 4 replaces the MV/LV transformer and rectifier by directly feeding the power from HVAC to MVAC with a 380 / 50 kV 260 MVA transformer followed by converters. The MV cables connecting the main transformers to the rectifier transformers can therefore be omitted. The auxiliary equipment and load do not change and is therefore not depicted in the Figure 10.

The proposed power converter is not available in short-term requiring necessary development in both hardware and software. Special attention to galvanic isolation is required due to MV connection with different (grounding) potentials.

10. Electrical performance

From the electrical point of view the conventional electrical layout and the new layout with proposed power converter scheme should work properly, providing correct voltage profile and loading of the equipment within the rated values. A comprehensive modelling and analysis of both layouts was performed in specific software to ensure the proper performance, including:

- Power flow: which showed the active power flowing through the equipment, the voltage profile, loading in the transformers and cables, the efficiency and losses
- Reactive power necessities, to size the equipment responsible to compensate of Q
- Power quality analysis, with harmonic distortion at the different buses of the plant

The results of the modelling are presented in Table 3 and explained in this section.

Table 3. Electrical performance conventional and new electrical layout and converter topologies

Electrical layout	Conventional	New
Evaluation criteria	Based on GW design[14]	New layout (option 4) and converter design
Efficiency [15]	97.94%	98.68%
Reliability	0	+
Footprint	0	30% reduction of electrical plot
Harmonics emissions	0	80% improvement
Power factor	STATCOM required	No additional compensation needed
CAPEX and OPEX	0	t.b.d.

The harmonic distortion was also compared, demonstrating the proposed design reduces the THD at the POI bus from 0.752 % to 0.1437 %, fulfilling the requirements from the TSO, see section 7.

- In the state-of-the-art design, the harmonic profile requires the installation of filters in the MV busbars connected to the rectifier transformer.
- In the new power converter solution, the harmonic distortion is below the limits so no filters should be needed.

The reactive power compensation is the second important parameter that provides a differentiation between both designs.

[14] Based on a thyristor B6 topology, losses includes compensation equipment's
[15] Energy consumption = (Average yearly load rate) * Power (at POI) [MW] *24 (hours/day)*365 (days/year)* x [€/MW]

- In the new design no additional compensation was used while performing the power flow, so the obtained reactive power consumption and power factor is due to the existing electrical equipment, mainly transformers and cables.
- The requested reactive power at the 380 kV main substation in the state-of-the-art design is 350 Mvar (excluding the Q demanded from the auxiliaries) while with the new power converter is 111 Mvar (excluding the Q demanded from the auxiliaries), so additional 240 Mvar should be necessary (STATCOM)
- The results showed that the cables generate additional 112 and 22.5 Mvar respectively between the POI and the 380 kV main substation.
- If such cables should not exist, with the state-of-the-art design, should be necessary to add ≈300 Mvar of additional compensation to achieve the power factor 0.9 at POI, which means the 30% of total rated power, which is the typical rates used actually to compensate the green hydrogen plant. That additional cost must be added to the CAPEX.

The overall electrical efficiency measured at the POI increased from 97.94% with the current design while to 98.68 % with the new converter design mainly through avoiding one conversion step.

It is suggested that the CAPEX will be slightly higher and OPEX slightly lower (due to efficiency). Maturity is low and uncertainty level is high so it is too early to draw conclusions on the economics. This needs to be determined (t.b.d.). Further analysis needs to be performed to confirm the cost competitive solution.

11. Conclusions and recommendations

A new electrical layout with new innovative converter design on medium voltage level has been explored for hybrid coupling of a GW green hydrogen plant to an offshore wind-park and the HVAC grid. A feasibility study with electrical modelling has been done for the new power converter scheme compared with an electrical layout with transformer-rectifiers for a state-of-the-art green hydrogen plant. The modelling suggests that the proposed solution could result in improved electrical performance, concerning efficiency, power factor compensation and harmonic emissions.

The following actions are recommended to conduct further specific studies:

- The further investigations of the proposed innovative converters;
- The optimized techno-economic size and design based on the total power considering the necessary assets that could lead to a change in the cost;
- Power quality analysis with operation at different power levels, i.e. when operation providing grid services controlling frequency restoration and/or possibly reactive power (Q);
- More clarity is needed on maintainability and reliability of new power converters;
- Further analysis regarding the galvanic isolation due to the direct connection of the power converter;
- Interfaces with electrolyser, regarding ramping up and down, response times, impedances and ripples.

Colophon

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Authors
Hans van 't Noordende (ISPT), Javier Iglesias (Hitachi Energy), Weichi Zhang (Hitachi Energy)

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Franka Wijnbergen (ISPT)

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Address
Groen van Prinstererlaan 37, 3818 JN Amersfoort, The Netherlands

Telephone number
+31 (0)33 700 97 97

E-mail
info@ispt.eu

Website
ispt.eu

Consortium partners

Equinor, Hitachi Energy, HyCC, Ørsted, Port of Rotterdam, YARA and the Institute for Sustainable Process Technology (ISPT).

Join us!

ISPT.EU

The Institute for Sustainable Process Technology (ISPT)
Groen van Prinstererlaan 37
3818 JN Amersfoort
The Netherlands
t. +31 (0)33 700 97 97
info@ispt.eu

Hans van 't Noordende
Principle Expert
ISPT
hans.vantnoordende@ispt.eu

Siu Fai Au
Program Manager Hydrogen
ISPT
siufai.au@ispt.eu