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TNO report

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Feasibility study for a zero emission, hydrogen fuel cell powertrain for the Gouwenaar II

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Note:
This report should be seen as a high level case study. The presented results will be different for other inland shipping applications, vessel routes or for different H2 supply chains (local versus centralised, or combinations with other modes of transport

Summary

This study evaluates the technical and financial feasibility of a fully zero emission sailing with the Gouwenaar II, with a H_2 fuel cell powertrain. The Gouwenaar II is a 104TEU inland ship, which is currently equipped with diesel-electric powertrain. The following topics are covered in this document: sailing profile with energy demand, fuel cell power system, H_2 bunkering options, onshore H_2 production and TCO calculations. The analysis is done for one ship as well as for six (Gouwenaar) ships, sailing on the same route.

The study is supported by the Port of Rotterdam subsidy program ‘Schone binnenvaart en duurzame logistiek’ (clean inland shipping and sustainable logistics) and is carried out by a number of industrial partners[1] and TNO.
The project also includes a similar evaluation with a fully battery-electric driveline, which is reported in a separate report (1).

Operational profile
The operational profiles of the Gouwenaar for container transport from Alphen a/d Rijn to Maasvlakte II and Antwerp have been analyzed, leading to key numbers for power profile, energy consumption and trip durations. This leads to the specifications of the fuel cell driveline and H_2 storage requirements. The power system is consequently configured of a 600 kW fuel cell stack (6 units), combined with a peak shaving battery of about 330 kWh. The maximum electric energy consumption on roundtrips to Antwerp is around 11.5 MWh, which corresponds to about 760 kg of H_2 consumption. With safety margins for extra consumption (20%) and spare capacity (also 20%), this leads to a H_2 storage requirement of 1050 kg (bunkering on one location).

H_2 bunkering options and modularity
350 and 500 bar H_2 storage pressure levels are evaluated. With 500 bar pressure, the required 1050 kg for the return trip to Antwerp fits in one 40 ft container (21 ton total weight), but 500 bar (or 700 bar) pressure makes filling of H_2 tanks more complex than with 350 bar.
Three options for modularity and H_2 bunkering are evaluated. This includes bunkering with a high pressure hose from shore, exchangeable H_2 tanks containers, as well as exchangeable powerpacks (H_2 tank + fuel cells in one container).

The main advantages of modular units are:
- Flexibility: ships can switch between different kind of energy systems. For example between H_2 fuel cell powertrain to container batteries, or to diesel generator sets
- Standard modules can be made at lower costs (when series increase).
- It makes it easier to allow for a business model ‘energy as service’, in which the ship owner pays only for H_2 or for electricity onboard.

H_2 bunkering via exchange of H_2 container(s) takes about the same time as filling with a high pressure hose (about 2 hours).

[1] Partners are: Siemens, Wärtsilä, Damen shipyards and CCT-Nedcargo. Also supported by ENGIE, Eneco, Ballard and Linde.

The difference between separate modules for H_2 tanks and fuel cells or integrated modules (power packs) is not enormous. 'Separate modules' seems to have more advantages, because of the higher H_2 storage capacity per container and flexibility to independently size the fuel cell power system.

Safety considerations
The applicable legislation, as well as a long list of safety considerations have been summarized (in section 3) for the three bunkering options.
Main safety concerns regarding the hydrogen storage are loss of containment due to accidents or permeation of the hydrogen through the tank or pipe walls. The biggest gap is the lack of dedicated regulations, codes and standards for hydrogen as fuel in shipping.

Some existing codes and standards to provide guidelines for safe operation, are:
- IMO has no standards for hydrogen as alternative fuel, but there are several alternatives,
- DNV-GL have developed guidelines for most of the operations with fuel cell system,
- An alternative design process based on IGF code,
- A risk based approach as specified in SOLAS regulation II-1/55,
- IGF code covers the bunkering on the ship side, but the shore side needs further development.

Onshore H_2 production
For this project, dedicated onshore H_2 production via electrolysis at the CCT terminal location (Apherium) is evaluated based on the H_2 consumption for one and for six Gouwenaar ships. This consequently served as basis for overall investment costs and TCO calculations. Six Gouwenaar ship require four standard electrolyzer of 1.25 MW in order to produce sufficient H_2. For one ship, one electrolyzer is needed. For filling the high pressure H_2 tanks (350 or 500 bar), so called 'high pressure tubes' are evaluated. This is a good option for single ships or a small number of ships, because then there is no need for large buffer tanks.

Investment costs and TCO
Based on the on-board and the onshore investment costs, energy consumption and maintenance costs, the 'levelized costs of energy' for both H_2 and electricity (to be fed to the ship driveline) are calculated. It should be noted that most H_2 related components such as electrolyzers and fuel cells are produced in very small series (market introduction phase). This leads to relatively high prices and investment costs, which has its impact on the TCO calculations. The prices per kWh are given in the table below. The results show that the 2020 kWh price reduces from 0.63 to 0.51 when more ships take part in the battery exchange system This is mainly due to the more efficient use of the electrolyzers. The LCoE of (renewable) H_2 ranges from 7.16 to 5.32 EUR/kg (1 versus 6 ships). The LCoE of electricity (on-board) is substantially higher than the 0.17 EUR/kWh of electricity produced with diesel generator sets. The additional total costs for sailing on H_2 is consequently about EUR 750,000 annually per ship (based on six ships in 2020). This is based on the small scale decentralized H_2 production. All costs are calculated without any tax[2] on fuel, nor without any environmental subsidies[3].

[2] According to the Act of Mannheim taxation of fuel for inland shipping is not allowed
[3] These are for example the Dutch MIA, VAMIL and EIA arrangements

The table also gives the kWh costs projection for 2030, which is based on lower costs and higher efficiency for electrolyzers and fuel cells. This leads to a price range between 0.37 and 0.48 EUR/kWh.

Also future possible supply from centralized large H_2 production facilities could lead to substantially lower H_2 costs and consequently also lower electricity costs onboard. All costs are calculated without any tax[4] on fuel, nor without any environmental subsidies[5].

Table 1: Projection of CAPEX, OPEX and LCoE for 2030, based on expected efficiency improvement and costs reductions of electrolyzers and fuel cells (2).

	2020 (€/kWh)			2030 (€/kWh)		
	CAPEX	OPEX	Total	CAPEX	OPEX	Total
1 Ship H_2 fuel cell	0.26	0.37	0.63	0.21	0.27	0.48
6 Ships H_2 fuel cell	0.16	0.35	0.51	0.12	0.25	0.37
Stage V diesel direct	0.01	0.14	0.15			
Stage V diesel genset	0.03	0.14	0.17			

Recommendations
The following recommendations are made regarding safety aspects:
Qualification of compressed hydrogen tanks for maritime use.

More research with respect to:
- Understanding of and safety measures for fuel containment (compressed, liquid) during hazards like fire, collision, explosion.
- Development of requirements for piping of liquid hydrogen, based on LNG.

Regarding the further roll out of the H_2 fuel cell powertrain, we see a need for making choices on a European level on standardization in the H_2 supply chain and bunkering, especially with respect to:
- The H_2 pressure level for compressed H_2 storage, in relation to the preferred bunkering and H_2 supply chain options.
- The possible supply options and business models for sustainable H_2.

It is also very important to build demonstration ships, such that further experience is build up with qualification and classification of ships with H_2 storage and fuel cells and to build up operational experience on H_2 handling, energy consumption and other operational aspects.

[4] According to the Act of Mannheim taxation of fuel for inland shipping is not allowed
[5] These are for example the Dutch MIA, VAMIL and EIA arrangements

Contents

1 Introduction

Zero-emission inland shipping, with battery electric and H_2 fuel cell powertrains, is seen by both the government and industry as one of the important options for fulfilling climate objectives for 2050 for inland shipping. The advantage of inland shipping is, that the average power consumption is relatively low, but also with quite some space on-board for large batteries or H_2 storage. The diesel-electric powertrain is also becoming more popular. This powertrain is basically easy to transfer to a battery driveline or a H_2 fuel cell powertrain, which is important for a transition phase.

Green corridors are a concept launched by Freight Transport Logistics Action Plan of the European Commission symbolizing energy efficient freight transport corridors with reduced environmental impact (3). In the Zoeterwoude-Rotterdam route, various stakeholders including ship operators, authorities, transporters, suppliers and knowledge institutions are working together to develop the first green corridor in Europe. During this process, a wide range of ideas are developed to realise zero-emission transport along this corridor (4).

The objective of this project is to investigate the feasibility of zero-emission inland shipping with the Gouwenaar II on the routes from Alphen a/d Rijn to Rotterdam or to Antwerp. The project is supported by the Rotterdam subsidy program ‘Schone binnenvaart en duurzame logistiek’ (clean inland shipping and sustainable logistics).

In the overall project, two zero emission powertrain options are evaluated:
- Fuel cell powertrain in combination with hydrogen storage;
- Full battery-electric with exchange of battery containers only.

The results are reported in two separate reports: this report evaluates the battery-electric powertrain, as they only power source. The batteries are built in containers, who can be exchanged (or charged from shore at the home base). The feasibility study focusses on operational profiles and power and energy storage requirements, dimensioning of powertrain, safety aspects and regulations, infrastructure requirements and costs (TCO; Total Costs of Ownership).

In literature, there are a number of papers focusing on the overall fuel cell systems for maritime applications (5) (6). These are for background information, it is not the purpose of this report to summarize them.

The project is carried out as a cooperation between industry (Siemens, Wärtsilä, Damen shipyards, Ballard and Linde, the end-user: CCT-Nedcargo) and TNO as research institute. Except for Ballard and Linde, these were official project partners of the project.

2 H_2 Fueled Gouwenaar II

The inland waterway vessel Gouwenaar II, built in 2017, is 90 m long, 10.5 m wide, and has a capacity of 104 TEU. The single propeller is powered by a diesel electric driveline, with a 600kW electromotor. It sails between the container terminal Alpherium (in Alphen aan den Rijn) and Rotterdam or Antwerp.

To achieve zero-emissions sailing, electrical power provided by the generator sets are replaced by a fuel cell stack, which usually includes a battery for peak shaving. Considerable space is needed for compressed hydrogen storage. The option for liquid, cryogenic H_2 storage is not evaluated in this study. It should be noted that even at such high pressures or low temperatures, the energy density of hydrogen remains low compared to that of diesel: ± 1 kWh/l for compressed hydrogen at 350 bar or 2.3 kWh/l for cryogenic liquid H_2 at -253 ºC compared to 9.7 kWh/l for diesel (6). Also cylindrical tanks for H_2 take up more space than the flexible shaped tanks for diesel fuel. Therefore, bunkering needs to be done more frequently (every round trip) and the space requirement is higher than for diesel fuel.

The main parameters for defining the fuel cell power system are:
- Required power: the electric power that is needed to propel the ship and power board systems.
- Energy capacity refers to the amount of energy needs to be bunkered. This is equivalent to the electrical energy from the generator sets during the total trip length.

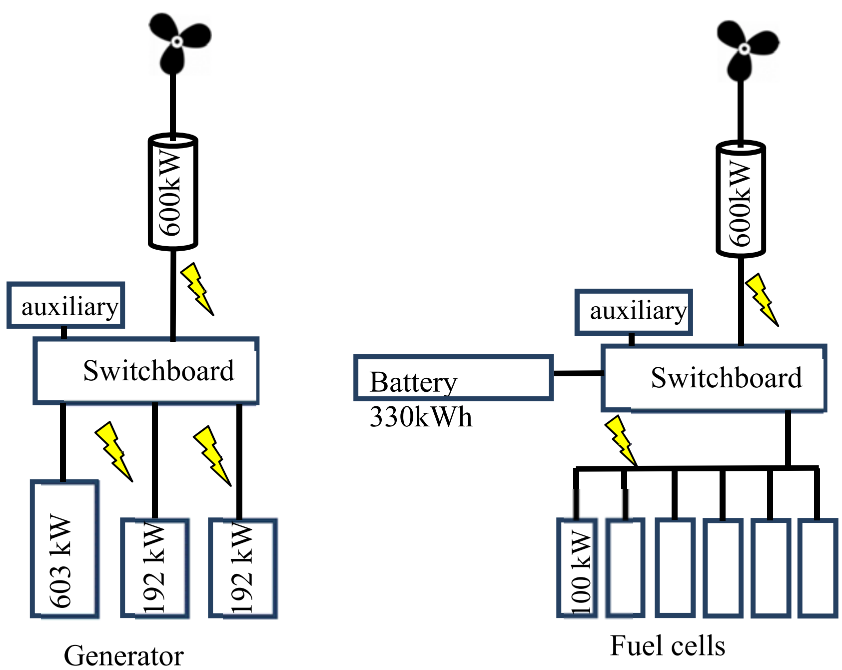


Figure 1: Drawing of the current diesel electric driveline (left) and fuel cell driveline (right). Converters for AC and DC are not drawn.

2.1 Hydrogen storage and bunkering options

The following three bunkering options are considered:

1. Bunkering with a (high pressure) hose from shore. The H_2 storage and fuel cells are installed permanently on-board of the ship.
2. Exchange of H_2 storage containers. The H_2 storage is done in 20' or 40' foot containers, which are exchanged by a crane during bunkering. The fuel cells are fixed on-board of the ship or also mounted in a separate container (usually permanently on-board of the ship).
3. Exchange of Power Packs. The hydrogen storage and fuel cells are combined in a container. The connection with the ship is an electrical connection. Complete power packages are exchanged by a crane during bunkering.

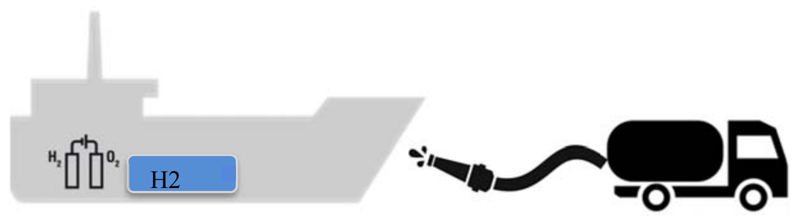


Figure 2 (option 1): Fuel cell power system and hydrogen storage are installed (semi) permanently on-board of the ship. Hydrogen is bunkered from shore to ship via hydrogen hoses.

Option 1: Bunkering with a hose from shore
Main characteristics of this option:

- In this option, hydrogen tanks (gaseous) are installed on-board (below or above deck).
- Shore to ship bunkering is needed.
- Bunkering needs to be done in the time that the ship is moored[6] (takes 5 hours at Alpherium). This may be achieved by using Constant Pressure Tubes (CPTs, see 2.4.4).
- Positioning the hydrogen storage and the fuel cell system on-board of the ship can be optimized (especially in the ship design phase).

Option 2: Exchange of H_2 storage containers
Modular system: The H_2 storage is done in 20' or 40' foot containers, which are exchanged by a crane during bunkering. Two sub options are distinguished:
a) the tank is put on shore, then relatively quickly filled (e.g. with constant pressure tubes) and loaded back on the ship, b) the H_2 container(s) is exchanged for a charged one which is on stock at the terminal. The fuel cells are fixed on-board of the ship or also mounted in a container (usually permanently on-board of the ship).

[6] In case of LNG bunkering, simultaneous operations (SIMOPS) such as loading/unloading cargo and embarking/disembarking passenger during bunkering shall be addressed in a risk assessment, and if overall project risk criteria can be met SIMOPS may be allowed (50).

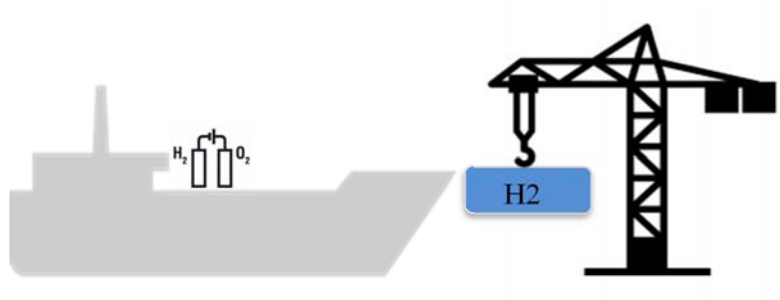


Figure 3 (option 2): Hydrogen tanks are packed in a container, fuel cells are installed on-board. Hydrogen tanks are hoisted on and off the ship. Bunkering occurs by lifting the empty container off the ship and refilling on land.

Main characteristics of this option:

- Power equipment is installed on-board (can still be modular).
- Ship owner can choose renting the equipment or 'energy as service' in which storage costs are included in the H_2 price.
- One 40'ft hydrogen container per ship
- Fast 'bunkering' by exchanging containers
- A hydrogen container in the cargo space leaves less cargo capacity (also valid for option 3), unless the design of the ship is optimized for this option. For example, by omitting part of the engine room or crew rooms.
- The fuel cell power system can also be standardized and modular, such that lease instead of purchase might be an option.

Option 3: Exchange of Power Packs
The hydrogen storage and fuel cells are combined in a 40 ft container.
The connection with the ship is an electrical connection. Complete power packages are exchanged by a crane during bunkering. For option 3 also the two sub options mentioned at option 2 apply: a) the powerpack(s) are put on shore, then relatively quickly filled (e.g. with constant pressure tubes) and loaded back on the ship, b) the powerpack(s) are exchanged for a charged ones which are on stock at the terminal. The choice between the two options are determined by operational aspects and investment costs. Exchanging is quicker (option b), but will often require higher investment costs. With more H_2 fueled ships in service option b will likely become more attractive.

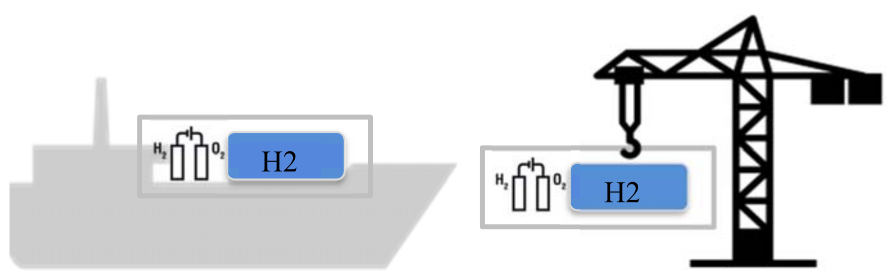


Figure 4 (option 3): using containers with both hydrogen tanks and fuel cells, so called "power packs". To refill the container, the power packs are lifted off the ship and refilled or replaced by full power packs.

Main characteristics of this option:
- Fast ‘bunkering’ by exchanging powerpacks.
- Modular power packs can be used for other purposes
- Fuel cell powerpack can be (temporarily) exchanged by diesel powerpack if the mission profile would require this.
- Modular system can be combined in systems where powerpacks (battery, diesel generator set) are shared between vessels (operators)
- A power pack in the cargo space leaves less cargo capacity (also valid for option 3), unless the design of the ship is optimized for this option. For example, by omitting part of the engine room or crew rooms.
- The power pack can also be standardized and modular, such that lease instead of purchase might be an option.
- When power pack is used for other ships or applications, the power demand of these applications should be explored to ensure the right dimensioning of the power pack. Mainly with the focus on the fuel cells to avoid excessive investments due to over dimensioning.

2.2 Vessel power and propulsion system design

2.2.1 Option 1: Fixed hydrogen storage

The Gouwenaar II container vessel is currently equipped with a modular diesel electric propulsion system. The fixed pitched propeller is directly driven by a permanently magnet electrical machine with a rated speed of 350 rpm. This electric motor is powered via a frequency converter. The power is generated by a diesel generator set of approx. 600 kW and two diesel generator sets of 200kW each. The diesel generator sets are installed in two 40 ft high cube containers which are located in the front of the vessel. A primary AC switchboard connects all electrical power sources and consumers.

For the conversion of the Gouwenaar II, the hybrid fuel cell system will replace the diesel generator sets. In order to independently control the energy flow from the fuel cells and the batteries, two incoming feeders are used. The battery storage system is directly connected to the existing primary ac switchboard and so are the fuel cells. An energy management system (EMS) controls most effective use of the energy sources. In Figure 5 an overview of the standard electrical design for an AC grid is given.

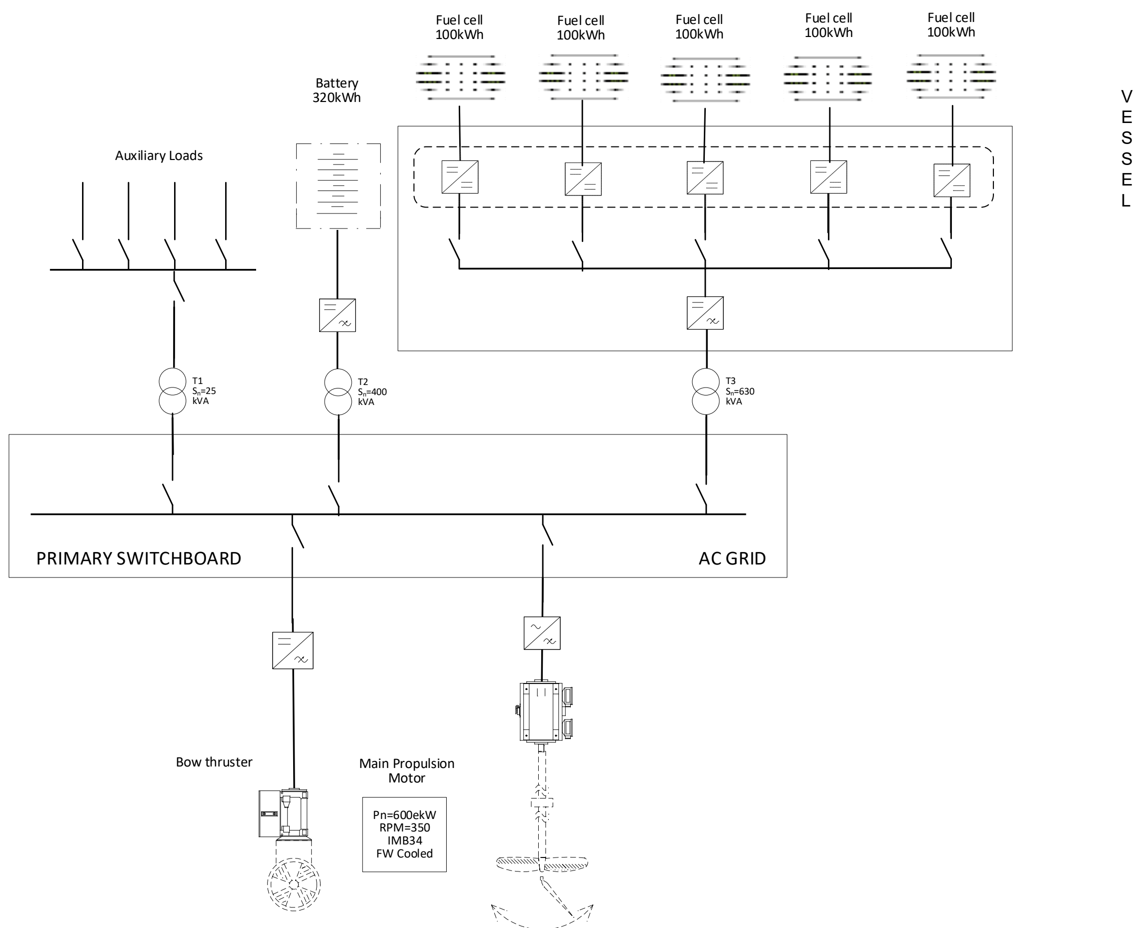


Figure 5: Key-one-line diagram after conversion to hydrogen fuelled propulsion system e.g. Gouwenaar II.

For newbuild vessel it is possible to optimize this concept regarding number of components and efficiency by using a DC grid for the hybrid fuel cell integration. The key-one-line diagram is shown in Figure 6.

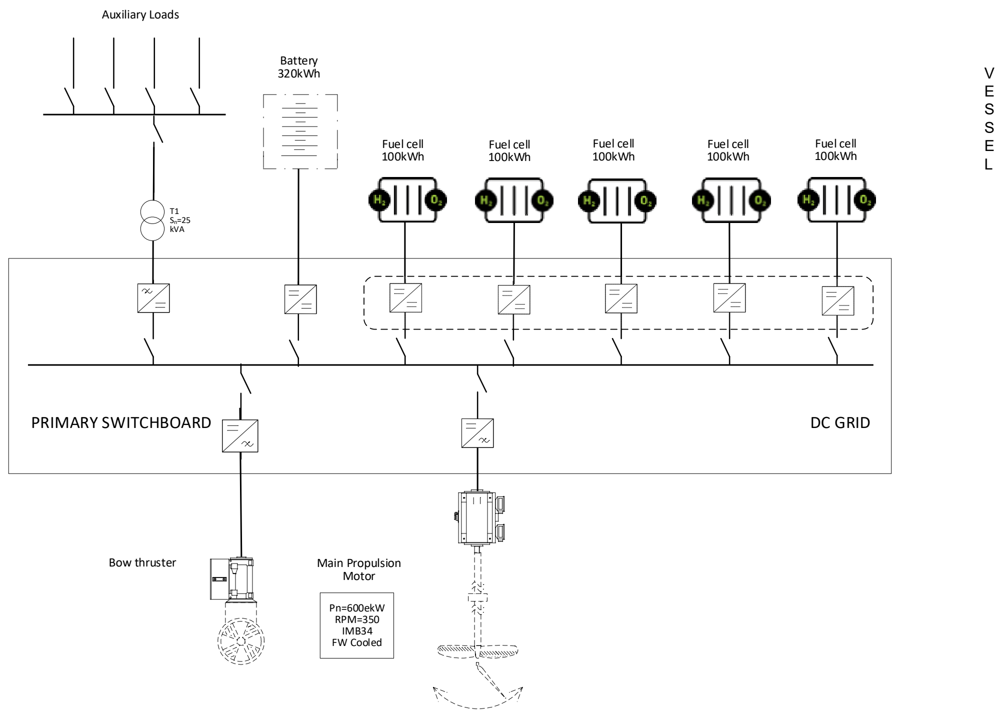


Figure 6: Optimized power grid in case the hybrid fuel cells are permanently installed on-board.

Similar to the AC concept the energy flow is managed by the EMS system. Examples are for instance optimization of charging and discharging cycles of the battery and the operation of the fuel cells in their most optimum operation point. Independent of the power and propulsion system, a Safety Instrumented System for the hydrogen and fuel cell system has to be introduced.

2.2.2 *Option 2: exchangeable hydrogen storage container*

The power and propulsion system is identical compared to option 1. The permanent or temporary installation of the gaseous hydrogen does not influence the electrical system. Safety Instrumented Systems will deviate slightly compared to option 1.

2.2.3 *Option 3: exchangeable Power pack concept*

In option 3 the power electronics for the fuel cell equipment is located in the hydrogen storage container. To ensure that the equipment is powered during handling of the container a single battery string is included in the container. Also the Safety Instrumented System is solely installed in the container.

In Figure 7 an overall single line is shown in case the hydrogen containers are also equipped with the fuel cells.

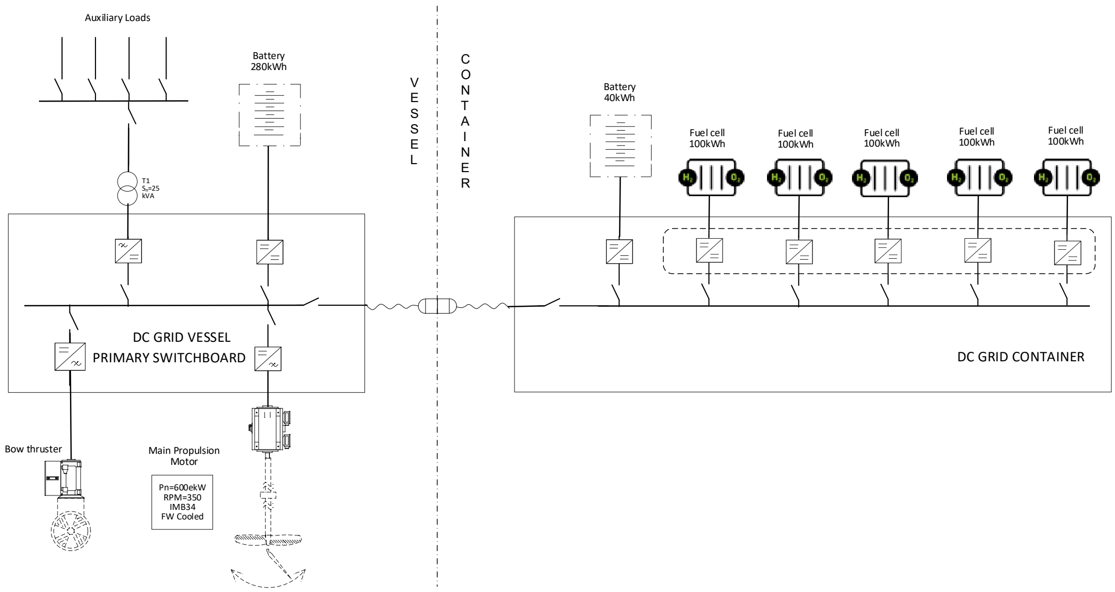


Figure 7: Overall key-one-line diagram for the power generation and propulsion system for option 3.

The primary battery stack of the hybrid fuel cell is installed permanently on-board the vessel. During exchange of the hydrogen storage container the vessel is powered by this battery stack. It is assumed that limited manoeuvrability or emergency operation is guaranteed.

The mechanical, electrical, communications , EMC and performance requirements for the connection is not yet defined. Recommendation is to follow the standard IEC 61851 as it gives guidance on these requirements for Electric Vehicle supply equipment.

2.3 Operational sailing profiles

2.3.1 Round trips

A set of operational profiles was obtained by CCT during a logging campaign in the spring of 2018, with the aim of providing insight in the use of the ship.

During this campaign the following parameters where monitored from the switchboard:

- Power on the propeller shaft,
- Combined generator electrical power,
- Auxiliary load,
- Electrical power production on all 3 generator sets,
- Fuel use rates on all 3 generator sets,
- Combined fuel rates,
- GPS data.

These are divided here into round trips, which each start and stop at the Alpherium. GPS data was combined with AIS information to distinguish the different round trips, for which two routes are visualized on Figure 8. At the end of the logging period, eight round trips were registered: five to Maasvlakte, and three to Antwerp. In each of the round trips, different terminals and quays where called.

a) 

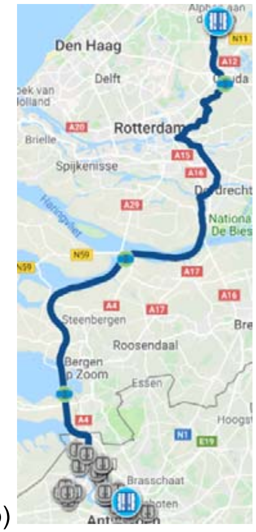
b) 

Figure 8: Sailing routes of Gouwenaar II; a) Route between Alpherium and Maasvlakte, and b) Route from Alpherium to Antwerp (created on blueroadmap.nl)

2.3.2 *Energy demand*

The delivered energy and the round-trip durations are important parameters for the dimensioning of the hydrogen equipment. Therefore, the delivered energy is calculated from the logs, by integrating the electrical power of the generator sets over the time of the roundtrip. The trip duration represents the full period between departure and return to the Alpherium. Therefore, it includes both sailing and waiting periods. The data is summarized in the histogram shown in . For this study, the maximum observed energy demands of 6.2 MWh (for Maasvlakte trip) and 11.5 MWh (Antwerp trip) are taken as representative. The maximum values are used because this is the very least capacity that the ship should bunker.
The round trip to Antwerp takes up to 48 hours. The observed duration for Maasvlakte round trip vary between 27 and 46 hours. It should be noted that the crew is allowed to sail for 18 hours within a period of 24 hours, and after 18 hours, the crew needs to pause for 6 hours.

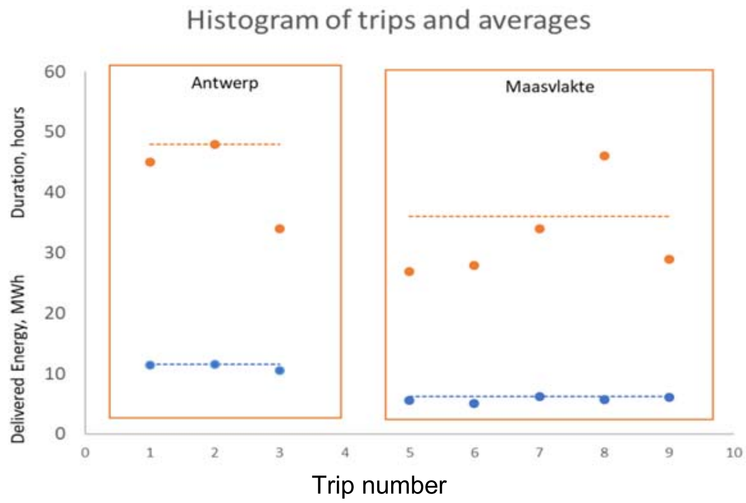


Figure 9: Consumed energy (blue dots) and duration (orange dots) for both the Antwerp and Maasvlakte round trips.

Table 2: Round trips of the Gouwenaar II in February 2018. Including duration and total energy delivered by the generator sets.

id	Depart.	Return	Destination	Delivered energy [MWh]	Duration [hours]
1	1-2-2018	2-2-2018	Antwerp	11.4	45
2	3-2-2018	4-2-2018	Maasvlakte	5.6	27
3	7-2-2018	8-2-2018	Maasvlakte	5.1	28
4	9-2-2018	10-2-2018	Maasvlakte	6.2	34
5	10-2-2018	12-2-2018	Maasvlakte	5.7	46
6	12-2-2018	14-2-2018	Antwerp	11.5	48
7	14-2-2018	16-2-2018	Antwerp	10.5	34
8	16-2-2018	17-2-2018	Maasvlakte	6.1	29

2.3.3 *Power profiles*

The delivered power from the generator sets needs to be replaced by the fuel cell power. Installation of excess fuel cell power should be avoided to avoid unnecessary investments in fuel cells. The graph shown in Figure 10 refers to the combined generator power for a roundtrip to Antwerp (the blue line). The power demand goes up and down due to varying conditions on the waterway, cargo loads, speeds and acceleration of the ship. Also, the ship regularly stops for locks, terminals and for the crew to rest.

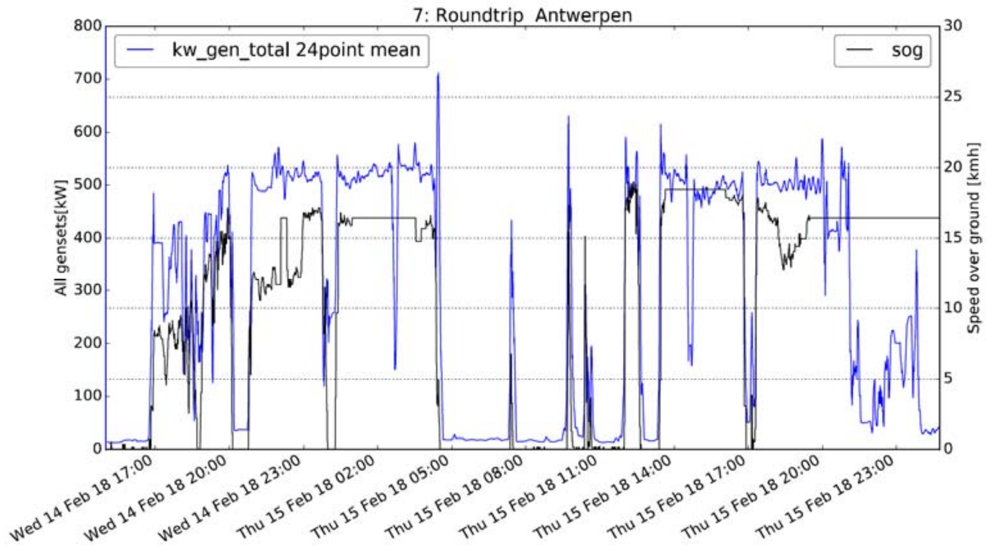


Figure 10: Total needed electrical power for a representative Antwerp round trip (blue, left axis). Speed over ground was derived from AIS (shown in black, right axis).

The power demand from the generators is typically 500 – 550 kW. The generator power is used since it included propulsion, auxiliary and power conversion losses in the electric system. While sailing (not manoeuvring) the power demand will not exceed 600kW by much, since the electromotor has a nominal power of 600kW, and only auxiliary power (about 20 kW) will be demanded on top of this.

2.4 Dimensions of on-board technical equipment

To find the dimensions of the needed on-board equipment, the following steps are taken:

1. Determine the required installed fuel-cell power,
2. Determine the capacity of the supporting batteries,
3. From the required energy per round trip, calculate the needed amount of hydrogen,
4. Determine the pressure and size of the containers for storage.

2.4.1 Fuel cell specifications and dimensions

From the power profile, an installed fuel-cell capacity of 600kW is sufficient, even though the fuel cells degrade 10% over the lifetime (see Table 3). This is because the typical power demand ranges up to around 500kW (paragraph 2.3):

- the maximum installed propulsion power of 600kW
- a battery is installed for peak shaving

Table 3: Fuel cell lifetime specifications as indicated by supplier.

Unit capacity (6 units used)	100 kW
Lifetime	30.000 - 35.000 hours
Lifetime for Gouwenaar II	8 years
Refurbishment cost, after lifetime	25 % of the new price
Performance degradation	10 % over lifetime
H_2 consumption	63,5 kg/MWh (g/kWh)
Fuel cell efficiency (higher heating value)	40% at nominal power
Fuel cell efficiency (higher lower value)	47% at nominal power
Output voltage (DC)	400-580 V

Fuel cells are produced in smaller units (up to 100 kW). Therefore, the Gouwenaar II would require 6 fuel cell units. The output voltage above 400V allows for parallel installation of the fuel cells.
Installation of 600kW of fuel cell power allows for safe navigation, in case of malfunction of one of the fuel cells. Due to 400 V output, voltage level is maintained in a malfunction scenario.

2.4.2 *Supporting batteries*

Fuel cells are supported by batteries to handle short term power peaks and dips. The battery calculation in this section is based on liquid cooled Lithium Ion NCM batteries. Discharge up to 5 CP/Charge up to 3 CP. The State of Health end of life in all cases is approximately 91%.

2.4.2.1 *Battery sizing in case of peak shaving operation only*

The battery capacity is estimated using a 500kW fuel cell power. This leaves a safety margin for the 600kW stack, for 10% degradation over the lifetime, or malfunction of one of the 100kW fuel cell units.

From registered round trips, higher demand period than 6 hours at 530 kW is observed. This would imply that with a fuel cell stack with 500 kW, for every hour ~30 kWh would be needed from the battery. For 6 hours trip this would add up to 180 kWh of batteries capacity. At a State-Of-Charge policy of 37,4 % - 60 % [7] this comes down to at least 355[8] kWh installed battery capacity.

The comparison between the conventional diesel electric and fuel cell powertrains are shown in the table below.

Table 4: Comparison of diesel electric and fuel cell driveline for the Gouwenaar

	Diesel electric	Fuel cell driveline
Max propulsion power (kW)	600kW	600 kW
Auxiliary power (kW)	± 20 kW	± 20 kW
Installed power (kW)	Generator sets 987 kW	Fuel cell: 600 kW
Battery capacity (kWh)	0	355[9] kWh

[7] State-of-charge (SOC) is an indication of a fuel cell capacity at that moment, 0% meaning empty and 100% meaning full
[8] 60 % - 37,4 % = 22,6 %
[9] TCO calculation in section 5 are done with 330 kWh battery capacity

2.4.2.2 *Battery sizing in case of dynamic generator power*

For sensitivity analysis the case of a 450 kW fuel cell installation is assessed. At a State-Of-Charge policy of 23,8 % - 78,8 % [10] this comes down to at least 950[11] kWh installed battery capacity.

	Diesel electric	Fuel cell driveline
Max propulsion power (kW)	600kW	600 kW
Auxiliary power (kW)	± 20 kW	± 20 kW
Installed power (kW)	Generator sets 987 kW	Fuel cell: 450 kW
Battery capacity (kWh)	0	950 kWh

Due to battery size (950 kWh) and corresponding costs, downsizing the fuel cell capacity is not advisable.

2.4.2.3 *Continuous running of generator*

In extreme case one could run the fuels cells continuously. When we would require 11,5 MWh in 48 hrs, this yields about 300 kW as a minimum fuel cell power, using a 20% safety margin. The calculated battery size is 2970 kWh with dSOC of 62,5%.

	Diesel electric	Fuel cell driveline
Max propulsion power (kW)	600kW	600 kW
Auxiliary power (kW)	± 20 kW	± 20 kW
Installed power (kW)	Generator sets 987 kW	Fuel cell: 300 kW
Battery capacity (kWh)	0	2970 kWh

Economic feasibility not given. This option is not advisable.

2.4.3 *On-board H2 storage capacity*

For the following calculations, a net efficiency of 40%[12] at nominal (max) power of the PEM fuel cell is used. It is known that the reported fuel cell efficiency varies per supplier (7), and that the efficiency increases towards part-load. The fuel cell supplier has indicated that the use of 40%[13] efficiency is realistic, since the 600kW fuel cell stack will run near nominal load when sailing. An example fuel cell specification is given in Annex II, which confirms the 40% efficiency.

At 40% efficiency, and a higher heating value for hydrogen of 141.7MJ/kg, 63.5 kg of H_2 is needed to generate a MWh of electricity. Using this reference number, the amount of hydrogen needed for a recorded trip is calculated.

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[10] State-of-charge (SOC) is an indication of a fuel cell capacity at that moment, 0% meaning empty and 100% meaning full

[11] 78,8 % - 23,8 % = 55 %

[12] Based on higher heating value, equivalent to 47% based on lower heating value (to be compared with combustion engines)

[13] 40% efficiency is based on higher heating value. This corresponds to 47% efficiency based on the Lower Heating Value. This number can best be compared with the diesel engine efficiency (40%-45%).

For example, the amount of hydrogen for the most demanding round trip to the Maasvlakte is found by:

$$6.1\ \mathrm{MWh} \times 63.5 \frac{\mathrm{kg}}{\mathrm{MWh}} = 387\ \mathrm{kg} \qquad (1)$$

For all recorded Alpherium-Maasvlakte round trips the required H_2 is given in Table 5.

Table 5: Energy and hydrogen demand for the Maasvlakte round trip.

	Electric energy consumption [MWh]	H_2 required [kg]
2	5.6	356
3	5.1	324
4	6.2	394
5	5.7	362
8	6.1	387

For the most demanding Antwerp round trip:

$$11.5\ \mathrm{MWh} \times 63.5 \frac{\mathrm{kg}}{\mathrm{MWh}} = 730\ \mathrm{kg} \qquad (2)$$

Table 6: Energy and hydrogen demand for the Antwerp round trip.
Duration is between departure and arrival at the Alpherium.

	Electric energy consumption [MWh]	H_2 required [kg]
1.	11.4	724
6.	11.5	730
7.	10.5	667

On top of the calculated hydrogen quantity that is found here from the recorded trips, more hydrogen must be taken on a round trip.

The main motivation for this is:
1. It is likely that for some round trips to Antwerp, the ship needs more than 11.5MWh. This study only possesses 3 round trips to Antwerp. An additional margin of 20% is assumed for peak demands. This can be due to bad weather, currents or additional port calls.
2. A safety margin should for unforeseen conditions should be used. Here 20% is used. This can also be labelled as bunker reserve. This applies on top of the previous margin.

Based on these two points, it is recommended to bunker $730\mathrm{kg} \times 120\% \times 120\% = 1051\mathrm{kg}$ for the Antwerp round trip.

2.4.4 *On-board hydrogen storage tanks*

2.4.4.1 *Fixed installation*

For a fixed installation in the Gouwenaar II, the hydrogen tanks can be installed in the front engine room. In the figure below a sketch is made with 120 H_2 cylinders of 500 mm diameter, 2560 mm long.

These cylinders will be mounted in a rack and are EC79 approved. At 350 bar pressure, the storage capacity would be about 960 kg in total (effectively about 8 kg per cylinder). It is recommended to enlarge this to about 1050 kg.
The H_2 storage must be built in a separately vented room or container (refer to section 3).The sketch also shows the position of the fuel cell stack, the (peak shaving) batteries and the switchboard.

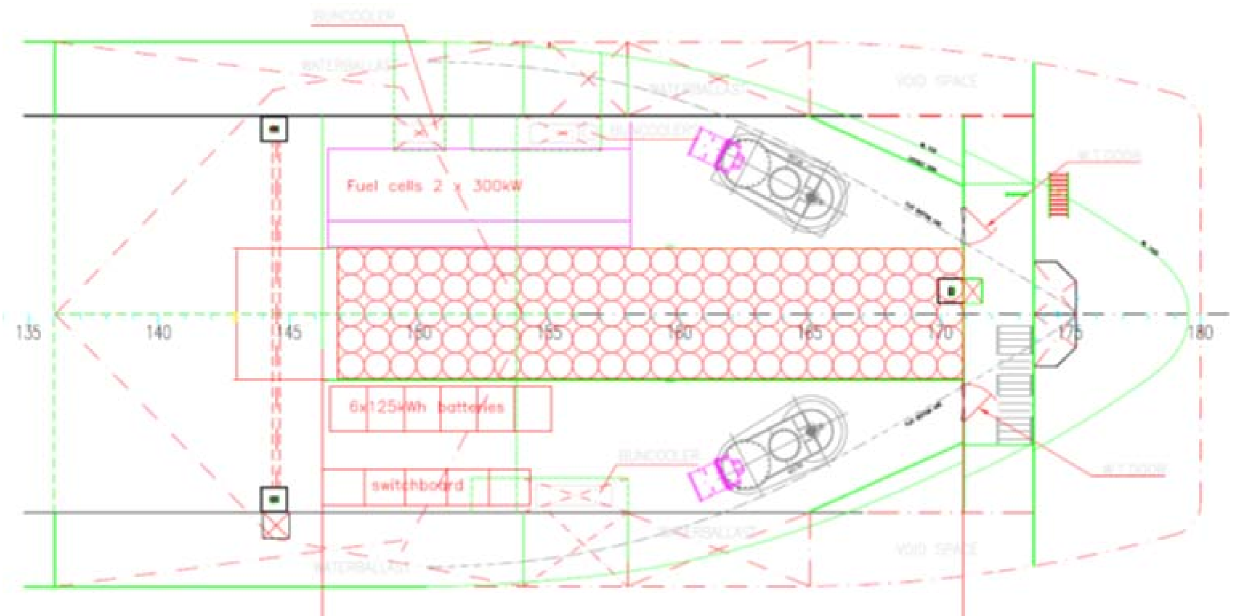

Figure 11: Lay out of the front engine room with the H_2 storage, fuel cell system and batteries.

2.4.4.2 *Exchange solution*

The required amount of 1051 kg of hydrogen can be packed in standard sized containers. Lightweight composite tanks (also called type 4 tanks for full composite) can store hydrogen at 350, 500 or even 700 bar. High pressure tanks require a minimum residual pressure that should be left in the tank. For tanks found in this study, this residual pressure was 10 bars (see Table 7). For the required 1051 kg of hydrogen, this would mean that an additional of capacity of 1072 kg of storage capacity is needed (using a 500 bar container).

Table 7: Storage capacity for ISO containers at 300 bars and 500 bars, total weight of the 500bar variant. The minimum residual pressure for both types is 10bar. Specifications where received from the manufacturer.

	20 ft	30 ft	40 ft
Capacity at 350 bar (kg)	405 kg	625 kg	845 kg
Capacity at 500 bar (kg)	520 kg	815 kg	1085 kg
Residual pressure (bar)	10 bars	10 bars	10 bars
Total container weight (500bar)	~15mton	~23mton	~31mton

Looking at the available options in Table 7, the 40 ft container at 500 bar matches these specifications and would be the optimal choice for the Gouwenaar II with trips to Antwerp.

At 350 bars, three 20ft containers would be needed. For choosing the standard container size and pressure level, also other ships with other operational profiles should be considered though. In addition, the energy loses and investment costs should be considered when choosing the appropriate pressure option. This should be a part of a further study covering a range of ship types and operational profiles, and also covering the H_2 supply chain.

3 Safety

3.1 On-board safety

There are different requirements based on the certain applications and the operation. We list here the most relevant ones, but the authorities should state if these requirements apply. It is necessary to check if additional certification is required. The placement of the main components; hydrogen tanks, fuel cells and batteries on-board of the ship is dependent on the modularity and bunkering options.

We distinguish between three configurations, as described in section 2.1:
1. Bunkering with a (high pressure) hose from shore.
2. Exchange of H_2 storage container(s).
3. Exchange of Power Packs (H_2 storage container including fuel cells).

All these solutions require a fuel cell on-board of a ship.

The safety cautions for the use of fuel cell systems on ships are listed here (8):
- Single failure criterion: Fuel cell (FC) system should be designed such that no single failure can lead to dangerous situation.
- Two barrier principle: To ensure the safe containment, each gas volume should be surrounded by two independent barriers.
- Separation of systems: Gas storage room and fuel cell installation space have to be separated from safe areas, engine rooms, etc.
- Safe venting: The vent lines should be installed in such a way that no ignition sources are in the vicinity of the vent.
- Explosion protection: This should be done following EN 60079-10.
- High pressure storage vessel protection: Avoid rupture of the tank, include pressure relief solutions, etc.
- Protection from external influences: Designing the system according to the operational conditions and protecting the whole systems against collisions, mechanical damage, etc.
- Monitoring the safety: Installing alarms, shut-down systems, gas detection sensors, etc. (8)
- PEM fuel cells operate between 50-100ºC. High temperature PEM can operate at temperatures up to 200ºC (9). High temperatures can be considered as safety concern.

3.1.1 Common safety concerns for all configuration options

EU regulations and directives impacting the fuel cell technologies are provided in the deliverable of the HyLAW project (10). We provide a summary in this document. All the equipment used in the hydrogen storage and transfer system should be designed and operated for hydrogen conditions. Materials should be selected carefully. It is well-documented fact that hydrogen cause embrittlement in metals. Therefore, the materials selected for tanks should not react with hydrogen, and have good mechanical properties. For example, cast iron pipe and fittings should not be used (11).

Hydrogen is stored at high pressure in gaseous state. If ruptures, high pressure tanks may release a large amount of energy, depending on the rupture size and the internal pressure. Hydrogen leaks and flames are hard to detect without dedicated instrumentation considering that it has no colour and odour, and the flames have low heat radiation (6).

On-board compressed hydrogen tanks are usually composite tanks, made of carbon fiber, may have metal or polymer liner, and are usually pressurized to 350 or 700 bars. To allow sufficient hydrogen storage, usually several tanks are arranged in stacks, as shown in Figure 12.

Figure 12: All-composite hydrogen pressure vessel trailer by Hexagon Lincoln (12).

Ignition energy of hydrogen is relatively low; 0.019 mJ which is 1/10th of that of propane (13). This is a safety concern as well. Reported ignition sources include sparks from rapidly closing valves, sparks from electrical equipment, welding and cutting.

European legislation relevant to hydrogen storage are (10):
- SEVESO Directive (Directive 2012/18/EU): above 5 tons,
- ATEX Directive 2014/34/EU: Equipment and protective systems to be used in potentially explosive atmospheres,
- SEA (Directive 2001/42/EC) and EIA (Directive 2011/92/EU): Environmental impact assessment procedure,
- Pressure equipment directive: Applies to the design, manufacture and conformity assessment of pressure equipment (10).

European legislation relevant to transportation and distribution of hydrogen are (10):
- Directive 2008/68/EC : this regulation extends the rules from ADR,RID and ADN to national transport. In Europe ADN regulation for inland waterways applies.
- Directive 2010/35/EU: Applied to the design, manufacture and conformity assessment of cylinders,
- EU no 453/2010: Requirements for safety data sheets, etc. (10).

The containers shall have MEGC (Multi Element Gas Container) certification and the pressure vessels inside the containers are according ADR 6,2 TEPED EN12245 certified.

These certifications allow you to transport hydrogen via truck over the road within Europe. This will be necessary as you want to exchange the containers in the harbor. Then you want to transport the empty container to a filling point and back.

CSC certification, which is the general certification for handling of containers in harbors, is also required. The containers will be part of the vessel and the hydrogen will be used for consumption during the trip.

Safety of hydrogen and hydrogen systems is reported in the report of NASA (14). Another comprehensive resource, is the Hydrogen Technologies Safety Guide from NREL published in 2015 (11). For more detailed information it is recommended to read these references.

3.1.2 Bunkering with a (high pressure) hose from shore.

In this option, the components can still be modular, and be installed anywhere on the ship. They do not need to be reachable with a crane on a trip basis. This is the most space efficient option considering that the hydrogen storage tanks and the fuel cells can take the place of the diesel engine, and be placed in a distributed manner within the ship to optimize the use of available volume. The ship designer needs to include the components during the ship design phase. They also need to comply with additional safety requirements.

If the ship is to be retrofitted, the volume available for the fuel cell and hydrogen tanks will be given. The volume that is available in the ship should be sufficient to accommodate the required tank and fuel cell size. Similar exercise has previously been performed for different case studies by Sandia Labs (15), and in their scenario it was decided that the available space can accommodate sufficient hydrogen only if the storage tanks contain liquid hydrogen (maritime vessels). For inland shipping energy consumption and storage requirements are considerably lower compared to this maritime example.

The fact that hydrogen is a very low-density gas, following any small size leakage, H_2 rises. In a contained space this may cause safety risks. The containment units need to be well ventilated and additional safety measures should be taken to detect the amount of leaks.

Permeation of hydrogen through the tank or pipe walls, which refers to the travel of the hydrogen molecules, is practically unavoidable[14].

[14] Even though it is not directly related to the Gouwenaar scenario, regulations for hydrogen-powered motor vehicles give an indication of the allowable permeability levels. As cited in the section 4.2.12.3 of the European Commission Regulation No 406/2010, EU rules limit the allowable permeation rate of hydrogen tanks to 6 Ncm^3 per hour of hydrogen per liter internal volume of the container (Ncm^3 is used for volume in normal conditions which are 1 atm pressure and 0°C temperature) (20).

This is a safety concern if the tanks are stored in enclosed spaces, such as under the deck of a ship. In confined spaces, good ventilation should be arranged to make sure the concentration of the hydrogen in the air remains below 1/4th of the lower flammability level (LFL) of hydrogen (LFL of hydrogen is 4 % by volume of air) (16). The fact that gaseous H_2 has a lower density than air is a big advantage for the overall ship safety compared to conventional fuels e.g. butane or propane, because H_2 can easily escape the ship provided there are correctly installed vents. In confined spaces, the inlets for ventilation should be located close the floor and the outlet should be close to the highest points of the room.

3.1.3 *Exchange of H_2 storage container(s)*

Option 2 is based on having a fuel cell in a compartment, on-board of a ship, and replacing the empty and full hydrogen tanks at the harbor or bunker location. In this option, before/after every exchange, hydrogen connections should be remade on-board by the professionals. The most feasible position for placing the hydrogen tanks is the deck considering the easy access and quick replacement.

For both the options 2 and 3, the H_2 container(s) or the powerpacks need to be reachable with a crane. One of the main concern here is the fact that such sensitive and expensive equipment is being hoisted and placed by a crane, which requires extra attention and time. Shaking, tilting, dropping may cause damage to the hoisted equipment and other components effected by any accident that may occur. Hydrogen storage tanks for mobile use is designed for certain level of accelerations and slushing relevant for road transport. The relevant loads should be identified for the crane lifting and H_2 storage container or fuel pack replacement operation, and the used equipment should be designed for these loads.

ISO 11623:2002 Transportable gas cylinders – Periodic inspection and testing of composite gas cylinders, and ISO technical committee 197 (also includes hydrogen bunkering procedure for airports) are relevant sources for hydrogen tank requirements and bunkering.

ADR (Accord européen relatif au transport international des marchandises Dangereuses par Route) and IMDG (International Maritime Dangerous Goods Code) codes include hydrogen tanks carried as cargo, but not as fuel. Packing instructions of hydrogen gas cylinders to be carried on road are included in ADR (17). ISO 17519 is the standard that can be used to design gas cylinders (18). Other guidelines are listed in Table 8.

Table 8: Overview of Regulations, Codes, and Standards Related to Hydrogen technologies (11).

Hydrogen Technologies Component, Performance, and Installation Standards	
ASME B31.3 and B31.12 Piping and Pipelines	Piping design and installation codes that also cover material selection
ASME Boiler and Pressure Vessel (BPV) Code	Addresses design of steel alloy and composite pressure vessels
CGA S series	Addresses requirements for pressure relief devices for containers
CGA H Series	Components and systems
UL 2075	Sensors
CSA H series of hydrogen component standards	
CSA FC1	Stationary fuel cells
SAE J2601/SAE J2600	Dispensing and dispenser nozzles

Some safety considerations are listed here (19):

- Recognize hazards, predict hazardous zones and use safety distances and other mitigation measures.
- Provide effective ventilations and prevent hydrogen accumulation. Place inlets low to the ground and exhausts close to the ceiling of the room. The maximum level of hydrogen in the room should be below the 25% of the lower flammability limit (LFL).
- Use equipment and sensors to detect leaks and fire. Hydrogen fire is almost invisible in the daylight, and the flames radiate low heat, which makes it difficult to detect even from short distance.
- European Commission Regulation 406/2010 states that thermally activated pressure relief devices (TPRD) have to be included in the tank structure which allow the controlled release of the content in the event of fire (20).
- Use noncombustible materials.
- Collision onto hydrogen storage tanks
- Storage zone under crew accommodations
- Low flash point of hydrogen: Requires sufficient ventilation, alarm systems, fire protection (9)

3.1.4 Exchange of Power Packs (H_2 storage container including fuel cells).

Option 3 is based on having the fuel cell and the hydrogen tanks together in an ISO container (30 or 40 ft). Exchanging the power pack may provide a relatively faster solution compared to the Option 1 (filling the on-board storage tank) since the power pack can be ready to be exchanged when the ship arrives to the exchange location. Similar option is also considered within the MariGreen European project (7).

In this case, connections between hydrogen tanks and the fuel cell remain connected inside the container. The ship crew need to make an electric connection to the propulsion unit on-board of the ship. The ideal placement for Option 3 is, similar to the Option 2, on the deck of the ship for ease of handling/ hoisting. In the last two options, the hydrogen tanks are hoisted by cranes, this is a scenario to be included in the safety considerations. As depicted in Figure 13, having fuel cell / hydrogen tank packs on the deck means that the payload capacity will decrease. It probably is the most practical to form one vertical stack, such that they do not interfere with the loading and unloading of cargo containers.

SF-Breeze project that started in 2015 studies the feasibility of having a hydrogen fuel cell passenger ferry, where 41 fuel cell units with 120 kW power capacity each are considered. In the design, they place the fuel cells and the liquid storage units above deck (21).

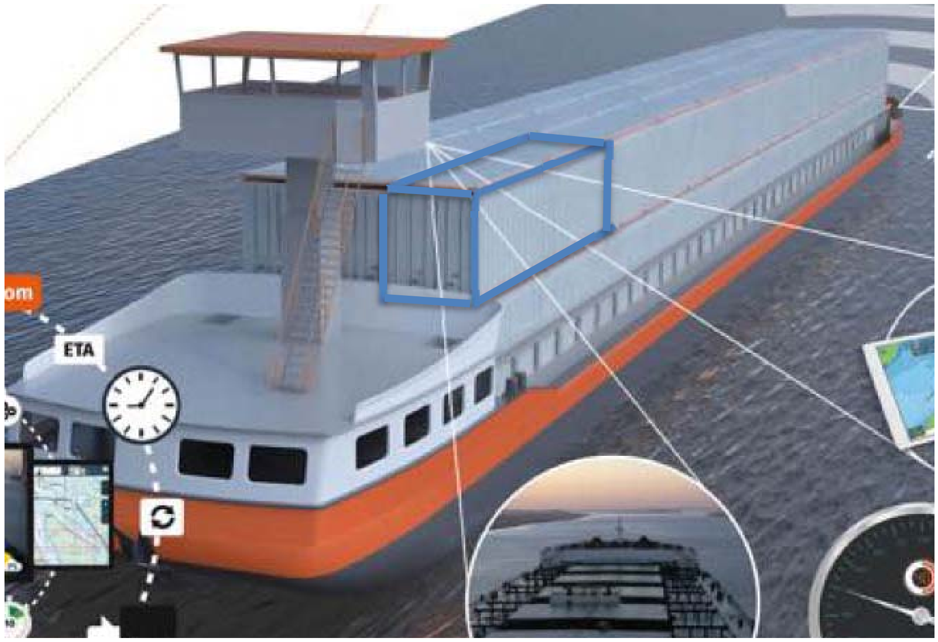

Figure 13: Drawing of the deck view of Gouwenaar II, and depiction of the fuel cell pack replacing of a container (22).

Based on a Maritime Fuel Cell Generator Project (23) the following dimensions can be assumed: for a 40 ft container → 10ft for 200 kW fuel cell and auxiliaries (no power electronics) and 30ft would contain H_2 bottles with the capacity of 755 kg at 500 bar.

3.2 Infrastructure safety

There are some European guidelines or initiatives to develop as such (24);

- CESNI: European committee for drawing up standards for inland navigation,
- ES-TRIN: European Standard for transport on inland navigation vessels,
- EU Directive 2016/1629/EU: special permits for new technologies

A well-established hydrogen infrastructure for bunkering inland waterway vessels will result in having small number of on-board hydrogen tanks, since frequent stops can be made if needed instead of carrying more fuel. European Alternative Fuels Observatory (EAFO) has the ambition of being the EU reference point for alternative fuels and vehicles, including road transport and shipping sectors (25). The website offers interactive map for charging points and refilling stations, which is for the moment limited to road transport since there is no functional infrastructure to refuel ships with hydrogen. By time, as infrastructure develops, this hub can provide guidance to the fleet operators. In 2010, ZemShips project ended with a demo case of a hydrogen fuel cell driven inland waterways ship, shown in Figure 14, and corresponding hydrogen infrastructure (9), (26).

Figure 14: FCS Alsterwasser at the hydrogen refueling station (9)

Note that at the moment, there are no standards for hydrogen bunkering in the amounts needed for ships (27). For fueling up to 10 kg of hydrogen SAE J2601 can be used (28). IGF code, which is The International Code of Safety for Ships using Gases or other Low-Flash-Point Fuels, published by IMO, currently contains requirements for LNG and CNG. The new version of this code, which is under development, will include the requirements for fuel cells (9). IGF code covers the regulations of the bunkering operation on the ship side, but not the shore side (9). Fulfilling requirements of the IGF Code (29) is mandatory for ships built or refurbished after 1 January 2017 and use low flash point fuels (9). However, it mostly details the use of LNG or CNG as fuel. Ships with fuel cells are required to follow SOLAS regulation II-1/55, which suggests the demonstration of an equivalent level of safety (9).

Walls and roofs should be constructed of noncombustible materials. The area should be well ventilated. Ventilation inlet should be located near the floor and outlet should be at the high point on the wall or the roof. The area of the inlet and outlets should be minimum the 1 ft^2 per every 1000 ft^3 of the room volume. There should be no source of ignition.

A study performed by Matthijsen and Kooi (30) have resulted that the safe distances of hydrogen filling stations from habited areas are found to be similar for gasoline and compressed natural gas. Safe distances for LPG are higher compared to the hydrogen. Similarly, a quantitative risk analysis study should be performed for the onshore installation for the Gouwenaar case to determine the safety zones.
In more international setting, National Renewable Energy Laboratory of US (NREL) reports safety concerns regarding hydrogen bunkering (11). Requirement for hydrogen fueling stations are given in International Fire Code (IFC) / NFPA 1 Uniform fire code. SAEJ2601/ SAE J2600 is the standards for Dispensing and dispenser nozzles. SCA FC1 is the standards for the stationary fuel cell. In the Annex, a table is given listing some of the relevant standards for hydrogen infrastructure safety.

3.2.1 *Conclusions (on safety)*

The requirements for hydrogen as a shipping fuel are not currently covered in a dedicated document, however, the existing codes, such as ADR, provide valuable information for developing such standards and guidelines. There are significant codes and guidelines for LNG and CNG, and hydrogen is considered at least as strict as natural gas (9).

The biggest gap is the *lack of dedicated regulations*, codes and standards for hydrogen as fuel in shipping. Existing guidelines for LNG/CNG fueled ships, hydrogen fuel cells motor vehicles and safety guidelines for ships using other low flashpoint fuels (such as IGF code) can be used while developing dedicated codes for hydrogen fuel cell ships and bunkering operations. For bunkering procedure and allowable simultaneous operations (such as loading/unloading cargo) risk studies shall be performed using the specifications of the considered scenario.

There are already commercial solutions for high pressure storage of hydrogen in cylinders, which are subjected to extreme scenarios via the thermomechanical testing for qualification. Nevertheless, *use of high pressure tanks* require case specific evaluation regarding safety zones, distances, fire and explosion protection and other risk mitigating measures.

Hydrogen embrittlement, which is referred to the metals getting brittle with diffusion of hydrogen, should be accounted for considering safe operation. Another hydrogen storage related concern is the permeation of hydrogen through the tank walls. Enclosed spaces containing hydrogen tanks should be well ventilated, equipped with relevant sensors to monitor the hydrogen level in the room. There should be no source of spark or ignition in the venting zones. Well trained handling crew should be responsible for the operation.

A transition to hydrogen fuel cell power in the inland waterway transport requires available and reliable *bunkering infrastructure*, which is certainly a significant gap at the moment.

4 Onshore infrastructure

For this case study, the choice was made to produce the H_2 with electrolyzers at the Transferium location in Alphen a/d Rijn. This is the location where the cargo containers are loaded for transport to Rotterdam Maasvlakte II or to Antwerp.

In this section the electrolyzer and bunkering infrastructure are configured for two cases:

a) Gouwenaar II ship sailing on H_2 fuel
b) Six Gouwenaar II ships sailing on H_2 fuel

The components foreseen for production, compression, storage and bunkering are shown in Figure 15. For every step, the paragraph in the flow chart discusses the technical relevance and makes the necessary calculations for dimensioning and energy consumption.

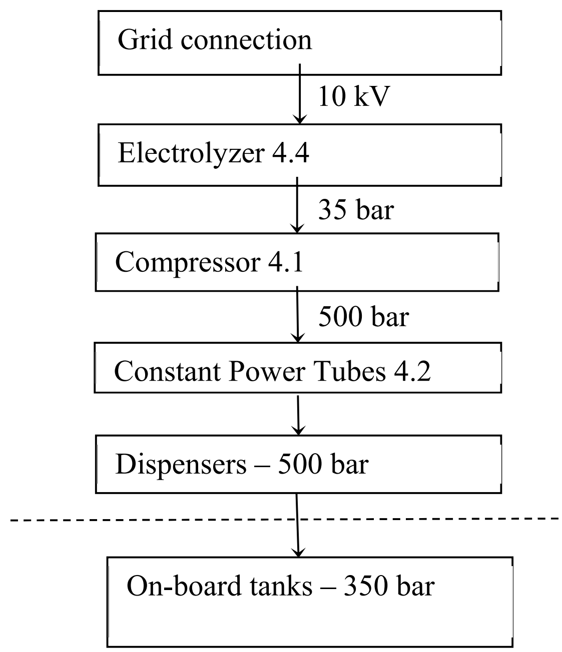

Figure 15: Production pressure from electricity to compressed hydrogen.

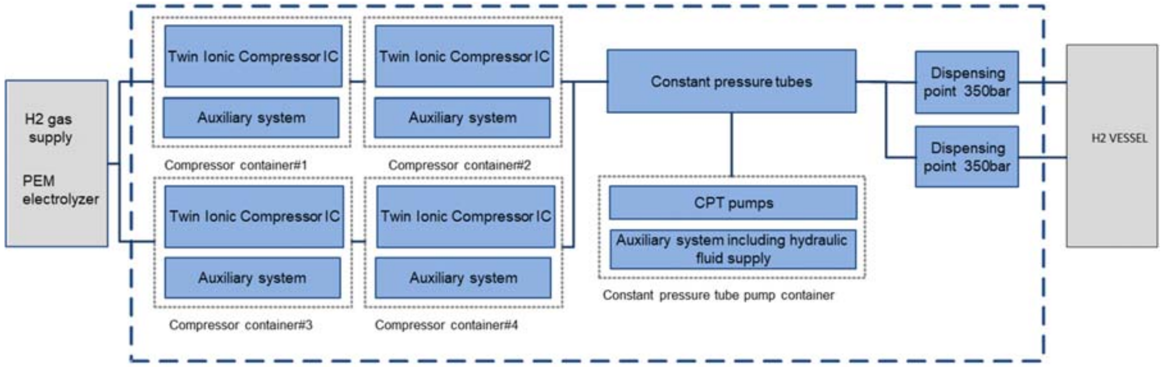

Figure 16: Courtesy Linde ATZ H_2 Overview refueling System Inland Vessel;

4.1 Compressor

The Hydrogen produced from the electrolyzer is at 30 bar after production.
To fill the pressure tanks at 500 bar, compressors are needed. For hydrogen compression positive displacement compressors and more specific reciprocating compressors are industry standard. For the application Hydrogen Refueling Stations the Ionic compressors[15] a special type reciprocating compressor are identified as the preferred option by the project partners. Ionic compressor have less moving parts and limited number of seals and bearings. The used ionic fluid prevents hydrogen leakage and removes heat from the cylinder. These can deliver compressed hydrogen at 500 bar with a rate of max. 28 kg/hour. Compared with the max production rate of 21 kg/hour (Table 9) a single compressor can process the hydrogen from a single electrolyzer. For redundancy reasons, an additional compressor is advised, because the compressor requires maintenance. Duplication removes the compressor as a single point of failure in the hydrogen supply chain.

The energy consumption of the compression is 2kWh per kg of hydrogen. This is taken into account in the operational costs in paragraph 5.2.

4.2 Onshore storage in 40 ft hydrogen storage containers

In case one would dispense 1050 kg of hydrogen in a container not using a compressor or constant pressure tubes but only based on differential pressure following calculation applies:

Volume	34.7	m^3
Capacity	1082	kg @ 25degC & 500 barg
Capacity	758	kg @ 25degC & 350 barg
Utalization	325	kg
Min required number containers	3.08	

Dispensing using the differential pressure is not feasible. It would require a minimum of three (3) 40 ft containers with composite type 4 vessels to fill one (1) exchange container.

[15] Number used here are from Linde's Ionic Compressor 90 MPa – IC90

4.3 Onshore storage in Constant Pressure Tubes (CPTs)

On the shore, hydrogen may be stored under different conditions. With respect to the fact refueling in all scenarios(paragraph 2.1), the option of constant pressure tubes (CPT, see figure 17) is quite feasible. These tubes stay at constant pressure while refilling the on-board tank, sustaining a significant pressure difference with the on-board tank. This makes it possible to quickly refill the on hydrogen tank. Also, the onshore storage volume is used more effectively, compared to conventional tank that has a large dead volume. The CPTs can refill 900 kg in 75 minutes (about 2 hours including fixing dispensers), and is thus fast enough to refill the tanks. Energy needed to operate the CPT is 0.5 kWh/kg H_2 .

Figure 17: Picture of Constant Pressure Tubes (CPT) as filling system (Linde).

4.4 Electrolyzer capacity for multiple ships

The electrolyzer produces the hydrogen that the fuel cells on-board use.
The ingredients for this are water and electricity. The capacity of the electrolyzer must be such, that it produces enough hydrogen such that the ship can bunker when it returns to the Alpherium. The production rate thus depends on the hydrogen use of the Gouwenaar, as well as the time a round trip takes. The specifications of a typical electrolyzer are found in Table 9. When the production rate is not fast enough, multiple electrolyzers may be combined.

Table 9: Specifications of the Siemens Silyzer 200 electrolyzer.

Electrolyzer	
Electrical DC power	1.25 MW
Power grid connection	1.6 MVA
Hydrogen production	225 Nm^3/h
Hydrogen production	21kg/h
Pressure out	35 bar

4.4.1 Infrastructure for one Gouwenaar II

4.4.1.1 Production time

The production capacity of the electrolyzer (or multiple electrolyzers) needs to match average consumption rate of the Gouwenaar. The time it takes to produce the needed amount of hydrogen is calculated below. The main parameters are the hydrogen demands in Table 5 and the production rate of 2kg/h from Table 9.

For the most demanding round trip to Maasvlakte the production time becomes

$$\frac{387\ \text{kg}}{21\ \text{kg/h}} \approx 18.5\ \text{hour}, \qquad (3)$$

and the most demanding round trip to Antwerp

$$\frac{730\ \text{kg}}{21\ \text{kg/h}} \approx 35\ \text{hour}. \qquad (4)$$

The production times for all round trips is found in Table 10 and Table 11.

4.4.1.2 Energy consumption for hydrogen production

The electrolyzers demands electricity to produce hydrogen. The required electrical energy is calculated using the nominal power, production rate from Table 9.

For the most demanding Maasvlakte round trip:

$$18.5\ \text{hour} \times 1.25/0.95\ \text{MW} = 24.3\ \text{MWh}, \qquad (5)$$

and for the most demanding Antwerp round trip:

$$35\ \text{hour} \times 1.25/0.95\text{MW} \approx 45.7\ \text{MWh} \qquad (6)$$

The energy cost of hydrogen production for all round trips is also presented in Table 10 and Table 11. The electrical energy drawn by the electrolyzer, is approximately four times the amount of the electrical energy consumed on-board.

4.4.1.3 Available and needed production time

Before comparing the trip times with the production time needed from Table 10 and Table 11, it is important to realize that the Gouwenaar spends 5 hours at the Alpherium between the round trip. Therefore the total duration of the round trips becomes the sailing durations increased by 5 hours at Alpherium. This leads to typically 32 (27+5) hours to Maasvlakte and 53 (48+5) hours to Antwerp. This time is also available to produce hydrogen, and is found in the column “total trip duration“ in Table 10 and Table 11.

The column “Production energy” is calculated multiplying the power of the electrolyzer and the production time. This production energy is used as input for the operational expenses in paragraph 5.2.

Table 10: Duration of round trips to the Maasvlakte, including 5 hours at Alpherium. Relation between hydrogen consumption of one ship and hydrogen production of one electrolyzer

	Total trip duration[hours]	H_2 required[kg]	Production time[h]	Electricity consumption electrolyzer [MWh]
2	32	356	18	22.2
3	33	324	16	20.2
4	39	394	20	24.6
5	51	362	18	22.6
8	34	387	19	24.2

Table 11: Duration including 5 hours at Alpherium.

	Total trip duration[hours]	H_2 required[kg]	Production time[h]	Electricity consumption electrolyzer [MWh]
1.	50	724	36	45.2
6.	53	730	37	45.6
7.	39	667	33	41.7

When comparing the total trip duration, and the needed production time, it is seen that a single electrolyzer can produce enough hydrogen for one Gouwenaar.

4.4.2 *Scale up to 6 ships*

During a round trip journey to the Maasvlakte (typical total duration time of 32 hours), a single electrolyzer takes 18 hours to produce the needed hydrogen. Therefore a single electrolyzer has 178% of the required production capacity. For a round trip journey to the Antwerp of 53 hours, a single electrolyzer needs 36 hours to produce the hydrogen, and has 139% of the needed capacity. One electrolyzer produces 39% more than the average consumption of ship.

When scaling up, the number of electrolyzers will thus be less than the number of ships. In the table below, the ratio between the number of electrolyzers and the number of Gouwenaar ships is shown: two electrolyzers can cover ~3 ships, and 4 electrolyzers can provide sufficient hydrogen for ~6 ships.

Table 12: Number of electrolyzers when upscaling to multiple ships. Also, the required grid connection capacity is listed.

	Number of ships	Required DC power [MW]
1 Electrolyzer	1	1.25
2 Electrolyzers	3	2.50
4 Electrolyzers	6	5.00

4.5 Grid connection and reserve market

The electrolyzers will require a grid connection between 1.3 MW to 5,3 MW (one to four electrolyzers). This connection capacity is normally connected to a medium-voltage grid e.g. 10kV). The electrolyzer requires an input voltage of 2kV. This power must be made available on the grid and depends on the local capacity. It is not yet clear if and how this can be made available at the Alpherium, and how far the grid connection is from the Alpherium.

With a high power connection income can be generated on the primary and secondary reserve market, basically if you can increase or decrease your power consumption for a certain amount of time, on request of the grid operator. I n Europe, the power grid operates at a frequency of 50Hz (31). To keep this frequency constant, the power demand must be matched by the power supplier adequately. Powerplants have only limited flexibility to meet short term variations in power demand. A pool of power suppliers and consumers that is used to obtain balance and conserve the grid frequency. For a single electrolyzer, the relevant pool is at the shortest time scale (seconds), which is called the Primary Reserve or Frequency Containment Reserve (FCR) (32). This section calculates the revenues that may be generated from the FCR market. With the increase of wind and solar energy, which have rapidly varying power production, the FCR market is growing. In the Netherlands, installations of over 1MW and over are eligible to operate in this market.

Electrolyzers can participate in FCR by allowing their hydrogen to fluctuate around the desired mean production rate. With an upgrade of the power connection, electrolyzers such as the 1.25MW Silyzer 200 have the capability to temporarily run at 1,6 times the rated power. The response time of the electrolyzer for this is quick enough to participate in FCR. It can contribute 1.25MW since the power can be increased by 0,75 MW and decreased by 1.25MW. If overproduction of hydrogen occurs, it must be stored in a low (for example) pressure tank.

For multiple electrolyzers, the Secondary Reserve can be addresses as well. The secondary reserve contracts require that for a period of one week, power can be consumed or reduced on a notice of 15 minutes, for an undetermined duration (in practice not more than several hours). If multiple electrolyzers (Silyzer 200's) are installed, the group of electrolyzers can bid for the secondary reserve. The electrolyzers can be shut off (no electricity consumption), or they can run above nominal power (up to 160% of nominal power consumption). If hydrogen production at a more than nominal power is demanded (so over 1.25MW), the electrolyzers take turns in consuming the power and cooling down.

OPEX can benefit from the FCR income, but this is uncertain. Prices fluctuate on short term and are uncertain for the future. For the TCO calculations in section 5, an effective income of 100k€/MW per year per MW available power is used. This is based on 100% availability, both extracting from and providing power to the grid. Secondary Reserve prices are comparable to FCR and are used at 100k€/MW as well. These prices were provided by the stakeholders.

The actual yearly income is calculated based on the mentioned power and revenues. This comes down to 125k€/year for a single electrolyzer based on FCR, and 250 k€/year for 4 electrolyzers based on FCR and secondary reserve

5 Business cases

The TCO model quantifies the costs directly related to sailing on hydrogen for the Gouwenaar II. The approach is to consider both capital expenditure(CAPEX) as well as operational expenditure(OPEX). Then, the total delivered energy and costs are compared over a period of 15 years, using a levelized cost of energy approach. The costs listed below mainly originate from technical considerations.

The TCO calculations are based on the first H_2 storage and bunkering option: The H_2 tanks are fixed on-board of the ship, with bunkering via a high pressure hose. The costs for options two and three would be about the same, if the H_2 container or powerpack is lifted on shore, where it is filled, and consequently put back on the ship. This takes more time than swapping a container or powerpack for a 'loaded' one, but this time is available, since the overall time on the quay is five to six hours. In this way, the investment costs are lower, at the expense of some flexibility in cases where that would be needed.

Organizational costs for setting up the pilot and operating the hydrogen supply chain unclear since the concept is still in an early stage of development.

Prices listed in this paragraph are estimated prices, indicated by suppliers of the technology, and exclude taxes. Exact prices will be influenced by the engineering decisions, energy prices and reseller margins. All costs are calculated without any tax[16] on fuel, nor without any environmental subsidies[17].

5.1 CAPEX

The capital expenditure(CAPEX) is the investment expenses needed before the operations take place, and income is produced. In this analysis, only the costs related directly to sailing on hydrogen are considered.

For the on-shore infrastructure this comes down to (see Figure 15, section 4, for an overview):
- The electrolyzer(s) including building
- Hydrogen HP pumps, dispensers, constant pressure tubes for bunkering.
- Costs related to the grid connection (10 kV intermediate voltage hub) and cable to the electrolyzer location is not included.

The CAPEX for on-board components include the following:
- Fuel cells
- Batteries
- Storage tank
- Converters
- Electric propulsion motor

Price estimations where obtained from the project partners and from equipment suppliers. The prices per unit (of power or energy) are presented in Table 13.

[16] According to the Act of Mannheim taxation of fuel for inland shipping is not allowed
[17] These are for example the Dutch MIA, VAMIL and EIA arrangements

Table 13: Price parameters used for the CAPEX calculations.

Battery costs	0,5	k€/MWh
H2 tank price	1	k€/kg
Fuel cell price	2	k€/kW
Electrolyzer	2	M€/unit

An overview of the total prices for both on-shore and on-board is given in Table 14, which includes CAPEX for one ship (with one electrolyzer) and for six ships (with four electrolyzers). The column 'factor' shows the scaling of the price from one to six ships. The electrolyzer prices include all accessories needed for a fully operational electrolyzer plant. The overview is graphically presented in Figure 18.

Table 14: CAPEX costs sailing with hydrogen fuel cells: for one ship and for 6 ships. The factor indicates the scaling factor from one to 6 ships. * not included.

	1 ship	factor	6 ships
On shore	**k€**		**k€**
Electrolyser + acc.	2000	4	8000
Pumps, CPTs & storage	3700	2	6450
Housing etc.	150	4	600
Grid connection	*		*
On board			
Fuel Cell(600kW)	1200	6	7200
Batteries(330kWh)	231	6	1386
On board tank	1050	6	6300
Converters + el. motor	350	6	2100
Total	8681		32036

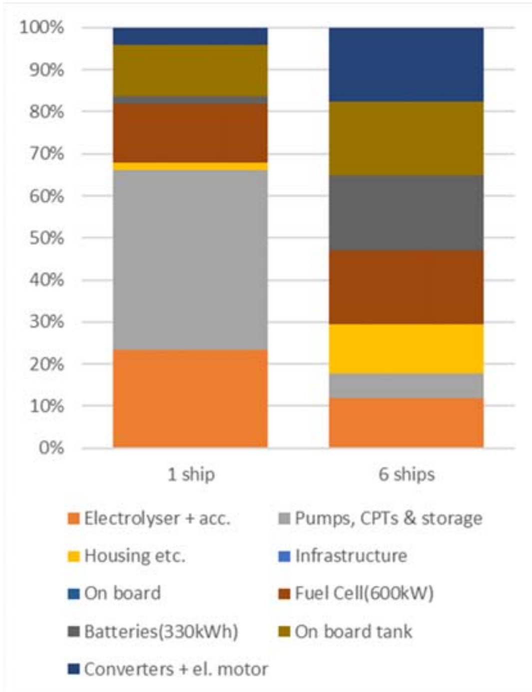

Figure 18: CAPEX percental costs of hydrogen sailing, see Table 14 for numerical figures.

From Table 14 and Figure 18 it can be seen that the hardware costs on the shore, contribute most to CAPEX. Due to more effective use, the relative CAPEX costs of the onshore equipment reduce at scale up. Naturally, the on-board equipment takes a larger share, as purchase of tanks and fuel cells for the additional ships increase costs. Costs of connecting electrolyzer to the power grid were not taken into account.

5.2 OPEX

The operational expenditure are the non-investment costs of running the ship on hydrogen, expressed on a yearly basis. Note that the numbers are based on average prices which do not reflect current contract prices.

The operational expenditure considered are:

- Electricity costs from hydrogen production
- Electricity costs from hydrogen compression
- Loss of cargo space (due to hydrogen container)
- Periodic refurbishment of the fuel cells (refer to section 2.4.1 table 3)
- Fixed contract costs for the power connection
- Maintenance costs of the equipment
- Organizational costs
- Income due to alternative cashflows (e.g. FCR)

The unit prices used to calculate the cashflows are given in Table 15.

Table 15: Used unit prices for OPEX analyses. FCR income based on 100% availability and participation.

OPEX parameters		
Price 1TEU	13	k€/year
FCR	100	k€/MW/year
Electricity price	0,06	€/kWh
Price time loss	0,15	k€/hour
Power	0,7	MW/container
Capital costs	4%	

From analysis of the yearly number of trips to Antwerp and Maasvlakte, the yearly required effective energy is about 2200MWh per year for a one ship, or 142 (metric) ton of hydrogen per year. Electricity costs are combined costs of hydrogen production and electric energy for compression (2kWh/kg).

Revenues may be gained from alternative use of the facility, such as the FCR market. Income is shown as negative costs. The yearly fixed operational expenses are given in Table 15 and visualized in Figure 19.

Table 16: OPEX for sailing with 1 and 6 ships on hydrogen. Includes energy costs for producing compressed hydrogen, loss of income due to lower cargo capacity, refurbishment of fuel cells and income from FCR.

	1 ship	**6 ships**	
Electricity	549	3296	k€/year
Loss of cargo (2 TEU)	26	153	k€/year
Power connection	10	60	k€/year
Fuel cell refurbishment	50	297	k€/year
Rent location			
Maintenance	190	445	k€/year
Organisational			
Revenues			
FCR	-125	-250	k€/year
Total	699	4251	k€/year

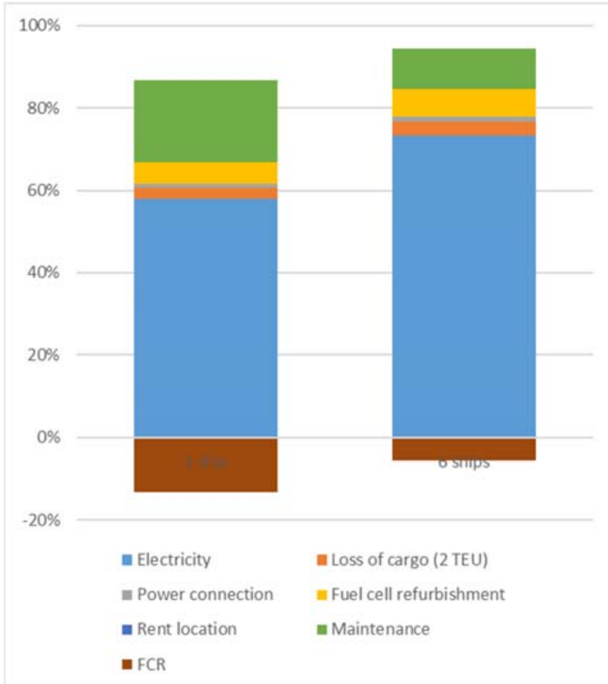

Figure 19: OPEX percental breakdown. Electricity costs are most important and is mainly required for electrolysis. Maintenance of the shore infrastructure is significant, but these costs become relatively less important at scale-up.

The main observations with respect to OPEX are:

- Electricity costs are the main yearly expenses for both cases; one and six H_2 fueled ships. The feasibility of the hydrogen case is therefore sensitive to changes in the electricity price.
- A significant income (125 k€ to 250 k€) can be generated from the FCR and Secondary reserve markets when a single ship sails on hydrogen. For six ships, this revenues decreases due to the relatively lower electrolyzer capacity.
- The share of maintenance costs decreases with scale up, due to relatively lower number of compressors and CPTs.

Loss of cargo may be prevented by optimizing the ship design.

5.3 Levelized cost of energy (LCoE)

The Levelized cost of energy (LCoE) calculates the costs per kWh of electricity. This includes capital and operational costs. Because the fuel cells replace the generator sets, the energy is calculated at the switchboard. Calculating the price per unit of energy makes it possible to compare the costs of different energy sources, or different scenarios.

The LCoE calculations are found in Table 17 (one ship) and Table 18 (six ships) for a period of 15 years. Shown are only the first and last 2 years. Capital costs are calculated over the first 10 years, at a rate of 4%. The bottom 2 rows show the total and relative costs (per kWh) for each of the expenses.

Table 17: Levelized cost of energy for single ship on hydrogen.

Year	Production	CAPEX	Capital costs	Electricity costs	FCR + maint. + cargo loss	
[-]	[MWh]	[k€]	[k€]	[k€]	[k€]	
0		8681				
1	2200		313	549	150	
2	2200		278	549	150	
14	2200			549	150	
15	2200			549	150	
	33000 kWh	8681 k€	1563 k€	8240 k€	2251 k€	20735 k€
		€ 0,26	€ 0,05	€ 0,25	€ 0,07	€ 0,63

Table 18: Levelized cost of energy for six ships on hydrogen.

Year	Production	CAPEX	Capital costs	Electricity costs	FCR + maint. + cargo loss	
[-]	[MWh]	[k€]	[k€]	[k€]	[k€]	
0		32036				
1	13200		1153	3296	955	
2	13200		1025	3296	955	
14	13200			3296	955	
15	13200			3296	955	
	198000 kWh	32036 k€	5766 k€	49442 k€	14330 k€	101574 k€
		€ 0,16	€ 0,03	€ 0,25	€ 0,07	€ 0,51

LCoE prices are found to be 63 and 51 cents/kWh for the 15-year period. Both capital and electricity costs are the main components of the price, see also relative contributions in Figure 20. When upscaling, the main reduction in price comes from reduction of CAPEX and maintenance costs.

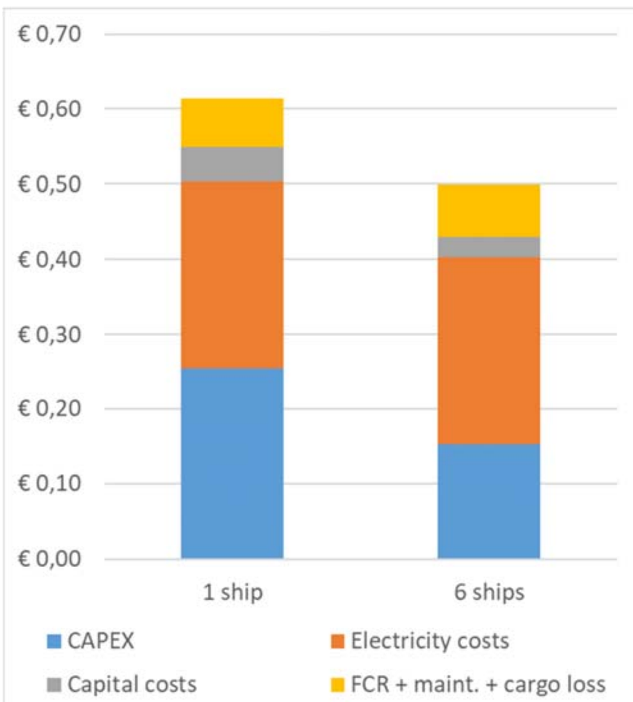

Figure 20: Breakdown of the costs from the levelized cost of energy in Table 17 and Table 18.

For comparison with other hydrogen sources, the price of a kg of compressed hydrogen is listed in Table 19. The hydrogen prices here are relatively low compared to the numbers reported in (2) for the Netherlands, which range 6-6.5 €/kW for uncompressed hydrogen. There are also several sources which H_2 cost projections for sustainable large scale production in the range of EUR 2 to 3 per kg and even below 2 EUR/kg, refer to (33), (34), (35). It should be noted that this is without distribution costs to the bunker locations and cost of the installations for fuel bunkering.

Table 19: Price per kg of compressed hydrogen (500bar).

	per kg
1 ship	€ 7,16
6 ships	€ 5,32

5.4 TCO for 2030

Reduction in electrolyzer price is expected and may be 46% in 2030 (2).
Also, efficiency of electrolysis is expected to go to 50 kWh/kg (vs 64 kWh/kg in this study, 22% better). For fuel cells no values are available, but since the technology is comparable to electrolysis (PEM) the same efficiency increase is taken. Therefore, the electricity costs are expected to decrease with 39% (twice a 22% reduction) due to efficiency increase.

This would yield a reduction of 14 cents/kWh and 13 cents/kWh for the single ship and upscaling, respectively. A significant reduction of costs for the CPTs is also expected, as the technology is new. The overview of the expected CAPEX, OPEX and LCoE is found in Table 20.

Also in the case of an external H_2 supply from a centralized large H_2 production facilities, this could also lead to substantially lower H_2 costs and consequently also lower electricity costs. In that case the H_2 transport costs should be taken into account, which are substantial in case of truck-trailer transport. In long term future these will probably be replaced by a pipeline, which would reduce transportation costs.

Table 20: Projection of CAPEX, OPEX and LCoE for 2030, based on expected efficiency improvement and costs reductions of electrolyzers and fuel cells (2)

	2020 (€/kWh)			2030 (€/kWh)		
	CAPEX	OPEX	Total	CAPEX	OPEX	Total
1 Ship	0.26	0.37	0.63	0.21	0.27	0.48
6 Ships	0.16	0.35	0.51	0.12	0.25	0.37
Stage V diesel direct (36)	0.01	0.14	0.15			
Stage V diesel genset (36)	0.03	0.14	0.17			

6 Conclusions and recommendations

6.1 Conclusions

This study evaluates the technical and financial feasibility of a fully zero emission sailing with the Gouwenaar II, with a H_2 fuel cell powertrain.

Operational profile
The operational profiles of the Gouwenaar consists of container transport from Alphen a/d Rijn to Maasvlakte II and Antwerp. The power system is configured of a 600 kW fuel cell stack (6 units), combined with a peak shaving battery of about 330 kWh. The maximum electric energy consumption on roundtrips to Antwerp is around 11.5 MWh, which corresponds to about 760 kg of H_2 consumption. With safety margins for extra consumption (20%) and spare capacity (also 20%), this leads to a H_2 storage requirement of 1050 kg (bunkering at one location). The average trip durations are respectively about 33 and 42 hours.

H_2 bunkering options and modularity
350 and 500 bar H_2 storage pressure levels are evaluated. With 500 bar pressure, the required 1050 kg for the return trip to Antwerp fits in one 40 ft container (total weight 21 ton), but 500 bar (or 700 bar) pressure makes filling of H_2 tanks more complex than with 350 bar.

Three options for modularity and H_2 bunkering are evaluated. This includes bunkering with a high pressure hose from shore, exchangeable H_2 tanks containers, as well as exchangeable powerpacks (H_2 tank + fuel cells in one container).

The main advantages of modular units are:
a) Flexibility: ships can switch between different kind of energy systems. For example between H_2 fuel cell powertrain to container batteries, or to diesel generator sets
b) Standard modules can be made at lower costs (when series increase).
c) It makes it easier to allow for a business model ‘energy as service’, in which the ship owner pays only for H_2 or for electricity onboard.

H_2 bunkering via exchange of H_2 container(s) takes about the same time as filling with a high pressure hose (about 2 hours).
The difference between separate modules for H_2 tanks and fuel cells or integrated modules (power packs) is not enormous. ‘Separate modules’ seems to have more advantages, because of the higher H_2 storage capacity per container and flexibility to independently size the fuel cell power system.

Safety considerations
The applicable legislation, as well as a long list of safety considerations have been summarized (in section 3) for the three bunkering options.
Main safety concerns regarding the hydrogen storage are loss of containment due to accidents or permeation of the hydrogen through the tank or pipe walls. The biggest gap is the lack of dedicated regulations, codes and standards for hydrogen as fuel in shipping.

Some existing codes and standards to provide guidelines for safe operation, are:

- IMO has no standards for hydrogen as alternative fuel, but there are several alternatives:
  - o DNV-GL have developed guidelines for most of the operations with fuel cell system
  - o An alternative design process based on IGF code
  - o A risk based approach as specified in SOLAS regulation II-1/55.
- IGF code covers the bunkering on the ship side, but the shore side needs further development.

Onshore H_2 production
For this project, dedicated onshore H_2 production via electrolysis at the CCT terminal location (Apherium) is evaluated based on the H_2 consumption for one and for six Gouwenaar ships. This consequently served as basis for overall investment costs and TCO calculations. Six Gouwenaar ship require four standard electrolyzer of 1.25 MW in order to produce sufficient H_2. For one ship, one electrolyzer is needed. For filling the high pressure H_2 tanks (350 or 500 bar), so called 'high pressure tubes' are evaluated. This is a good option for single ships or a small number of ships, because then there is no need for large buffer tanks.

Investment costs and TCO
Based on the on-board and the onshore investment costs, energy consumption and maintenance costs, the 'levelized costs of energy' for both H_2 and electricity (to be fed to the ship driveline) are calculated. It should be noted that most H_2 related components such as electrolyzers and fuel cells are produced in very small series (market introduction phase). This leads to relatively high prices and investment costs, which has its impact on the TCO calculations. The prices per kWh are given in the table below. The results show that the 2020 kWh price reduces from 0.63 to 0.51 when more ships take part in the battery exchange system This is mainly due to the more efficient use of the electrolizers. The LCoE of (renewable) H_2 ranges reduces from 7.16 to 5.32 EUR/kg (1 versus 6 ships). The LCoE of electricity (on-board) is substantially higher than the 0.17 EUR/kWh of electricity produced with diesel generator sets. The additional total costs for sailing on H_2 is consequently about EUR 750,000 annually per ship (based on six ships in 2020). This is based on the small scale decentralized H_2 production.

The table also gives the kWh costs projection for 2030, which is based on lower costs and higher efficiency for electrolyzers and fuel cells. This leads to a price range between 0.37 and 0.48 EUR/kWh.

Also future possible supply from centralized large H_2 production facilities could lead to substantially lower H_2 costs and consequently also lower electricity costs onboard. All costs are calculated without any tax[18] on fuel, nor without any environmental subsidies[19].

[18] According to the Act of Mannheim taxation of fuel for inland shipping is not allowed
[19] These are for example the Dutch MIA, VAMIL and EIA arrangements

Table 21: Projection of CAPEX, OPEX and LCoE for 2030, based on expected efficiency improvement and costs reductions of electrolyzers and fuel cells (2).

	2020 (€/kWh)			2030 (€/kWh)		
	CAPEX	OPEX	Total	CAPEX	OPEX	Total
1 Ship H_2 fuel cell	0.26	0.37	0.63	0.21	0.27	0.48
6 Ships H_2 fuel cell	0.16	0.35	0.51	0.12	0.25	0.37
Stage V diesel direct	0.01	0.14	0.15			
Stage V diesel genset	0.03	0.14	0.17			

6.2 Recommendations

The following recommendations are made regarding safety aspects:

- Qualification of compressed hydrogen tanks for maritime use.
  - More research with respect to:
  - Understanding of and safety measures for fuel containment (compressed, liquid) during hazards like fire, collision, explosion
- Development of requirements for piping of liquid hydrogen, based on LNG.

Regarding the further roll out of the H_2 fuel cell powertrain, we see a need for making choices on a European level on standardization in the H_2 supply chain and bunkering, especially with respect to:

- The H_2 pressure level for compressed H_2 storage, in relation to the preferred bunkering and H_2 supply chain options.
- The possible supply options and business models for renewable H_2.

It is also very important to build demonstration ships, such that further experience is build up with qualification and classification of ships with H_2 storage and fuel cells and to build up operational experience on H_2 handling, energy consumption and other operational aspects.

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8 Abbreviations

AC	Alternating Current
CAPEX	Capital Expenditures
DC	Direct Current
EC	European Commission
FCR	Frequency Containment Reserve
H2	hydrogen
LCoE	Levelised Costs of Energy
OPEX	Operational Expenditures
SOC	State of Charge
TCO	Total Costs of Ownership
UNR	United Nations Regulation

9 Signature

The Hague, 28 March 2019	TNO
Signature in original report	Signature in original report
Bilim Atli-Veltin Projectleader	Ruud Verbeek Author

A H$_2$ storage properties

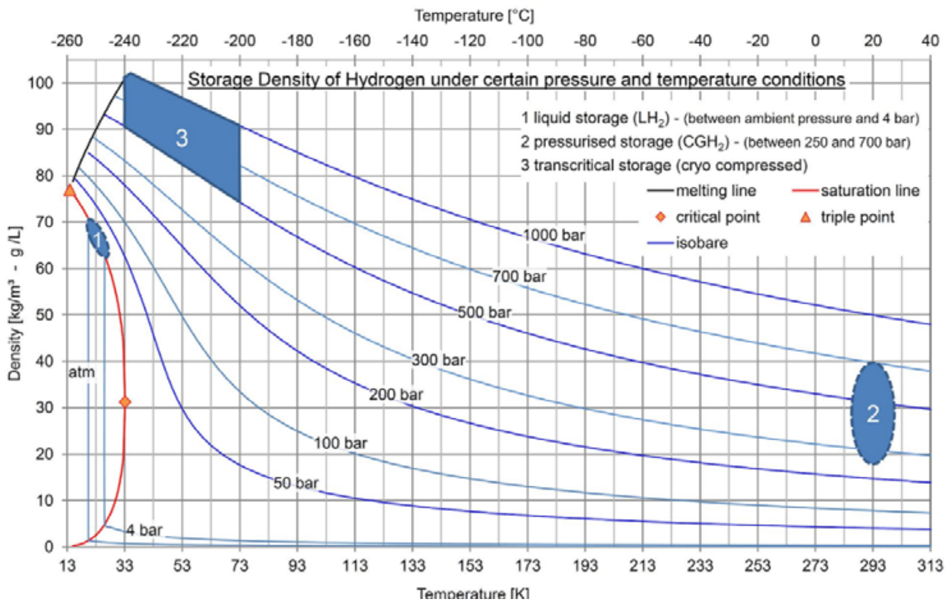

Figure 21: The density of hydrogen is function of temperature and pressure (37).