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TNO report

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Feasibility study for a zero emission, battery-electric 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 or for different boundary conditions such as for component costs developments.

Summary

This study evaluates the technical and financial feasibility of fully battery-electric, zero emission sailing with the Gouwenaar II, a 104TEU inland ship. The following topics are covered: sailing profile with energy demand, available battery systems in the market, battery charging and exchange logistics, and a TCO calculation. The is done for one ship as well as for six (Gouwenaar) ships, sailing on the same route. The study is supported by the 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 H2 fuel cell driveline, which is reported in a separate report [1].

Operational profile
The Gouwenaar II mostly sails within the ARA area, making roundtrips to Maasvlakte 2 and to Antwerp. Each round trip starts and ends from the Alpherium terminal in Alphen aan de Rijn. The ship is already equipped with an diesel electric propulsion system consisting of an electric propulsion system and diesel generator sets for power generation. In the conversion to a battery electric ship, the diesel generator sets are replaced by large battery containers. Using data logs that registered the electrical power demand from the switchboard, the energy demands for Maasvlakte were found to be around 6.5MWh, and for Antwerp around 11.5MWh.

Battery specification
The industry currently can install 2 MWh batteries in one standard 20ft container (1 TUE). This is currently the recommended configuration with DC output and no inverters in the container. This fits well to the mainly DC grid of modern electric powertrains.

The 2 MWh battery guarantees a minimum usable electric energy of 1.3MWh during their lifetime. This is after subtracting aging (20% capacity loss) and using a 10% - 90% State-Of-Charge strategy. The batteries can deliver plenty of power for an inland ship. They can be charged in two hours provided the charger and grid connection can deliver about 700 kW per battery.

Battery container logistics
The Gouwenaar round trips require the energy content of 5 to 6 containers for the roundtrip to Maasvlakte 2, and about 9 containers for the roundtrip to Antwerp, which includes a safety margin. It is concluded that battery exchange points (for replacing empty batteries by charged ones) are needed in addition to the charging point in Alphen a/d Rijn.

For roundtrip to:
- Maasvlakte 2: one exchange points at Maasvlakte 2
- Antwerp: one or two exchange points, in between Alphen and Antwerp and optional also in Antwerp.

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

The number of batteries onboard is then limited to three, which reduces the cargo loss and the investment costs in batteries.

The total system of batteries becomes more efficient, when more and more ships are sailing on batteries. This is because the number of batteries onshore is then relatively lower. A modelling exercise showed, that the total number of batteries needed for 1 and for 6 ships is respectively 12 and 24 batteries. This is a reduction from 9 to 4 batteries per ship.

Safety
There are some safety concerns related to heating, fire and risk of explosion. Damaged battery cells could lead to exothermic reaction, which can cause chain reactions and explosions. This can also happen when lithium comes in contact with water. So good safety measures are needed. Classification societies DNV GL, ABS, BV and SOLAS have developed rules for type approval for battery systems, for 'Direct DC power distribution systems (ABS) and for fire (SOLAS). There are also international regulations under development for the electric charging infrastructure, (IEC/ISO/IEEE 80005) and Fire Code (IFC 608).

Investment costs and TCO
To estimate the costs of sailing on batteries, a TCO model was constructed based on the trips energy demand and simple battery exchange system model.
The TCO model considers investment costs for purchasing battery containers and charging stations. For a single ship, the investment is estimated on 15 million €, increasing to 37 million € for 6 ships. The TCO calculation are based on a rather safe battery price assumption of EUR 700 per kWh (2020) and EUR 450 per kWh (2030). There are indications that the price may go down faster than this.
Operational expenses include loss of cargo space, time loss for exchanging containers and electricity costs. Also a potential income arising from Frequency Containment Reserve is included, in which idle (on shore) batteries operate in a pool to balance the electricity grid. The total revenues are estimated at 234k€ and 144k€ for 1 and 6 ships, respectively. It must be noted that these revenues are uncertain for the future and depend on many aspects.

CAPEX and OPEX were combined using a levelized cost of energy approach. This is used to calculate the lifetime cost of one kWh electric energy delivered onboard, including investment and operational costs. The prices per kWh are given in Table 1.

The results show that the kWh price reduces when more ships take part in the battery exchange system, due the lower number of batteries needed per ship. The kWh price for 2030 is expected to be about 25% lower, due to lower battery prices. The table also shows the reference price for diesel Stage V. It is concluded that for 6 ships, the diesel equivalent energy price is about 50% lower in 2020 and about 33% lower in 2030. If you would use six battery-electric Gouwenaar ships, this would lead to additional costs of about 330,000 EUR per ship per year (2020). This will decrease, when more ships participate in electric sailing and battery prices would continue to go down. All costs are calculated without any tax[2] on fuel, nor without any environmental subsidies[3].

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[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

Table 1: Levelized cost of energy prices for a 15 year period of battery electric sailing. CAPEX share of kWh price shows the decline due to the declining battery prices.

	2020 (€/kWh)			2030 (€/kWh)		
	CAPEX	OPEX	Total	CAPEX	OPEX	Total
1 Ship battery electric	0.44	0.20	0.64	0.29	0.17	0.46
6 Ships battery electric	0.19	0.13	0.32[4]	0.12	0.12	0.24
Stage V diesel direct	0.01	0.14	0.15			
Stage V diesel genset	0.03	0.14	0.17			

Recommendations

It can be concluded that more shipping companies are needed to participate in battery electric sailing, in order to roll out the full concept for ‘energy as service’, and for companies to invest in batteries and infrastructure (charging and exchange locations). Potential investors in this value chain have indicated that a minimum of 50 ships are needed for the Netherlands, in order to make this a worthy value chain.

In order to make the step from about 6 ships (Gouwenaar) to a minimum of 50 ships, the following activities are necessary:

- To identify (much) more than 50 ships suitable for battery electric sailing
- To convince the owners to consider battery electric sailing
- To identify suitable battery charging locations, taking into account the possibilities of the grid
- To identify the most suitable battery exchange locations, to serve the first 50 and following ships.

Also, the pros and cons of FCR (Frequency Containment Reserve) should be further investigated. Among others the additional battery aging and associated costs should be compared to the revenues (compensation to deliver electricity back to the grid in certain periods).

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[4] Please note that the LCoE calculation cannot be directly compared to the recently published calculation from the partners of the Green Corridor (c. 0.16 €/kWh) for the reason that their LCoE calculation is based on a pay-per-use model in a market scale of 50 + vessels, while we calculate the LCoE in a model in which we include the investments for batteries on board the vessel.

Contents

1 Introduction

Zero-emission inland shipping, with battery electric and H2 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 H2 storage. The diesel-electric powertrain is also becoming more popular. This powertrain is basically easy to transfer to a battery driveline or a H2 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 [2]. 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 realize zero-emission transport along this corridor [3].

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).

The project is carried out as a cooperation between industry (ENGIE, Siemens, Wärtsilä, Eneco, 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 for the project.

2 Battery electric Gouwenaar II

2.1 Concept of battery electric sailing

For continuous, zero-emission, battery electric sailing of inland ships, the battery packs are installed in standard 20 or 40 ft containers. The battery containers are part of an exchange system, in which empty batteries in board of the ship are replaced by full battery containers with a crane. This will usually be the standard crane of a container terminal.
The battery containers is designed as an independent, modular power unit, which can be owned by a third partly, the ‘energy supplier’. This is then part of a value chain which sells ‘energy as service’. The ship owner or operator purchases the electricity and is relieved from the high investment costs of batteries.
The battery can also be used for other purposes. For example for earning money as ‘peak shaver’ when connected to the electricity grid. The battery container has a standard connection to via a DC hub of the ship to the ship power system.
A small fixed battery (100-200 kWh) or diesel genset should be installed onboard. This can serve as power supply in case no battery container is connected onboard, for example during battery exchange.

2.2 Operational sailing profiles

In 2017, the inland waterway vessel Gouwenaar II was build. The Gouwenaar II is 90 m long, 10.5 m wide, and has a capacity of 104TEU. The single propeller is powered by a diesel electric driveline, with a 600kW electric propulsion motor.

The ship sails in the Amsterdam-Rotterdam-Antwerp (ARA) region.
More specifically, the Gouwenaar II sails between the container terminal Alpherium (in Alphen aan den Rijn (NL)) and Rotterdam (NL) or Antwerp(BE). The cargo exists of containers from the Heineken brewery. This route is part of the Green corridor, a dedicated route on which a number of organizations aim to realize water transport without greenhouse gas emissions [3].

For application of batteries instead of diesel generators, the dimensions of the technical components in the emission free system must be calculated.
The main characteristics of dimensioning are:

- Required power: the electric installed power that is needed to propel the ship and power onboard systems.
- Energy capacity: refers to the amount of energy that needs to be bunkered. This is the electrical energy currently extracted from diesel by the generator sets.

The operational profiles were obtained by CCT during a logging campaign in the spring of 2018. During this campaign the following parameters where monitored from the switchboard:

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

As an example, the combined generator power for round trip 7 is found in Figure 1.

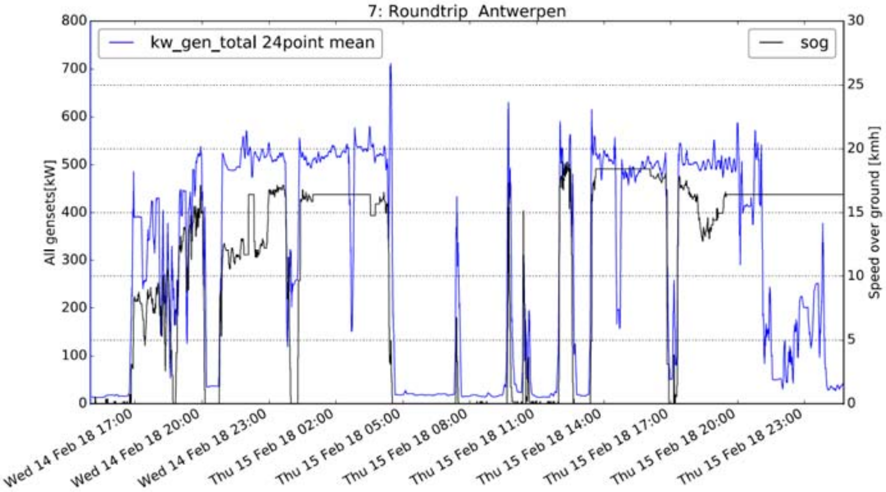


Figure 1: Combined power for a Antwerp round trip.

A round trip starts and stops at the Alpherium. GPS data was combined with AIS information to distinguish the different round trips. From the logging period, eight round trips were registered: five to Maasvlakte, and three to Antwerp. Characteristics of these trips are summarized in Figure 1. Round trips are visualized on Figure 2 and Figure 3.

Figure 2: Route between Alpherium and Maasvlakte 2 (created on blueroadmap.nl)

Figure 3: Route from Alpherium to Antwerp.

2.3 Container batteries

Li-Ion type of batteries technology are the most suitable for ship propulsion. The reason for this is the relatively high energy mass and volume density in combination with low energy loss for charging and discharging (Figure 4). Electric cars appear on the market with Li-Ion batteries at over 200Wh/kg. So the weight of batteries cells for a 2MWh container will be 10 metric tons (excluding container, cooling system, etc.). Total weight projection for a 2 MWh battery container is about 20 tons).

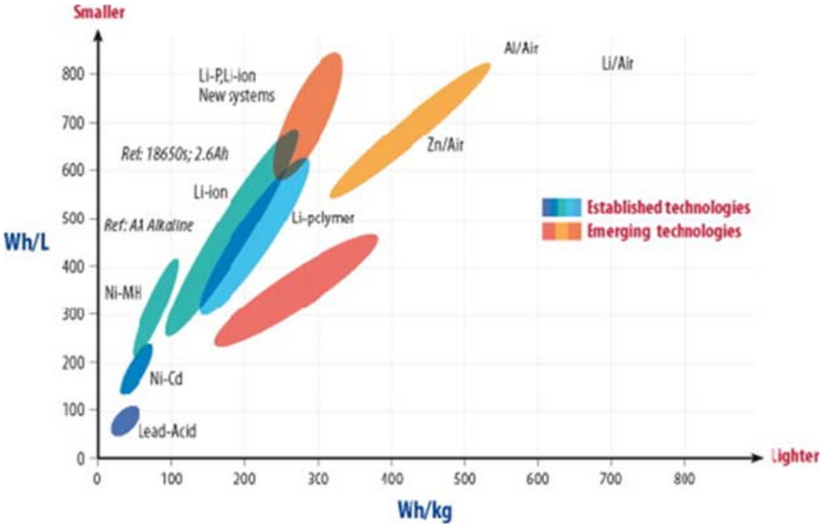


Figure 4: Energy densities of different battery types [17].

Marine batteries are usually more expensive than car batteries. That is primarily related to the small production series, the required certification and classification, cooling system and fire resistant container. For that reason the price projection for complete (DC) battery containers is rather broad and ranges from 350 to 800 EUR per kWh (2019). For the future a reduction is expected of about 10% annually. This results in a battery price for 2030 which is 60% to 70% lower. Uncertainties in this price reduction are related to raw material prices (such as Cobalt) and available battery production capacity. For this study, we use a rather conservative (safe) price of 700 EUR/kWh for 2019 and 450 EUR/kWh for 2030 for complete container batteries with DC input/output.

2.3.1 Battery container options

When defining the role of the battery container an energy carrier and more complete “power pack” can be distinguished:

1. The energy carrier consists of batteries only and have a direct current output. Battery management for the batteries in the containers is included. The ship has a multiple DC hubs, so that multiple containers can be connected. Inverters for the onboard AC grid are placed fixed on board the ship. An example layout is found in Figure 5.

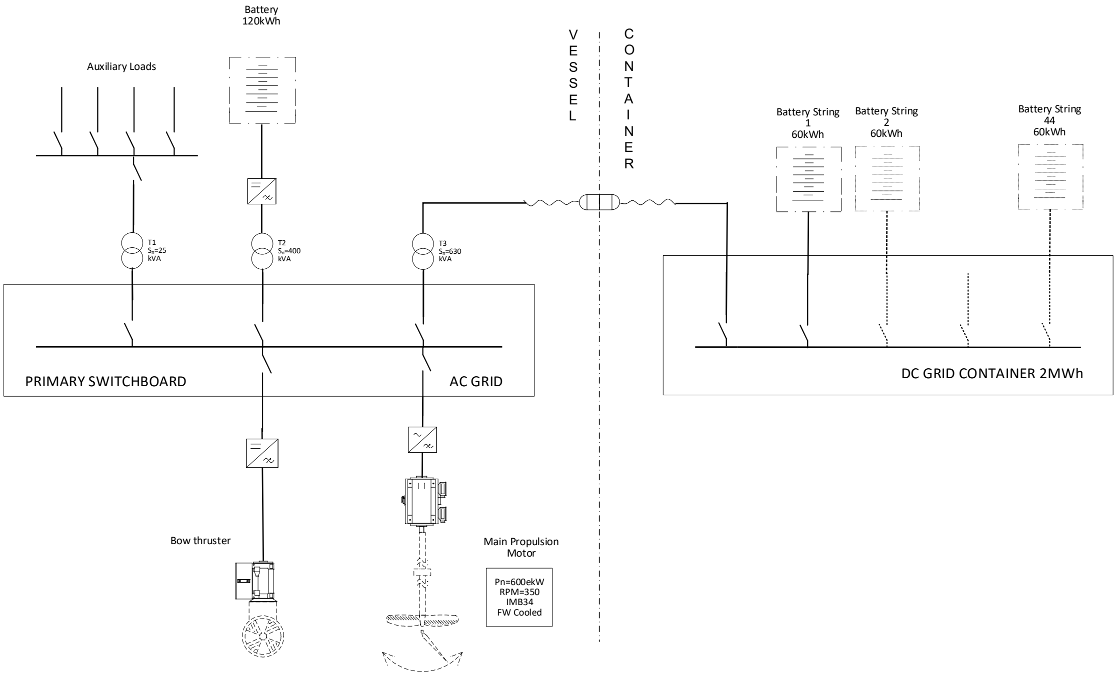


Figure 5: Key-one-line diagram after conversion battery electric propulsion system using exchangeable battery containers e.g. Gouwenaar II. (note: the transformer connecting the battery to the AC grid should be replaced by a inverter.)

2. The power pack includes power equipment (such as inverters) into the battery container. The advantage of this solution is that the container

becomes an independent, modular power unit. Therefore it may be deployed for other applications than ship propulsion. For example for land based temporary power requirements. This modular application is especially useful when the batteries have reached their End-Of-Life(EOL). After EOL, the batteries can be used in less critical on land applications, the build in inverters make it easier to switch to such applications. Application on board of a ship does not benefit from the build in power electronics: the battery ship requires a DC bus on the battery pack, since the ship has a variable speed drive (DC-AC or AC-AC converter for the electric propulsion motor). If only the AC bus is provided from the battery container, additional energy losses of 2-5% are expected.
A drawback of placing power equipment in the container is the additional expenses per container, and the reduction of space for batteries. Also additional investments have to be made for the power equipment.

An example of both roles for the battery container is delivered by Corvus Energy (Figure 6). Corvus' website lists a 20 foot and 40 battery container, with 546 and 1365kWh of capacity. These versions are without power electronics. The 40 foot container with power electronics, have a 500kWh lower capacity due to the space taken by the power electronics.

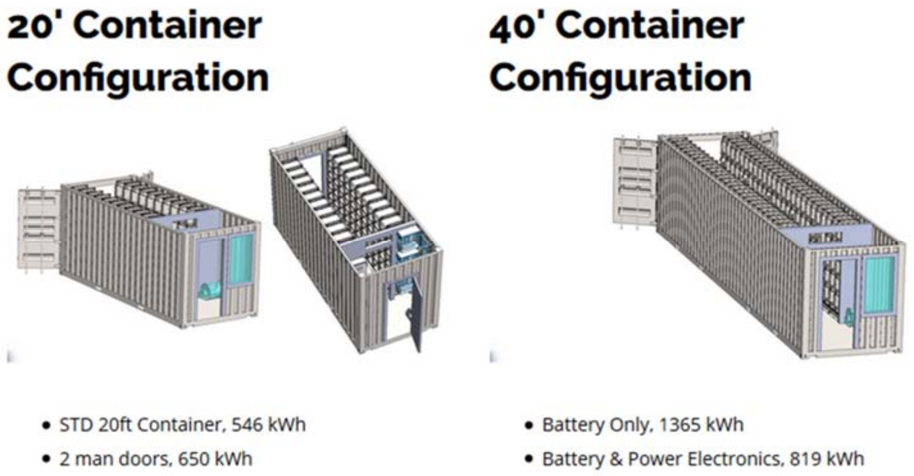


Figure 6: Energy storage system solutions from Corvus Energy [4]

The energy capacity of a containerized solution depends on the kind of batteries used, and the number of battery units that are fitted into the container. Enough free space must be reserved for maintenance and cooling. Other suppliers of battery containers are Siemens, Wartsila and Samsung. Capacities that have been reported by these supplier are in the range of 1365-2000kWh for a 40-foot container. Corvus has also planned higher capacities above 1365kWh, but not known to be in production yet.

In practice, not the entire capacity of the battery can be utilized. This is determined by the State Of Charge(SOC) upper and lower limit. These are important to be taken into account in normal operation, in order to reach the nominal life time of the battery.

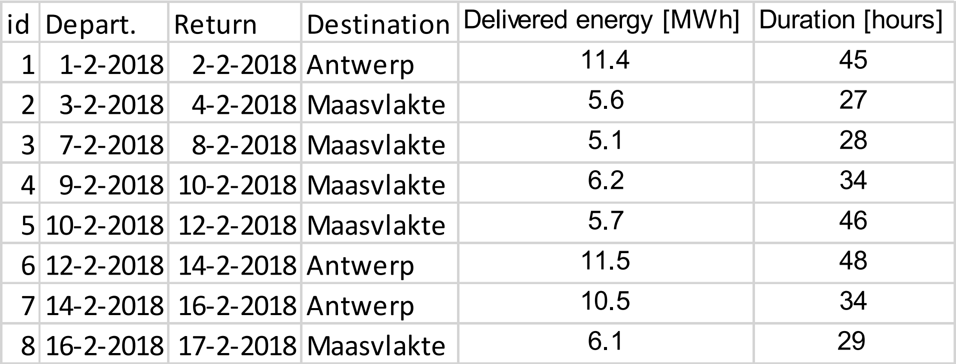
Full charging and depletion of the battery above or below these limits results in strong aging of the battery, i.e. it reduces the number of load cycles the battery can endure. With modern batteries, the usable SOC is usually between 10% and 90%. At a (exhaustive) 10%-90% SOC policy, 80% of the mentioned energy capacity is available. On top of this, aging plays a role in the available capacity, and End Of Lifetime, EOL capacity are typically 80% or the Begin-Of-Life(BOL) capacity. In total, SOC policy and aging give an useful capacity of 64% of the theoretical full capacity. Therefore, for the nominal 2000kWh battery container, the useful capacity ranges between 1300kWh and 1600 kWh for respectively the end of the battery life time and the new condition. This capacity is used to calculate the number of containers needed to complete the roundtrips to Maasvlakte and Antwerp.

Apart from the energy content of the battery container (expressed in kWh or MWh), also the maximum power (in kW) is important. For the power consumption of an inland ship, this is usually not a limiting factor, since battery containers typically have high power capacity, for example 700kW power per 20 ft container.
The number of battery containers needed for the Gouwenaar, is calculated in the section 2.5, based on the energy consumption determined in section 2.4.

2.4 Energy demand during the round trips

The delivered energy shown in this table was calculated from the logs. The energy is found by integrating the electric power of the generator sets over the time of the roundtrip. Results are found in Table 2 and visualized in Figure 7. The round trip duration represents the full period between departure and return to the Alpherium. Therefore it includes both sailing and waiting periods.

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

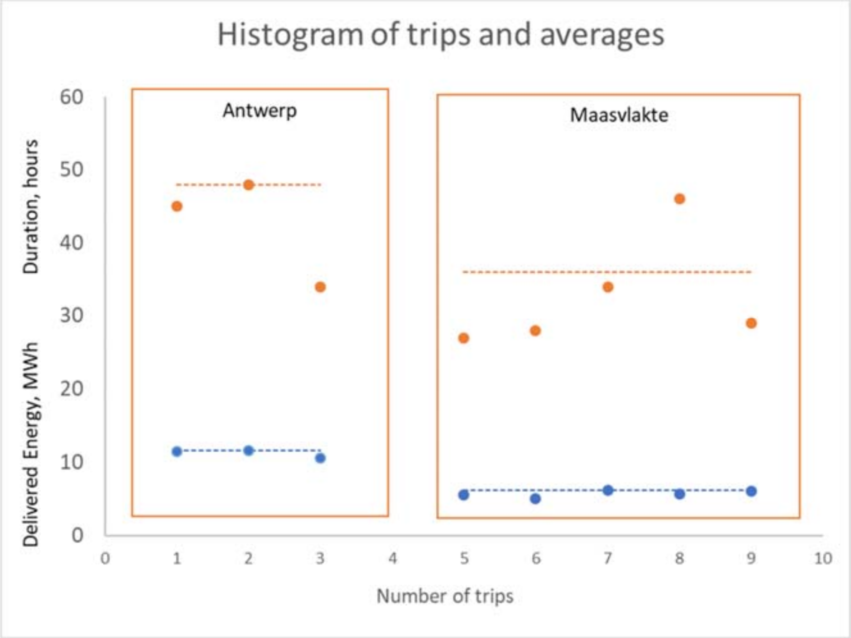


Figure 7: Energy demand and duration for both the Antwerp and Maasvlakte round trips. Numbers are found in Table 2 .

During the logging period, the most frequent round trip is between the Alpherium and the Maasvlakte. At the Maasvlakte, the ship visits various terminals. A typical one way trip time is 8 hours for the Maasvlakte, and roundtrip is 36 hours including waiting time, (off)loading at the Maasvlakte and resting time of the crew. The observed Maasvlakte round trip vary between 27 and 46 hours. The delivered energy from the generator sets is between 5.1 MWh and 6.2 MWh.

Three round trips to Antwerp were logged. The round trip to Antwerp takes up to 48 hours and the required energy is typically double the amount of a Maasvlakte round trip: 10.5 to 11.5 MWh.

For this study, the observed maximum demands of 6.2MWh and 11.5MWh are taken as representative for the round trips. The maximum values are used because this is the very least capacity that the ship should bunker.

High energy use can occur from:

- Stronger currents,
- Low water levels in the rivers,
- Disadvantageous tidal currents,
- Poor weather,
- Additional terminal calls,
- Additional waiting time,
- Energy inefficient navigational policies.

2.5 Battery exchange strategies

2.5.1 *Number of battery containers per trip*

2.5.1.1 *Maasvlakte*

The data log (Table 2) shows that the maximum energy demand is between 5.1 MWh and 6.2 MWh for a round trip between Alpherium (Alphen a/d Rijn) and Maasvlakte 2. Using the EOL (End Of Life) capacity of 1.3 MWh for calculations, at least five 20-foot containers are needed to complete the roundtrip (5x 1.3 MWh = 6.5 MWh).

2.5.1.2 *Antwerp*

The roundtrip between Alpherium and Antwerp requires 11.5 MWh energy, which corresponds to at least nine 20-foot containers (9x1.3=11.7MWh). Nine containers leave a margin of only 0.2MWh with the highest observed energy demand.
In practice, the margin is actually larger since the battery useful capacity is between 1.3 and 1.6 MWh. On the other side, the maximum of 11.5MWh was found in only three trips, so higher demands are likely.

2.5.2 *Optimization of battery container exchange infrastructure*

In the previous section, it was shown that for the roundtrips to Maasvlakte 2 and Antwerp respectively five and nine battery containers are needed. If you would take these onboard for the complete roundtrip, there would be two main disadvantages:

1. A big loss of a cargo space: some 5 to 10%
2. High investment costs of more than about ten battery containers per ship

The number of containers can be reduced by exchanging the battery containers on several locations during the roundtrip (not necessarily beginning and end).

The option considered here is to exchange containers during a round trip, at dedicated container charging and exchange points. Using such a system reduces the space needed for containers. Also, this makes it possible to share battery containers between ships, which will reduce the number of containers per ships. The logistical possibilities of such a system, and how the number of containers may be reduced are explored below. A simple model is presented to calculate the number of containers, the charging and idle time of the containers onshore and the operation and idle time onboard.

Sailing in a battery exchange system moreover has a significant impact on the operation of the ships. Energy consumption will have to be planned and monitored carefully. This is very different from the current diesel propulsion situation, where ships can travel large distances without bunkering.

There are many possible strategies and setups for utilization of battery containers in an exchange system. Setups differ in:

- Total number of containers in the system.
- The number of containers ships require, depending on their roundtrip, size and cargo.
- Optimal locations where ships need to exchange batteries.

The section is limited to the use of containers on a single Gouwenaar II, as well as the scale up to 6 Gouwenaars, with identical sailing profile and requirements.

2.5.3 *Goals of the battery container exchange system*

The main goals of the battery container exchange system are optimizing cashflows and minimizing capital investment. This comes down to the following optimization:

- Minimize time spent exchanging containers,
- Minimize cargo capacity loss,
- Maximize battery use on ship (in operation, not idle).

Which is respectively translated to implementation targets:

- Minimum number of battery exchanges
- Minimum amount of batteries on board

2.5.4 *A simple model for the number of battery containers*

For battery exchanges outside of the Alpherium, the following examples assumption are made:

- The batteries are placed in the cargo space at a reachable position. Therefore the crane has direct access to the battery containers, and does not need significant time to remove and place back cargo containers. This situation may be reached by placing the battery containers on top of each other.
- The minimum amount of containers is present in the exchange system. More containers may be needed for redundancy, in case a container is out-of-service or 2 ships arrive at the same time at an exchange point.

The model for the exchange system is derived by starting with a rather inefficient strategy, followed by iteration to a more efficient system.

The simplest, baseline strategy would be placing all required batteries on board in Alpherium. This would require at least 5 containers for the Maasvlakte, and 9 for the Antwerp round trip. The number of battery containers grows fast as the numbers of ships increases.

The following parameters are used:

- Time to exchange containers: 2 hours,
- Time to charge a container (½C): 2 hours.

Since the Gouwenaar II spends 5 hours at the Alpherium between the round-trips for cargo loading, this is considered an exchange point without time loss. Because of the idle time, there is sufficient time for the containers to be transferred onto the shore, be charged, and then placed back onto the ship. No additional batteries on-shore are needed.

2.5.4.1 *Alpherium - Maasvlakte roundtrip*

The number of batteries can be reduced by having an additional charge/exchange point on the Maasvlakte. Ships can drop empty batteries, and pick-up charged batteries there, this is visualized in Figure 8. Considering on exchange points, and a minimum amount 5 (paragraph 2.5.1.1) batteries needed in this round trip, the model uses batteries in groups of 3TEU batteries.

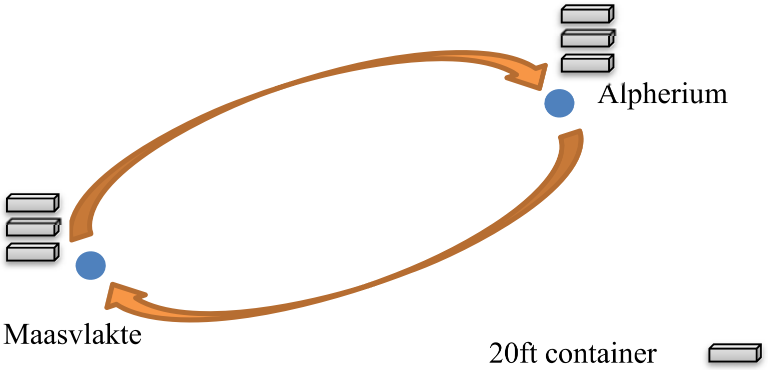


Figure 8: A schematic view of the Alpherium - Maasvlakte container circulation.

There is always a set 3 containers at the Maasvlakte, and 3 containers on the ship. With each additional ship, an additional 3 containers are added to the exchange system, the number of containers becomes $3 \times N_{ships} + 3$.
This can be done with any number of ships, as long as there is time for charging and exchange. The number of containers necessary are listed in Table 3.

Table 3: Number of containers for Alpherium-Maasvlakte only, and Alpherium-Antwerp only with one exchange point.

ships	containers
1	6
2	9
3	12
4	15
5	18
6	21

2.5.4.2 *Alpherium – Antwerp roundtrip*

For the Antwerp round trip, two scenarios are distinguished (see Figure 9):
A. Charge point at Alpherium, exchange point half-way and in Antwerp,
B. Charge point at Alpherium, exchange point at two-thirds to Antwerp.

The Antwerp round trip requires 9 battery containers (see 2.5.1.2), which needs two exchange moments (but leaving little energy margin of 0.2MWh). Batteries are exchanged on the way to Antwerp, and on the way back at the same location (see Figure 9, right). For a single ship, this system would yield six containers (three onboard and three on the two-third location). For every additional ship on this route, three containers are added. The total number of containers is equal to the Maasvlakte-only case (paragraph 2.5.4.1). This scenario will be used for the TCO calculation.

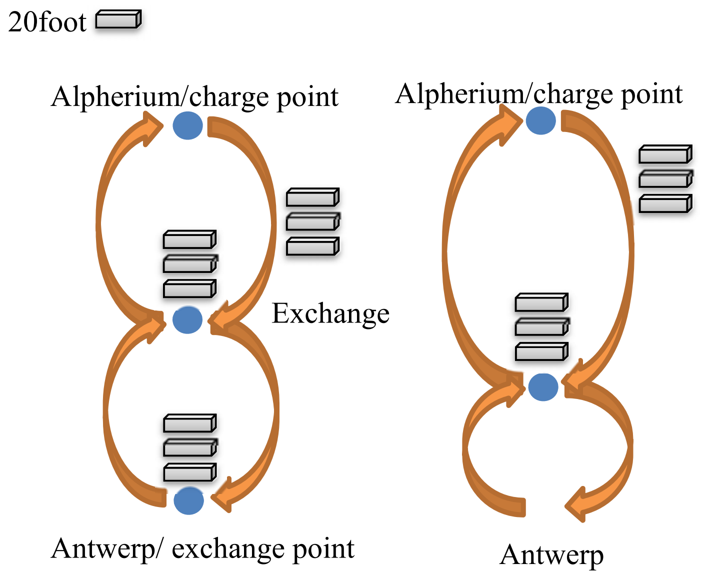


Figure 9: Two possible exchange concepts for the Alpherium-Antwerp round trip. Associated number of containers are found in Table 4. Left) scenario A has 2 exchange points. Right: scenario B with 1 exchange point.

The implementation targets give two possible ways to the increase the energy margin in the Antwerp round trip:

1. are placing an additional container on board on part of the journey
2. addition of an additional exchange point.

An additional exchange point in Antwerp may be logical, since many ships pass this port (see Figure 9). In this scenario batteries are exchanged three times on a round-trip, and 12 container charges can be used. Since two exchange points always have three containers stationed, the total number of containers is three higher than in the previous cases. Therefore the total number of containers becomes $3 \times N_{ships} + 6$. The numbers for upscaling are found in Table 4.

Table 4: Number of battery containers for Alpherium-Antwerp only with 1 and 2 exchange points.

ships	1 point	2 points
1	6	9
2	9	12
3	12	15
4	15	18
5	18	21
6	21	24

2.5.4.3 *Alpherium – Maasvlakte – Antwerp*

For a group of ships serving both Maasvlakte and Antwerp the two scenarios must be combined. There are respectively 2 and 3 exchange points for scenarios A) and B). The total number of batteries is $3 \times N_{ships} + 3 \times N_{exchange}$, for which the results are given in Table 5.

Table 5: Number of batteries required for the combined trips to Maasvlakte 2 and Antwerp.

	2 exchange points	2 exchange points	3 exchange points	3 exchange points
Number of ships	**Number of batteries**	**Batteries per ship**	**Number of batteries**	**Batteries per ship**
1	9	9,00	12	12,00
2	12	6,00	15	7,50
3	15	5,00	18	6,00
4	18	4,50	21	5,25
5	21	4,20	24	4,80
6	24	4,00	27	4,50
10	36	3,60	39	3,90

The number of batteries per ship is added to Table 5 as well, which is an important parameter for the CAPEX calculations (4.2.1). It is seen that the upscaling effect is significant for both scenario A and B, decreasing the number of batteries per ship from 9 to 3.6, and 12 to 3.90, respectively.

2.5.4.4 *Intensive energy planning and monitoring*

The number of containers obtained in the previous paragraphs calculate the minimum number of batteries per round trip. The study does not look into the subsections between the exchange points, and the precise locations of the exchange points is not calculated. When implementing the battery exchange system, calculating and optimizing these locations would be of most importance. Considering energy demand per round trip does not give enough detail to calculate the exchange points, since the energy use between exchange points is not considered. The energy use rate (power) will vary along the round trip, which may lead to shortages of energy in the containers. In practice, this would mean that the ship cannot ‘reach’ the next exchange point, which is obviously unacceptable.

Further research has to be done to calculate the exact locations, implement safety margins and define proper solutions for the stretches where exchange points may not be reached. Solutions may be found by loading additional batteries or place range extenders on board. Range extenders could be either emission free (hydrogen fuel cells), or small diesel generators.

Another important observation must be made for range extenders. The physical dimensions and costs of range extenders can only be kept small, if their power is low(for example <200kW). This is the case when they do not need to propel the ship entirely by themselves, and they operate in parallel with the batteries.
To achieve this, the range extender should be started in time to keep the batteries from depleting, and keep the high power output of the battery available. Such a control mechanism would require detailed energy planning and monitoring, and is key in keeping CAPEX costs low, if purchase of additional batteries can be avoided.

2.5.4.5 *Frequency containment reserve market*

In the battery exchange system there will always be batteries located at the exchange points. These need time to be charged, but there will be many hours left in which they are idle. This time can be utilized to generate income from an alternative source: helping electricity providers to enhance grid stability and maintain a constant frequency of 50Hz [5].

In Europe, the power grid operates at a frequency of 50Hz. 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. The pool of power suppliers and consumers that is used to obtain balance on the shortest time scale (seconds) is the Primary Reserve or Frequency Containment Reserve (FCR) [6]. With the increase of wind and solar energy, which have rapidly varying power production, the FCR market is growing. This section calculates the revenues that may be generated from the FCR market.

When participating in FCR, income can be generated by extracting power or delivering power when the grid frequency deviates from 50HZ. In the Netherlands, installations of over 1MW and over are eligible to operate in this market. The requirements for response time are met by installing appropriate battery installations and control mechanisms.

For OPEX, income from FCR is uncertain. Prices fluctuate on short term, and are uncertain for the future. For the calculations here, an effective income of 100.000Euro per year per MW available power is used, based on 100% availability, both extracting in providing power to the grid. This price was provided by the stakeholders. The actual availability percentage is of key importance for the OPEX calculations, and is the topic of the following paragraph.

2.5.5 *FCR station availability*

Calculating FCR revenues is a complex task that requires extensive knowledge of the electricity market. Furthermore, the electricity market is volatile in the sense that costs and demands change from year to year. It is therefore beyond the scope of this report to calculate the revenues in high detail. Nevertheless, since significant revenues may be obtained from FCR markets, it is tried to estimate the revenues using a simple model. T

he main parameters are:

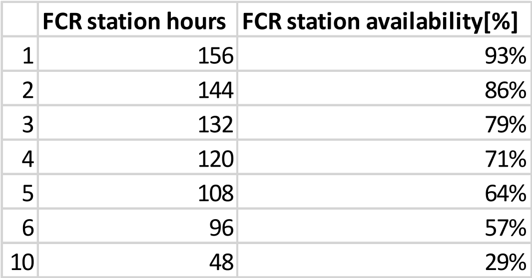
- T_{trip}: Total time of the combined roundtrip Alpherium-Maasvlakte-Alpherium-Antwerp-Alpherium (86 hours).
- $N_{stations}$: Number of charging stations that can operate in FCR (2 stations).
- N_{ships}: Number of ships in the system (1 to 6 ships)
- N_{calls}: Number of calls at a FCR point per ship per round trip (3)
- T_{call}: Time a call at an FCR exchange point takes (2hours)
- T_{charge}: Time it takes to charge the battery container to 50% FCR, and from 50% to 100% FCR, thus 2 hours in total.

Batteries at an FCR point are considered available for FCR if they are connected to the grid (not being exchanged), not charging the battery. This leads to the following expression for the availability:

$$\text{Availability} = \frac{T_{total} - T_{unavailable}}{T_{total}} = \frac{N_{stations}T_{trip} - N_{ships}N_{calls}\left(T_{call} + T_{charge}\right)}{N_{stations}T_{trip}}.$$

Numerically, the FCR station availabilities for 1 to 6 ships are given in Table 6. The number of hours based on one round trip to both Maasvlakte and Antwerp of 86 hours. Only the stations at Maasvlakte and the FCR station between Alpherium and Antwerp are taken as FCR station. The FCR station availability decreases with increasing number of ship, since batteries spend more time begin exchanged and charging.

Table 6: Total hours and percentage that a container triplet is available for FCR for scenario B.



	FCR station hours	**FCR station availability[%]**
1	156	93%
2	144	86%
3	132	79%
4	120	71%
5	108	64%
6	96	57%
10	48	29%

To calculate the yearly FCR revenues (in paragraph 4.2.2), a reference power of 2.1MW per station, or 4.2MW power for both stations is applied. The 2.1MW is the combined power of the 3 batteries that are present at each FCR station, with a unit power of 700kW.

2.6 Placement within the ship

A 20 foot battery container is approximately the same weight as a 20 foot cargo container ~22-30 metric ton. For the optimum exchange locations (at Alphen a/d Rijn, Maasvlakte 2 and two-third to Antwerp), three battery containers need to be stored onboard. Preferably this needs to be done in a vertical stack, so that this does not interfere with cargo container when exchanging batteries or cargo containers.

3 Safety and classification

3.1 On-board Safety

Safety characteristics of the individual cells and the pack are greatly affected by the design of the battery pack. In a series configuration cells may be subjected to forced over-discharge, and in parallel configuration it may lead to charging currents between batteries [7].
European industries are leading when it comes to electrification of ships [8].

Some safety concerns are relating to heating, fire and risk of explosion.
SOLAS Reg.ii-2/HSC Code Ch.7 provides requirements for fire in general.
The DNV GL RU SHIP Pt.6 Ch.2 requirements are on top of the SOLAS requirements.

Damaged battery cell could lead to exothermic reaction which causes more heat to be generated. Particularly for battery packs, this may cause chain reactions. Another safety risk is the reaction of water with lithium which produces hydrogen gas, which can cause fire or explosion if ignited. Therefore, management of lithium-ion batteries are highly important particularly in marine environment [9].
The thermal reaction that occurs in lithium-ion batteries generates intense heat that can lead to explosions and fires. Advanced cooling systems should be used.

Classification societies DNV GL, ABS and BV have rules for battery systems.

- DNV GL class programme - DNVGL-CP-0418 – describes the type approval scheme for lithium batteries [10]. This document supports the requirements of other relevant DNV GL rules, such as RU SHIP Pt.6 Ch.2 Sec 1 – Battery power.
- DNV GL released Chapter 2 Propulsion, power generation and auxiliary systems under Part 6: Additional class notations to the Rules for classification document [11].
- BV rules related to the battery systems are PT F, CH 11, Sec 22.
- American Bureau of Shipping (ABS) has released “Guide for Direct Current (DC) Power Distribution Systems for Marine and Offshore Applications [12]”.
- Hazard analysis process should be considered during the design phase to reduce the failure rate.

3.2 On-shore Infrastructure safety

EU Directive 2014/94/EU [13] is related to the deployment of alternative fuels infrastructure. This directive includes the aim to include shore - side electricity supply for inland waterway vessels and seagoing ships in maritime and inland ports. *“Member States shall ensure that the need for shore-side electricity supply for inland waterway vessels and seagoing ships in maritime and inland ports is assessed in their national policy frameworks. Such shore-side electricity supply shall be installed as a priority in ports of the TEN-T Core Network, and in other ports, by 31 December 2025, unless there is no demand and the costs are disproportionate to the benefits, including environmental benefits.“*
The European commission is also working on the International Fire Code IFC 608.

Figure 10 shows the electrical infrastructure at the shore side. Such system should comply with IEC/ISO/IEEE 80005 - 1 Utility Connections in port - Part 1: High Voltage Shore Connection (HVSC) system.

Figure 10: Example shore side infrastructure [14]

The standard for vessels requiring less than 1MVA of power is not yet released but a Public Available Specification is available (IEC IEC/ISO/IEEE 80005-3).
The final publication of this standard is planned for 2016 [14].
All design, installation and tests of Shore Side Electricity system for seagoing vessels should be done according to the specification of the
IEC/ISO/IEEE 80005 - 1 standard

4 Business cases

4.1 Energy storage company

The concept of shared battery containers, shared charging infrastructure and high investments, requires an investment which is too large for a small shipowner. One of suggestions from the market is to introduce a pay-per-use model, where batteries are owned and charged by an Energy Storage Company (ESC). The batteries are rented by the ship operator, and costs are charged per used kWh onboard of the ship.

In this study, the actual financing construction is ignored. The TCO focusses on total the costs of delivering the electricity on board, taking into account investment and operating costs. If a pay-per-use construction is implemented in an actual pilot, the costs per kWh will have to be split between the ESC and the ship operator.

4.2 TCO calculations

The TCO model quantifies the costs directly related to sailing with batteries 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 TCO calculations only cover the electricity costs onboard of the ship. It can best be compared with a diesel-electric ship, from which the diesel generator sets are replaced by battery containers. Also additional costs for market development such as running of pilots, are not included in the TCO. Also specific infrastructure costs such as the electric power cable to the grid and the logistics of battery containers are currently not included in the TCO calculations.

Notice that the prices listed in this chapter are mostly provided by component suppliers including project partners., and exclude taxes. Exact prices will be influenced by the engineering decisions and energy prices and reseller margins. The final price per kWh will be presented without (ESC) profit or margins. All costs are calculated without any tax[5] on fuel, nor without any environmental subsidies[6].

4.2.1 *CAPEX*

The capital expenditure(CAPEX) is the investment expense needed before the operations take place, and income is generated. In this analysis, the focus is on the costs related to the technical aspects of sailing on batteries. Shipyard costs to prepare for batteries in case of retrofit are not included.

The main components that make up CAPEX are:
- Batteries (700 €/kWh),
- Charging stations (508 k€/2.1kVa),
- On board power electronics and electric propulsion motor (350 k€).

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[5] According to the Act of Mannheim taxation of fuel for inland shipping is not allowed

[6] These are for example the Dutch MIA, VAMIL and EIA arrangements

Table 7: CAPEX numbers for sailing on a single and 6 ships.
Three charging stations are included.

	1 ship	**6 ships**
	kEUR	**kEUR**
Batteries	12600	33600
Charging station	1523	1523
Converter, Emotor	350	2100
Shore connection	132	132
total	14605	37355

CAPEX values are shown in Table 7, for both one and six ships. Relative costs are shown in Figure 11. It shows that more than 80% of CAPEX is for battery containers. The share of the charging stations reduces since the cost of three stations stays the same when upscaling. Costs connecting the charging stations to the net where not taken into account, since.

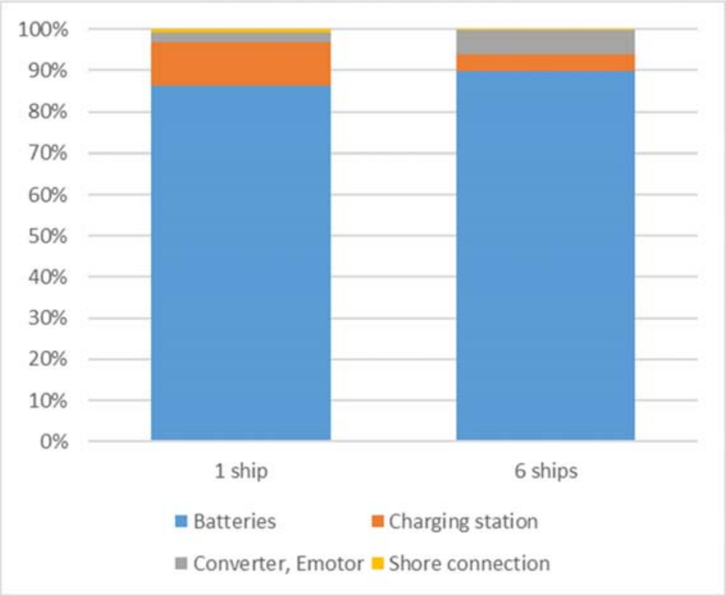


Figure 11: CAPEX for sailing on batteries, for a single an 6 ships.

4.2.2 *OPEX*

The operational expenditure are the returning total costs of running the battery exchange system, expressed on a yearly basis.

Table 8: Parameters used for OPEX calculations.

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%	

The interpretation of the parameters in Table 8 is as follows:
- Price 1TEU: revenue loss per TEU when replaced by battery containers,
- FCR: reference value for created revenues,
- Electricity price including transport 4-7ct (6 ct used for TCO).

Actual costs are found in Table 9. The costs are calculated as follows (scenario B, 2.5.4.2):

- Electricity: 2200 MWh times the number of ships and the electricity price
- Cargo loss: yearly revenues of a 20ft container times the number of containers in a stack(this is 3 containers)
- Time loss: unavailability of the ship due to exchanging containers
- Grid connection: yearly contract costs for access to the grid (high capacity connection) for 3 charging stations.
- Operational costs: expenses for planning and exchanging containers
- Maintenance: costs for maintenance on the charging stations and the batteries. Estimated at 1% of CAPEX, but detailed information is lacking.
- FCR: availability from Table 6, times the peak power of a battery container, times the number of batteries in a triplet (this is 3 containers).

This gives expenses of 250 k€/year for a single ship, and 1561 k€/year for 6 ships, which is made numerical in Table 9 and visual in Figure 12. The revenues from FCR are significant for a single ship, since there are many batteries, and the FCR stations are almost fulltime available. The FCR revenues decrease when scaling up to 6 ships, which is purely due to the reduction of FCR station availability. Total FCR power does not increase when scaling up, since the additional batteries in the system are on board, and cannot be used for FCR.

Table 9: OPEX for single and 6 ships based on scenario B. Negative numbers represent revenues.

Operational	**1 ship**	**6 ships**	
Sailing	4.264	25584	hours
Costs	**1 ship**	**6 ships**	
Electricity	132	792	k€/year
Cargo loss	38	230	k€/year
Time loss costs	28	171	k€/year
Grid connection	30	30	k€/year
Organisational costs	109	109	k€/year
Overall maintenance	146	374	k€/year
Revenues			
FCR	-234	-144	k€/year
total	250	1561	**k€/year**

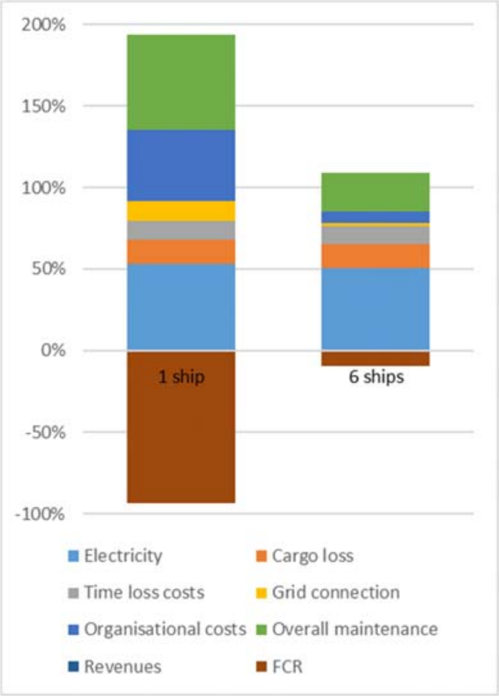


Figure 12: Operational costs and revenues for one ship sailing in a battery exchange system. Negative percentages are revenues, columns sum up to 100%.

4.2.3 *Levelized cost of energy*

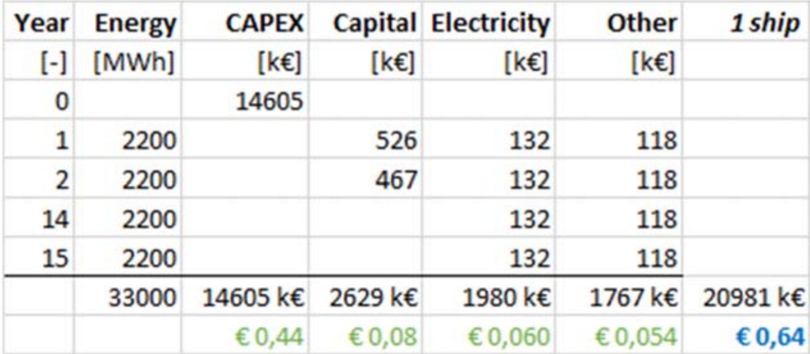
The levelized cost of energy(LCoE) calculates the costs of producing one kWh. For the application of emission free sailing, the energy is calculated at the switchboard, since the generator sets are replaced. The LCoE makes it possible to compare the costs of different electricity production scenarios. In this analysis the scenarios are one or six ships, the results are found in Table 10 and Table 11, respectively.

The column definition is as follows:

- Year: year number after the emission free sailing with batteries commences.
- Energy: the amount of electrical energy made available on the switchboard of the ship in the particular year, and the summation over 15 year.
- CAPEX: capital expenditure (see Table 7).
- Capital cost: interest costs over CAPEX, with linear decrease of CAPEX amount over 10 years.
- Electricity costs: energy price, including transport costs.
- Other: summation of maintenance, FCR income, costs of the power connection capacity.

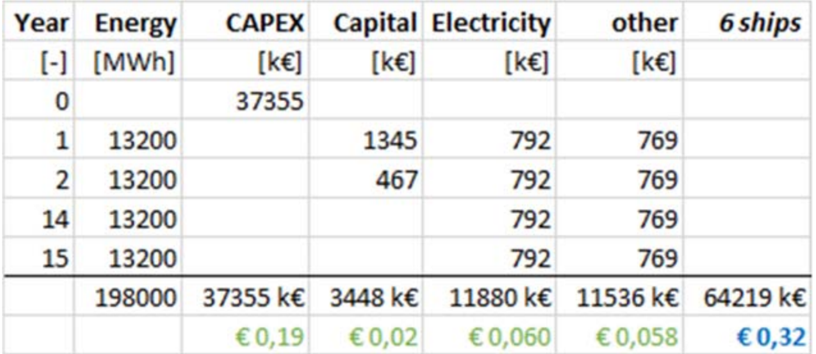
Costs numbers are excluding tax and profit margins.

Table 10: Levelized cost of energy for a single ship in a battery exchange system, ignoring actual financing realization by energy storage company or otherwise.



Year	Energy	CAPEX	Capital	Electricity	Other	*1 ship*
[-]	[MWh]	[k€]	[k€]	[k€]	[k€]	
0		14605				
1	2200		526	132	118	
2	2200		467	132	118	
14	2200			132	118	
15	2200			132	118	
	33000	14605 k€	2629 k€	1980 k€	1767 k€	20981 k€
		€ 0,44	€ 0,08	€ 0,060	€ 0,054	**€ 0,64**

Table 11 : Levelized cost of energy for a six ships in a battery exchange system, ignoring actual financing realization by energy storage company or otherwise.



Year	Energy	CAPEX	Capital	Electricity	other	*6 ships*
[-]	[MWh]	[k€]	[k€]	[k€]	[k€]	
0		37355				
1	13200		1345	792	769	
2	13200		467	792	769	
14	13200			792	769	
15	13200			792	769	
	198000	37355 k€	3448 k€	11880 k€	11536 k€	64219 k€
		€ 0,19	€ 0,02	€ 0,060	€ 0,058	**€ 0,32**

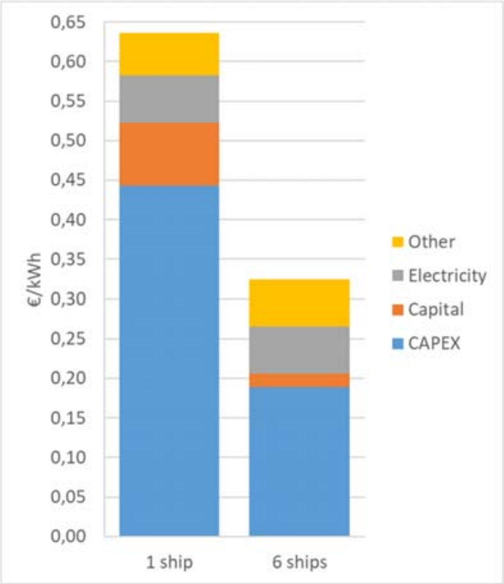


Figure 13: Levelized cost of energy composition (in €/kWh), for 1 ship and 6 ships. Electricity costs is fixed at 6 cents. CAPEX and capital costs decrease due to the reduction of the number of containers per ship. Other costs increase due to the reduction of FCR income, since FCR availability decreases.

The main conclusions from the levelized cost of energy are (summary in Table 12):

- The investment in the batteries make up a significant part of the life time costs. Battery price including interest yields ~81% of the costs for 1 ship, declining to ~62% with 6 ships.
- The table also shows the equivalent price for diesel Stage V, which is 0.15 to 0.17 EUR per kWh depending on the powertrain configuration, see also [15].

It can be concluded that for 6 ships, the diesel equivalent energy price is about 32 cent or 50% lower than the battery kWh costs (2020). If you would use only six battery-electric Gouwenaar ships and based on the yearly energy consumption, this would lead to additional costs of about 330,000 EUR per ship per year, compared to stage V diesel electric.

Table 12: Summary of cost per kWh of 1 and 6 ships. For reference, Stage V is included.

	2020 (€/kWh)		
	CAPEX	OPEX	Total
1 Ship	0.44	0.20	0.64
6 Ships	0.19	0.13	0.32
Stage V diesel direct	0.01	0.14	0.15
Stage V diesel genset	0.03	0.14	0.17

4.3 Outlook 2030

From the LCoE calculations it is clear that CAPEX costs are the main costs when sailing on batteries. In paragraph 2.3, the further decline of the battery price is discussed, which is likely to decrease to 450€/kWh in 2030 (for a complete battery container including cooling etc). While keeping the OPEX parameters from Table 7 constant, the energy costs onboard of the ship reduces to 0.64€/kWh (1 ship) and 0.32€/kWh (6 ships), due to battery and capital cost reduction.
The Levelized Costs of Energy is presented in presented in the Table 13 and Figure 14.

Table 13: Comparison LCoE between 2020 and 2025 for electricity costs onboard of the ship

	2020 (€/kWh)			2030 (€/kWh)		
	CAPEX	OPEX	Total	CAPEX	OPEX	Total
1 Ship	0.44	0.20	0.64	0.29	0.17	0.46
6 Ships	0.19	0.13	0.32	0.12	0.12	0.24

The equivalent diesel Stage V diesel electric energy price, remains the same as for 2030: about 0.17 EUR per kWh. So, it can be concluded that this is 15 cent or about 46% lower than for battery electric (based on 6 ships) in 2030.
Based on a total system of six ships with an annual energy consumption of about 2200 MWh per ship, the total additional costs for battery electric sailing are about 330,000 EUR and 154,000 EUR per ship per year, for respectively 2020 and 2030. It should be noted that all costs are calculated without any tax[7] on fuel, nor without any environmental subsidies[8].

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[7] According to the Act of Mannheim taxation of fuel for inland shipping is not allowed

[8] These are for example the Dutch MIA, VAMIL and EIA arrangements

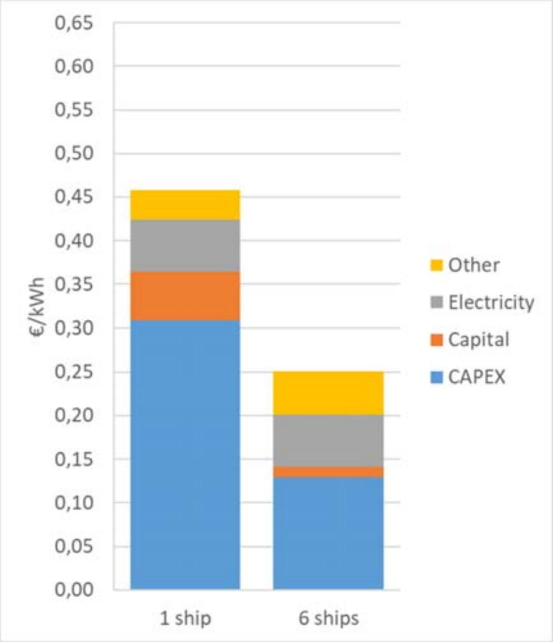

Figure 14: Levelized cost of energy in a future scenario 2030, where the battery container price decreases 450€/kWh. At upscaling to 6 ships, CAPEX and electricity costs become comparable.

Please also note that our LCoE calculation cannot be directly compared to the recently published calculation from the partners of the Green Corridor (c. 0.16 €/kWh) for the reason that their LCoE calculation is based on a pay-per-use model in a market scale of 50 + vessels, while we calculate the LCoE in a model in which we include the investments for batteries on board the vessel.

The main result of their research is that sailing on electricity becomes competitive compared to sailing on diesel from circa 50 ships onwards. In other words, the LCoE of battery electric sailing becomes competitive to diesel from the moment that more than 50 ships have joined the carbon free shipping movement. On first sight it seems that this conclusion differs from our results. After all, the LCoE of battery electric sailing is circa €0.32/kWh according to our calculations, while the LCoE of battery electric sailing in a pay-per-use model is circa €0.16/kWh according to the research of the Green Corridor. The gap of circa €0.16/kWh can however largely be explained by taking a closer look to the assumptions of battery prices in the two models. We consider a constant battery price over time of €700/kWh (2020 scenario), while the Green Corridor Partners expect a lower start price, which declines to 60% of the start price in 2025. Another reason for the gap can be found by the considered scale in the two different models: while we examine scale advantages till the point of six ships, the partners of the Green Corridor consider a scale-up of more than 50 ships in their model. At a level of 50 ships, more scale advantages can be achieved.

5 Conclusion and recommendations

5.1 Conclusions

This study evaluates the technical and financial feasibility of fully battery-electric, zero emission sailing with the Gouwenaar II.

Operational profile
The operational profiles of the Gouwenaar consists of container transport from Alphen a/d Rijn to Maasvlakte II and Antwerp. The energy demands for Maasvlakte were found to be around 6.5MWh, and for Antwerp around 11.5MWh. The average trip durations are respectively about 33 and 42 hours.

Battery specification
The industry currently can install 2 MWh batteries in one standard 20ft container (1 TUE). This is currently the recommended configuration with DC output and no inverters. This fits well to the mainly DC grid of modern electric powertrains.

The 2 MWh battery guarantees a minimum usable electric energy of 1.3MWh during their lifetime. This is after subtracting aging (20% capacity loss) and using a 10% - 90% SOC strategy. The batteries can deliver plenty of power for an inland ship. They can be charged in two hours provided the charger and grid connection can deliver about 700 kW per battery.

Battery container logistics
The Gouwenaar round trips require the energy content of 5 to 6 containers for the roundtrip to Maasvlakte 2, and about 9 containers for the roundtrip to Antwerp, which includes a safety margin. It is concluded that battery exchange points (for replacing empty batteries by charged ones) are needed in addition to the charging point in Alphen a/d Rijn.
For roundtrip to:

- Maasvlakte 2: one exchange points at Maasvlakte 2.
- Antwerp: one or two exchange points, in between Alphen and Antwerp and optional also in Antwerp.

The number of batteries onboard is then limited to three, which reduces the cargo loss and the investment costs in batteries.

The total system of batteries becomes more efficient, when more and more ships are sailing on batteries. This is because the number of batteries onshore is then relatively lower. A modelling exercise showed, that the total number of batteries needed for 1 and for 6 ships is respectively 12 and 24 batteries. This is a reduction from 9 to 4 batteries per ship.

Safety
There are some safety concerns related to heating, fire and risk of explosion. Damaged battery cells could lead to exothermic reaction, which can cause chain reactions and explosions. This can also happen when lithium comes in contact with water. So good safety measures are needed. Classification societies DNV GL, ABS, BV and SOLAS have developed rules for type approval for battery systems, for ‘Direct DC power distribution systems (ABS) and for fire (SOLAS).

There are also international regulations under development for the electric charging infrastructure, (IEC/ISO/IEEE 80005) and Fire Code (IFC 608).

Investment costs and TCO
To estimate the costs of sailing on batteries, a TCO model was constructed based on the trips energy demand and simple battery exchange system model. The TCO model considers investment costs for purchasing battery containers and charging stations. For a single ship, the investment is estimated on 15 million €, increasing to 37 million € for 6 ships. The TCO calculation are based on a rather safe battery price assumption of EUR 700 per kWh (2020) and EUR 450 per kWh (2030). There are indications that the price may go down faster than this.
Operational expenses include loss of cargo space, time loss for exchanging containers and electricity costs. Also a potential income arising from Frequency Containment Reserve is included, in which idle (on shore) batteries operate in a pool to balance the electricity grid. The total revenues are estimated at 234k€ and 144k€ for 1 and 6 ships, respectively. It must be noted that these revenues are uncertain for the future, and depend on many aspects.

CAPEX and OPEX were combined using a levelized cost of energy approach. This is used to calculate the cost of one kWh electric energy delivered onboard, including investment and operational costs. The prices per kWh are given in Table 14.

The results show that the kWh price reduces when more ships take part in the battery exchange system, due the lower number of batteries needed per ship. The kWh price for 2030 is expected to be about 25% lower, due to lower battery prices. Table 14 also shows the reference price for diesel Stage V. It is concluded that for 6 ships, the diesel equivalent energy price is about 50% lower in 2020 and about 47% lower in 2030. If you would use six battery-electric Gouwenaar ships, this would lead to additional costs of about 330,000 EUR per ship per year (2020). This will decrease, when more ship participate in electric sailing and battery prices would continue to go down. All costs are calculated without any tax[9] on fuel, nor without any environmental subsidies[10].

Table 14: Levelized cost of energy prices for a 15 year period of battery electric sailing. CAPEX share of kWh price shows the decline due to the declining battery prices.

	2020 (€/kWh)			2030 (€/kWh)		
	CAPEX	OPEX	Total	CAPEX	OPEX	Total
1 Ship battery electric	0.44	0.20	0.64	0.29	0.17	0.46
6 Ships battery electric	0.19	0.13	0.32	0.12	0.12	0.24
Stage V diesel direct	0.01	0.14	0.15			
Stage V diesel genset	0.03	0.14	0.17			

5.2 Recommendations

This study investigates technical feasibility and cost of ownership in a pilot case of battery electric sailing with the Gouwenaar II. More shipping companies are needed to participate in battery electric sailing, in order to roll out the full concept for 'energy

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

as service', and for companies to invest in batteries and infrastructure (charging and exchange locations). Potential investors in this value chain have indicated that a minimum of 50 ships are needed for the Netherlands, in order to make this a worthy value chain.

In order to make the step from about 6 ships (Gouwenaar) to a minimum of 50 ships, the following activities are necessary:

- To identify a minimum of 50 ships suitable for battery electric sailing
- To convince the owners to consider battery electric sailing
- To identify suitable battery charging locations, taking into account the possibilities of the grid
- To identify the most suitable battery exchange locations, to serve the first 50 and following ships.

Also, the pros and cons of FCR should be further investigated. Among others the additional battery aging and associated costs should be compared to the revenues.

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7 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

8 Signature

The Hague, 28 March 2019	TNO
Signature in original report	Signature in original report
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