D3.9 Evaluation of battery pack application on an inland vessel

Synergetics | Synergies for Green Transformation of Inland and Coastal Shipping

GRANT AGREEMENT NO.	101096809
DURATION OF THE PROJECT	42 months
DELIVERABLE NUMBER	D3.9
DELIVERABLE LEADER	MARIN
STATUS	FINAL
SUBMISSION DATE	15-06-2026
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Table of Contents

1. |Introduction 6
2. |Description of the vessel and the ZES system 7
 2.1 Description ZESpack containers 8
 2.2 Charging stations on shore 8
 2.3 Connection on board or at dock on shore 9
3. |Operational 10
 3.1 Wapping and handling operation 10
 3.2 Scale-up in Docking Stations 11
4. |Economics 12
 4.1 Levelized Cost of Energy assessment 12
 4.2 Business Case reflection 13
5. |Performance evaluation 15
 5.1 Data collection & monitoring 15
 5.2 Safety and reliability 16
 5.3 Achieved results 17
 5.4 Bunkered fuel vs. measured electric consumption 19
 5.5 Deviations in the measurements 21
 5.6 Adaptations to the system 23
 5.7 Points for improvement 23
 5.8 Energetic efficiency validation 24
6. |Lessons learned 25

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List of Figures

1 | ZESpacks placed on the Alphenaar 7
2 | Connector Box System (exposed) 9
3 | First generation ZESpacks with MQPC connector and Docking Station. 10
4 | Second generation ZESpacks with MCS connector and mobile shore power use case 10
5 | ZES‘ infrastructure development focus 11
6 | Yearly costs build-up 13
7 | Annual Cashflow comparison 14
8 | Example of a day operation of Alphenaar 15
9 | Measured electric consumption versus bunkered fuel of the Alphenaar 19
10 | Amount of lube oil and other engine-related mineral oil and grease disposed by the Alphenaar . 19
11 | Overview of the energy of the ZESpacks consumed on the Alphenaar per month 21
12 | Damages on the protection bulkhead on the Alphenaar 23

List of Tables

1 | Release Approval 4
2 | Main particulars of the Alphenaar 7
3 | List of real-time parameters recorded by the ZES system 15
4 | Operational data and calculated emission savings of the Alphenaar 17
5 | Diesel fuel (in m³) bunkered by the Alphenaar 17
6 | Energy consumption of Alphenaar (including electric energy estimated as Diesel m³ equivalent) . 17
7 | Consumables related to propulsion system 20
8 | Modifications implemented on the system 23
9 | Comparison of fuel and energy consumption without and with one or two ZESpacks 24

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Release Approval

1 | Release Approval

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Executive Summary

Battery-electric propulsion is one of the options to decarbonise inland shipping. Sailing with battery-electric propulsion reduces the impact on the climate, improves air quality locally, and reduces noise pollution. Due to its high Technology Readiness Level (TRL), this technology poses the advantage of allowing a fast implementation onboard, compared to other technologies which are still under development.

ZESpacks are 20ft containers containing batteries, which can be loaded onboard of a vessel. These batteries are provided by the company Zero Emission Services (ZES) through a Pay-per-Use (PPU) service. The first generation ZESpacks connect to ships or charging stations through a multipole quick power connector (MQPC), enabling automated transfer of DC power, auxiliary systems and data. This system has been working since its first use in September 2021 on board the inland container vessel Alphenaar, owned and operated by Combined Cargo Terminal (CCT) in Alphen aan de Rijn, Netherlands.

To facilitate the usage and robustness of the system so that it can be expanded to other ships, ZES is improving their current system with the next-generation ZESpack. This task is part of Work Package 3 Demonstration (WP3) of the SYNERGETICS project. Some adjustments have been made with regards to the shape of the container to reduce risk of damage. A major improvement of the technology is the replacement of the Multipole Quick Power Connector system to the Megawatt Charging System (MCS) type, which is becoming the worldwide standard.

In this deliverable the implementation of the ZESpack system on the inland container vessel Alphenaar is evaluated. Details of the battery system are given, including the operation, performance and economic impact of the use of the ZES system onboard.

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1. | Introduction

For the EU-funded Innovation Action SYNERGETICS, Zero Emission Services is demonstrating that retrofitting can be a successful method to make an inland or coastal ship 'greener'. Since 2021, the vessel Alphenaar has been transporting cargo with reduced tailpipe emissions, aiming to sail tailpipe emission free between the Dutch cities Alphen aan den Rijn and Moerdijk. This vessel serves as a demonstrator (Demo 3) within SYNERGETICS. Here, Zero Emission Services is demonstrating the extension of their ZESpack battery pack services on inland vessels. Electric sailing locally reduces the impact on the climate, improves air quality, and reduces noise pollution. The system uses ZESpacks: swappable energy containers that can be deployed flexibly on a Pay-per-Use basis.

Battery-electric inland waterway vessels, powered by technologies such as ZESpacks, can greatly reduce greenhouse gas (GHG) emissions compared to traditional diesel-powered ships. By adopting electric propulsion with batteries charged from renewable energy sources, these vessels can operate with zero direct emissions. This significant reduction in GHG emissions plays a key role in achieving global and regional climate goals focused on lowering carbon footprints, even when considering the full life-cycle emissions (well-to-wake). Additionally, electric vessels contribute to less noise pollution and improved air quality by eliminating NO_x and particulate matter (PM) emissions.

In terms of energy efficiency, electric motors powered by batteries are generally more efficient than internal combustion engines. In case of the vessel Alphenaar, the efficiency of the internal combustion engine is proven to be around 35 %, as showcased in this study. Electric motors, on the other hand, convert about 90 % of the electrical energy into vessel propulsion, leading to significantly less energy losses. This substantial efficiency improvement not only reduces energy consumption but also supports the broader sustainability of the transport sector.

This document provides an overview of the ZES system and provides performance measurements of the demonstrator vessel.

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2. | Description of the vessel and the ZES system

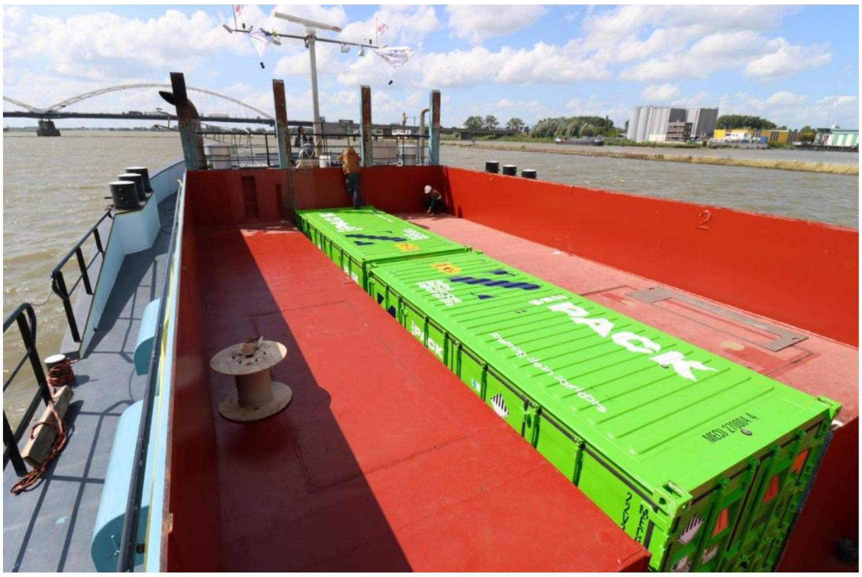
Alphenaar is an inland container vessel that transports containerised cargo between the Dutch towns of Alphen aan den Rijn and Moerdijk. In Table 2 the main particulars of the vessel are presented.

2 | Main particulars of the Alphenaar

Parameter	Value	Unit
Ship type	Inland container vessel	
Year of construction	2019	
Propulsion type	Diesel-Electric/Battery-electric	
Length over all	90	m
Beam, moulded	10.5	m
Draught, design	3.6	m
Deadweight, at design draught	1883	t
Container capacity	104	TEU
Propulsion type	Diesel-electric/Full electric	

Since the vessel sails through canals nearby inhabited areas, Combined Cargo Terminals decided to install swappable battery packs to reduce the negative impact of air pollution and noise on these residential areas. This measure allows the vessel to sail only with the power provided by the batteries, achieving a significant reduction in emissions and noise.

The ZESpacks are connected to the ship's grid via an onboard connection located at the forward end of the cargo hold. Two ZESpacks are placed on two 20ft container slots at the forward end of the hold, as shown in Figure 1.



1 | ZESpacks placed on the Alphenaar

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ZESpacks are charged by an onshore charging station which converts the AC current of the grid into DC at the voltage required by the ZESpack. To connect a ZESpack to a ship or charging station, a standardised system is used involving a Multipole Quick Power Connector, a mechanical docking frame, and electrical/data connections.

2.1 Description ZESpack containers

A ZESpack consists of a battery pack installed inside a 20ft container. The first generation ZESpacks have a total capacity of 2,100 kWh at full load and have a maximum output voltage of 936 V. With a C-rate of approximately 0.5 C, the batteries are able to be charged in 2 h and to deliver a maximum power of 1,000 kW. The new generation ZESpacks have an increased capacity of 2,900 kWh.

Thanks to its modular system, vessels can easily swap ZESpacks and travel long distances without being limited by long charging times. Several charging and swapping stations are now available in the Netherlands, but ZES expects to expand coverage throughout the entire country with a projected network of 14 charging stations in 2028, along the corridors to Antwerp and Duisburg.

In addition to the usage of the ZESpacks onboard, the battery packs can be used to support terminal electrification, addressing grid congestion and peak shaving. When no vessels have a container swap planned, ZESpacks can be used for grid balancing.

Finally, ZES leverages the technology through an innovative Pay Per Use service model, in which the containers are owned and managed by ZES, and the customer only pays for the use of the ZESpacks. This minimises the substantial investment that would otherwise be required to acquire and own these expensive assets.

2.2 Charging stations on shore

The Connector Box System includes three main connections: primary DC power, auxiliary systems (e.g. climate control, PLC), and communication lines. Electrical connections include high-current DC cables, grounding, AC auxiliary power, and communication lines (Ethernet and I/O). Data exchange uses the Modbus protocol and includes real-time battery status, safety indicators, energy metrics, and subsystem health, supporting cloud integration and system monitoring.

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2.3 Connection on board or at dock on shore

To connect a ZESpack, the same MQPC connector is used onboard and at the charging station on shore. On shore, a mechanical docking frame supports the ZESpack, and houses the electrical/data connections. The MQPC system enables automated coupling of power, auxiliary systems, and data through a male/female connector interface, where the female connector is fixed in the ZESpack and the male connector, with a self-aligning scissor lift mechanism, is part of the docking station or vessel.

Same as for the charging station on shore, the Connector Box System onboard includes three main connections: primary DC power, auxiliary systems (e.g. climate control, PLC), and communication lines. The system integrates components such as a control box, junction box, and connector box, all designed to ensure reliable and safe operation. The container is aligned using corner pins, allowing tolerances of ± 10 mm for final MQPC positioning.

Electrical connections include high-current DC cables, grounding, AC auxiliary power, and communication lines (Ethernet and I/O). Data exchange uses the Modbus protocol and includes real-time battery status, safety indicators, energy metrics, and subsystem health, supporting cloud integration and system monitoring.

2 | Connector Box System (exposed)

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3. | Operational

3.1 Wapping and handling operation

ZESpacks are standard 20ft containers and weigh approximately thirty tons. This weight is the upper limit of this type of containers and container terminals have the proper equipment to handle these containers.

As shown in Figure 3, CCT's reach stacker lifts the ZESpack from the docking frame to transport it to the waterfront. After the switch is executed, the reach stacker places the discharged ZESpack back onto the docking frame to start charging.

The MQPC is built in a steel frame. This configuration is robust in weight distribution but during the three years of operation, this set-up is proven to be too fragile in terms of connectivity and operability. It is impossible to transport ZESpacks to other locations to operate other type of use cases since it needs a connector feeding into the bottom of the container.

Over the years, the terminal operators have damaged the containers and the connectors multiple times. Several improvements have been implemented, the most significant being the switch from the MQPC to a new type of connector, allows ZES and operators to easily connect the connector on the side of the container. This significantly improves the operability, handling, and commercial allocation of the asset.

3 | First generation ZESpacks with MQPC connector and Docking Station.

Figure 4 shows the iteration into the second generation ZESpacks with MCS connector in combination with our Docking Station. In the new set-up, there is no longer the need of heavy structural steel to dock the ZESpacks. The new type of connector is fitted onto a swivel arm making it easy to connect. This also reduces the structural steel support lowering the cost of a Docking Station set-up.

With the new type of connector, it is possible to transport ZESpacks to other locations with the use of trailers and deploy the batteries to use for other purposes. Figure 4 shows the use case of mobile shore power. Through a pilot with Cargow and Port of Rotterdam, ZES charged six ZESpacks at one location, transported them to another location in the port area, connected these six ZESpacks to a discharge station and connected them through a single cable with the coaster from Cargow.

Through this proof of technology project, ZES demonstrated that the ZESpacks can be used for mobile shore power applications, an important use case for decarbonizing ports that aligns with the EU Fit-for-55 agreement.

4 | Second generation ZESpacks with MCS connector and mobile shore power use case

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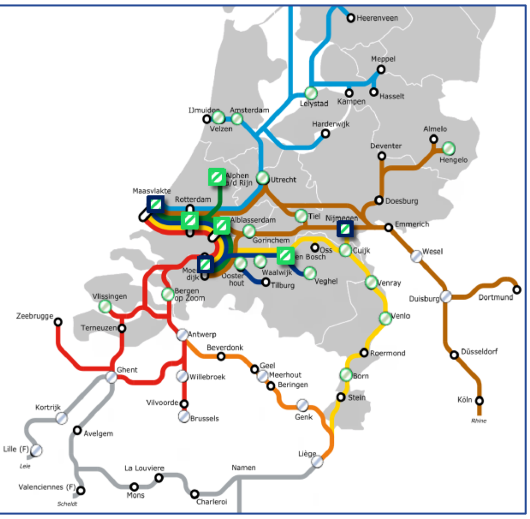
3.2 Scale-up in Docking Stations

The inland shipping sector is accustomed to bunker fuels, which can be stored in tanks for a long time. Operations such as side-bunkering are common practice and help reducing operational downtime. With a PPU and swappable business model, ZES minimises both upfront costs and operational downtime. Availability of energy is key to scaling up ZES' technology; therefore, ZES is expanding the network of Docking Stations along important TEN-T corridors. Figure 5 gives an overview of the current Docking Station development plan.

- **Priority 1 – Planned contracting and realization in 2025**
  - Moerdijk (Q4) — CCT
  - Rotterdam City (Q4) — Truck Parking Rotterdam (Mobile shore power)
  - Rotterdam Maasvlakte — Q Terminals (Kramer Rotterdam)
  - Nijmegen — ITG
  - Rotterdam City — UWT
- **Priority 2 – Planned realization in 2026 and after**
  - Infrastructure development along critical axes: Born, Utrecht, Gorinchem, Bergen op Zoom
  - Connecting important corridors: Amsterdam, Lelystad, Venray, Hengelo
  - Cross-border development: Antwerpen, Gent, Duisburg, Hull



5 | ZES‛ infrastructure development focus

Since the second generation ZESpacks are flexible to handle, transport and operate, ZES has increased the Docking Station development scope from only water-based locations (i.e., terminals with their own berth), to both water- and land-based sites. In addition to container terminals, ZES is also developing at non-container terminals, such as land-based electric truck charge locations. A good example is the truck parking facility by Truckparkings Rotterdam Exploitatie (TRE), where both truck charging and ZESpack charging are combined. This location is expected to be operational at the end of 2025.

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4. | Economics

4.1 Levelized Cost of Energy assessment

In basis, the economic performance is measured by the Levelized Cost of Energy (LCOE). The 2021 agreement with ZES' customer was agreed upon the basis of a monthly fixed price per kWh which was defined through the LCOE factor. The LCOE mechanism is defined as follows:

$$LCOE\ (€/kWh) = Avoided\ fuel\ cost + Avoided\ maintenance\ cost + Cost\ of\ CO_2\ emitted$$

$$Avoided\ fuel\ cost\ (€/kWh) = \frac{\text{Fuel cost per liter}}{\text{Energy per litre} * \text{Efficiency of fuel engine}}$$

<u>Assumptions from ZES' agreement:</u>

$Fuel\ cost\ per\ lite = given\ by\ customer$

$Energy\ per\ litre\ fuel = 10\ kWh/l$

$Avoided\ maintenance\ cost = 0{,}01\ €/kWh$

$Cost\ of\ CO_2\ emitted = 0\ €/kWh$

For CCT and the end customer, it was important that the economic assumptions were proven throughout the pilot project. As mentioned in chapter 3.2, together with both the operational data of CCT and the data from the ZESpacks, ZES has been able to confirm that the energy efficiency figure was sufficient to continue using this pricing mechanism within this pilot project.

With this pricing mechanism, ZES depends on the fuel market price. Per definition, this pricing mechanism is a way of calculating what the cost of fuel should be in terms of €/kWh, which is easy to follow for the customer. This pricing mechanism introduces two high risks and is explained as follows:

- This mechanism highly depends on the fuel price input of ZES' customer. This introduces the risk of fluctuating PPU pricing when the fuel market is under pressure raising the impact of not being able to cover ZES' cost basis;
- The price of electricity – needed to be paid to charge the ZESpacks – is not included in this mechanism. The price of electricity follows the gas price and does not move in the same manner as the fuel price does. Similar to the previous risk, this also leaves ZES exposed.

ZES and CCT have agreed upon a fixed LCOE rate, both risks occured leaving ZES heavily exposed to the market.

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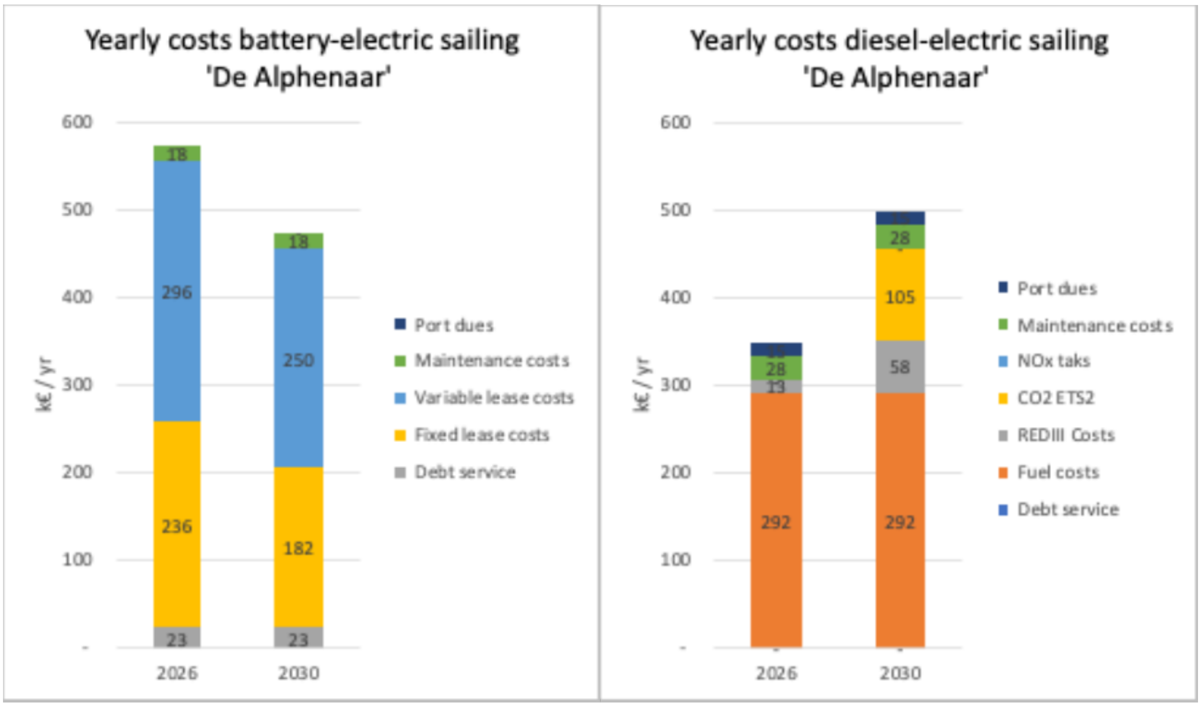
4.2 Business Case reflection

A study was done to investigate the costs of battery electric sailing compared to diesel electric sailing. A 5-year business model was developed and all the inputs for the vessel were put into the model to estimate future prices for different drivetrain technologies. It is assumed that the vessel is sailing 250 times back and forth between Alphen aan Den Rijn and Moerdijk. This is approximately 62 kilometers for a one-way trip. All current known National and European regulatory measures have been included in the model such as EU-ETS2 and RED3. The build-up of the Operational Expenditure in 2026 and 2030 can be seen in Figure 6. The EU-ETS2 is the new European carbon tax which will be included from 2027. The future prices of the carbon tax are 96 €/t in 2027, this will bring an extra cost for sailing on diesel of 105 k€ in 2030. The REDIII is the third version of the European Renewable Energy Directive. The revised directive aims to accelerate the energy transition. Bunkering companies must sell a portion of renewable energy in their diesel, which is why the price of diesel is expected to rise with 130 €/m³ in 2030 according to EICB. This will result in extra yearly costs of 58 k€ for the Alphenaar.



6 | Yearly costs build-up

The prices of diesel-electric sailing are expected to go up in the next five years and the cost of battery electric sailing is expected to drop. This is due to two main reasons; firstly, the price reduction of the batteries of the past 3 years and the upcoming years. Secondly, more docking stations will be operational, therefore it will be possible to sail the same route with only 1 ZESpack on board instead of 2 ZESpacks.

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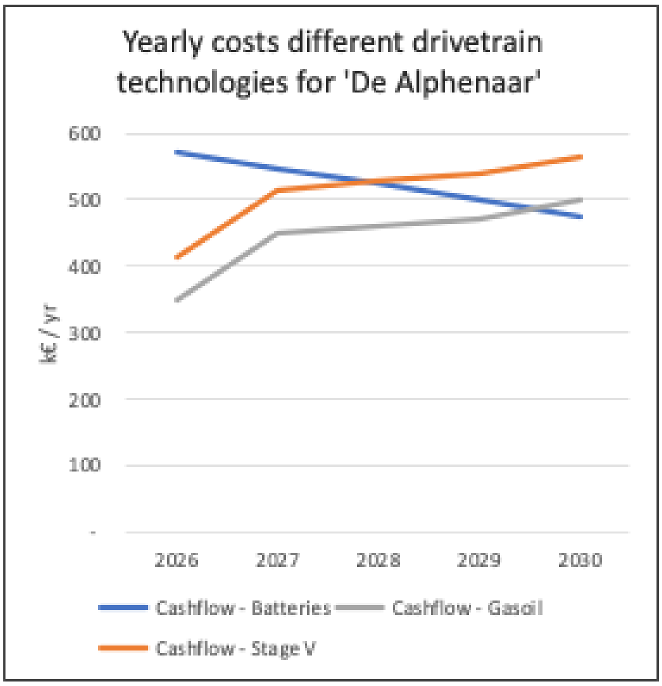
An overview of the annual cashflow for the next five years of battery electric sailing, diesel electric sailing and sailing with a stage V motor are shown in Figure 7. With all the regulatory incentives taken into consideration, and the assumption of diesel becoming more expensive and electricity cheaper, it seems that the financial gap between diesel and electric sailing could become break-even in 2029.

There is a price gap for at least the coming five years. This is an important reason why it is so difficult to convince inland shippers to convert to battery electric sailing. There is no customer willing to pay this premium. To accelerate the adoption of battery electric sailing, the financial gap in the operational expenditure must be supported. The options to close this gap are: 1) implement regulatory incentives, 2) push towards Shippers, 3) decreasing capital expenditure as upfront cost (decreasing cost of capital to be paid annually), and 4) implement operational expenditure subsidies.



7 | Annual Cashflow comparison

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5. | Performance evaluation

5.1 Data collection & monitoring

The monitoring system of the ZESpack collects real-time data on the parameters listed in Table 3.

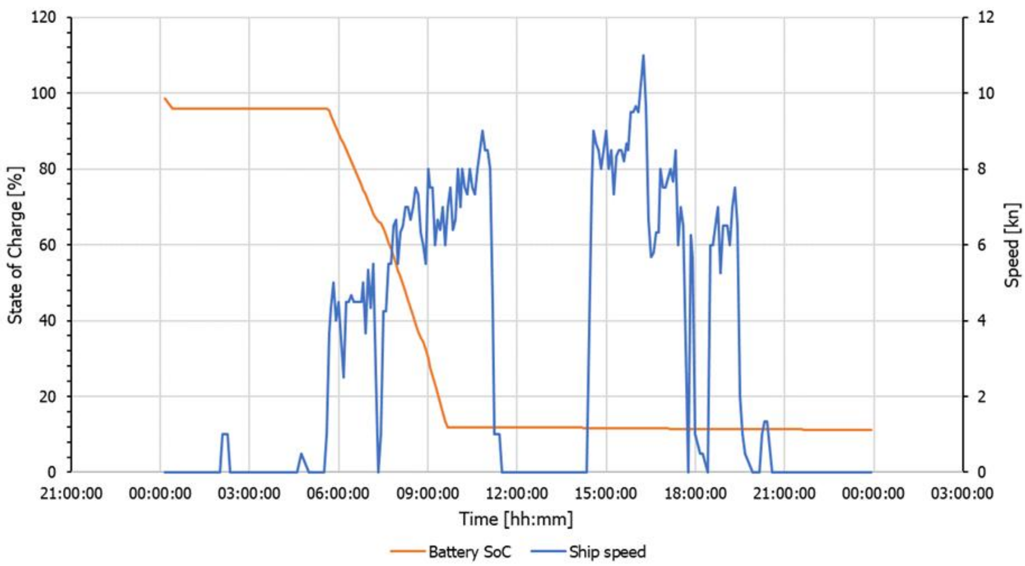
3 | List of real-time parameters recorded by the ZES system

Parameter	Unit
Time	hh:mm:ss
Ship speed	km/h
Available energy	kWh
State of charge	% (of maximum battery capacity)

The monitored data shows how the vessel is operating. A typical day is summarised below:

- In the morning the Alphenaar sails from Alphen aan de Rijn to Moerdijk with cargo, where it arrives at around noon;
- In Moerdijk the vessel remains at the quay, where it is unloaded. During this operation the batteries are not used;
- At approximately 14:30, the ship departs from Moerdijk back to Alphen aan de Rijn with new cargo, arriving at around 20:30.

Figure 8 shows an example of the measured data in a typical day. The graph corresponds to the data collected from one battery pack. When one battery pack is used completely, the ship continues operating with the other battery pack, the state of charge of the second battery pack is not in the dataset of the empty pack. This is the reason why in Figure 8 the ship continues operating even though the state of charge of the ZES pack as reached its lowest state of charge point. If the second battery pack is also empty the vessel will continue sailing on gasoil.



8 | Example of a day operation of Alphenaar

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5.2 Safety and reliability

The installation as designed and installed on board has proven to be very safe and reliable in terms of fire safety. Three 20ft battery containers were made suitable for use with a bottom connector (ZES 1.0) as installed on the Alphenaar.

During container handling in the terminal and onboard, the units are exposed to shocks and vibrations. Despite these conditions, no undesirable situations such as overheating or fire have occurred. In the unlikely event that this occurs, the units are internally protected against overheating and fire. Fifi4marine build an automatic fire extinguisher. In the event of an incipient fire, the system immediately activates and envelops the affected battery pack with targeted foam extinguishing from both above and below. As a result, the fire direct nipped in the bud even before it can spread. In case of an external heat source, the crew can flood the forward compartment to cool and maintain the batteries at a safe temperature.

During navigation, the nautical safety of the ship and its surroundings is of great importance. For this reason, a working group of stakeholders (ZES/CCT/Oechies/Wärtsila/Innovated) is active to:

- Maintain crew training levels
- Analyse and mitigate error messages
- Keep the installation in good condition

If power supply from the battery containers fails, the generator starts automatically. A blackout is prevented because the generator is started first, which takes about 20 seconds, after which the battery is disconnected.

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5.3 Achieved results

ZES and CCT are proud to say that the Alphenaar has sailed electrically for a significant part of the past three years. This is the first inland vessel to sail with 100 % electric propulsion. Naturally, problems have also occurred, as a logical consequence of pioneering, and these are listed in the following section. This section discusses the achieved results.

Since September 2021, the Alphenaar has been sailing electrically. After resolving some operational problems in the first months, the Alphenaar sailed from January 2022 to December 2022 without major issues. As shown in Table 4, in 2022 384 tons of Tank To Wake (TTW) CO_2 emissions were avoided by sailing electrically, which is a significant portion of the Alphenaar's total emissions (see Table 4). To calculate the emission reduction, the following figures are used from the source co2emissiefactoren.nl: 305 liters of gasoil are avoided if 1 MWh of electricity is used. This results in a reduction of 2.5 ton CO_2/m^3* 0.305 m^3 = 0.762 ton CO_2 reduction per MWh electricity used. As shown in Table 5 and Table 6, a 35 % diesel saving was achieved in 2022, compared to 2021.

4 | Operational data and calculated emission savings of the Alphenaar

Year	Days sailed full electric	Electricity Used [MWh]	Fuel saved [m^3]	CO_2 avoided [t]	Nitrogen avoided [t]
2021	28	62	19	47	0.8
2022	220	505	154	384	6.8
2023	50	69	21	52	0.9
2024	61	119	36	91	1.6

5 | Diesel fuel (in m^3) bunkered by the Alphenaar

Year	Q1	Q2	Q3	Q4	Total per Year
2021	92.7	118.6	117.9	96.2	425.5
2022	85.5	54.5	63.5	76.5	280.0
2023	88.5	97.3	93.9	101.5	381.2
2024	88.9	50.7	89.1	20.1	248.8[1]

6 | Energy consumption of Alphenaar (including electric energy estimated as Diesel m^3 equivalent)

Year	Q1	Q2	Q3	Q4	Total per Year
2021	93	119	120	113	444
2022	122	97	109	106	434
2023	100	102	99	101	402
2024	90	79	89	27	285[1]

[1] Data up to October used for 2024.

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With only one docking station at the Alpherium terminal and the number of battery containers currently in use, it is expected that the 2022 performance can be improved by 55 %, provided that two battery containers are always on board and downtime is minimised.

If the Alphenaar can operate optimally on battery containers with the current setup, an annual diesel saving of 240 m³ is expected. Under those conditions, in 2023 the Alphenaar would have sailed 60 % of the energy electrically.

If additional docking stations are built where the Alphenaar can exchange battery containers, the vessel could sail up to 95 % electrically in the future. The remaining 5 % would consist of longer trips and periods when maintenance is carried out on the battery containers.

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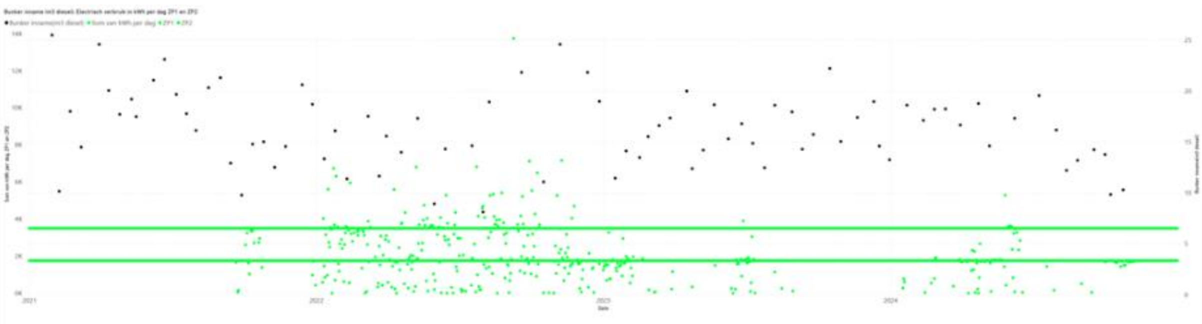
5.4 Bunkered fuel vs. measured electric consumption

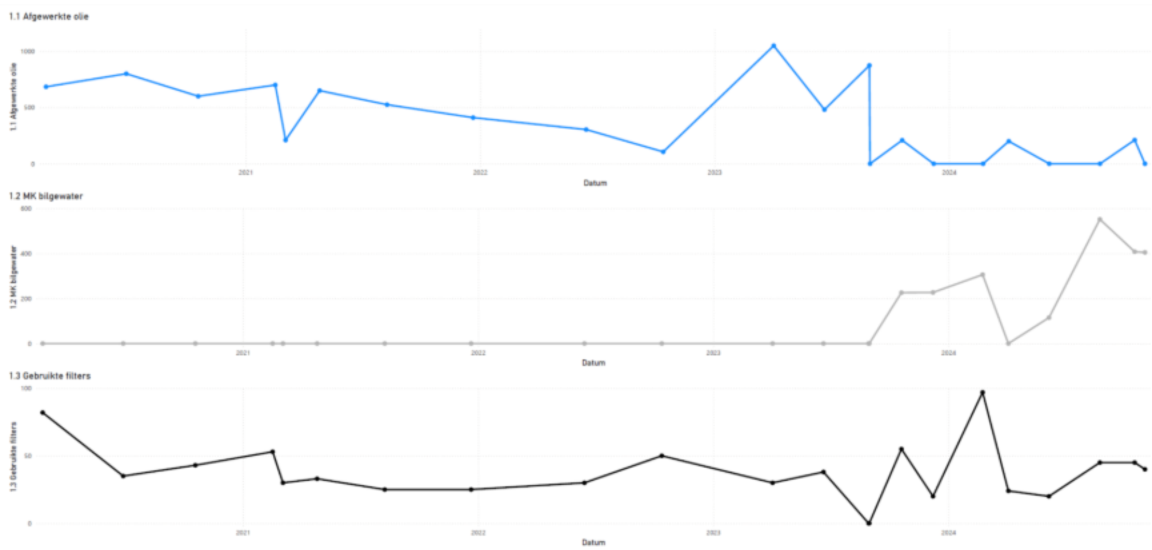
In Figure 9 an overview of the trend in bunkered fuel (diesel in m³) and measured electric consumption (in kW per day) is presented. The amount of bunkered fuel is now at the same level as in 2022, the year with the highest number of electric sailing days, despite only 27 % of that number of electric days. This indicates strong potential for improvement in 2025.

The two green lines represent the maximum usable power per battery container: 1,750 kW for one container and 3,500 kW for two containers.



9 | Measured electric consumption versus bunkered fuel of the Alphenaar

In addition to the fuel consumed, the ship also uses lubricating oil, filters, and other oils and greases. Figure 10 shows an overview of the quantities waste disposed of during the period 2021–2024.



10 | Amount of lube oil and other engine-related mineral oil and grease disposed by the Alphenaar

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7 | Consumables related to propulsion system

Date	1.1 Used oil	1.2 MK bilge water	1.3 Used cleaning cloths	1.3 Used grease	1.3 Used filters	1.3 Packaging
Tuesday 25 February 2020	684	0	64	0	82	42
Monday 29 June 2020	800	0	76	0	35	0
Monday 19 October 2020	600	0	35	0	43	0
Tuesday 16 February 2021	700	0	0	0	53	0
Thursday 4 March 2021	210	0	40	0	30	0
Monday 26 April 2021	650	0	41	0	33	0
Monday 9 August 2021	525	0	0	0	25	0
Tuesday 21 December 2021	410	0	0	0	25	0
Wednesday 15 June 2022	304	0	20	10	30	0
Thursday 13 October 2022	106	0	40	0	50	0
Monday 3 April 2023	1049	0	45	0	30	2
Wednesday 21 June 2023	481	0	32	0	38	0
Wednesday 30 August 2023	874	0	60	0	0	50
Thursday 31 August 2023	0	0	0	0	0	50
Friday 20 October 2023	209	226	70	0	55	0
Friday 8 December 2023	0	227	40	0	20	0
Friday 23 February 2024	0	306	100	0	97	12
Wednesday 3 April 2024	200	0	20	0	24	10
Wednesday 5 June 2024	0	115	65	0	20	0
Friday 23 August 2024	0	552	75	0	45	0
Wednesday 16 October 2024	211	408	87	0	45	0
Friday 1 November 2024	0	405	41	0	40	0

The amount of waste oil disposed of has clearly decreased. The peak at the end of 2023 was caused in part by the disposal of hydraulic oil from the steering system and various gearboxes.

The peak in the discharged engine room bilge water was caused by a small but difficult-to-repair cooling water leak. This issue has been resolved and it is now under control.

The quantity of disposed filters (in kilograms) has shown a slight upward trend due to the additional disposal of hydraulic filters. However, the extended replacement intervals for fuel filters have led to less frequent disposal.

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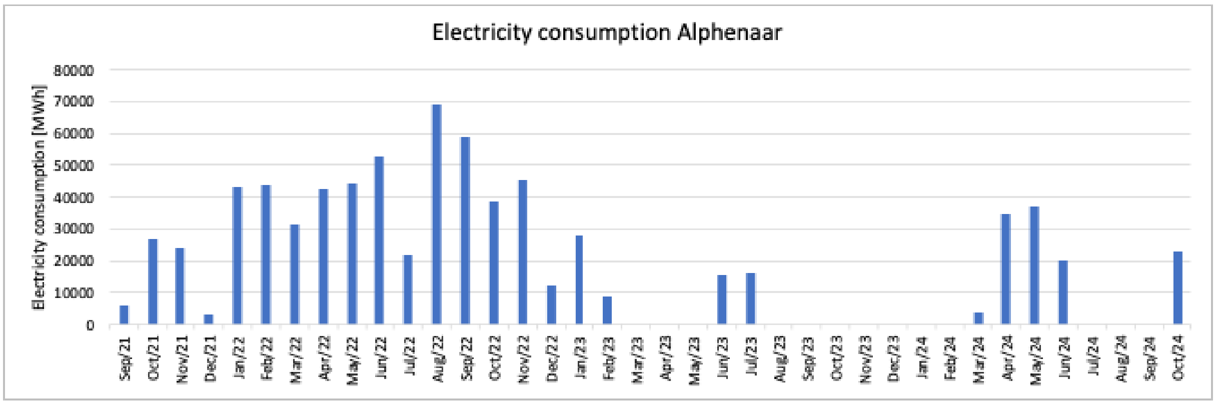
5.5 Deviations in the measurements

As previously mentioned, after resolving some operational issues in 2021, the Alphenaar sailed without major problems from January 2022 to December 2022, as reflected by the energy consumption data shown in Figure 11.



11 | Overview of the energy of the ZESpacks consumed on the Alphenaar per month

From Figure 11, it can be observed that there are several months during which no electric energy was drawn from the ZES packs. This is due to the events described as follows:

<u>Period from February to May 2023:</u> Inverter problems

In February 2023, electric sailing was stopped due to persistent inverter problems. Adjustments were made to the Alphenaar's Power Management System (PMS). The shutdown sequence on board was modified so that the breaker on the ship's side disconnects first, with power being regulated down to zero before disconnection. The Modbus voltage measurement was changed from the ZESpack reading to the BMS (Battery Management System) reading, replacing the separate energy meter. The droop settings of the grid inverter on the Alphenaar were lowered, and those of the generator increased, resulting in smoother regulation and better switching.

This issue was resolved in June 2023. The regulators for the electric motors were also cleaned, as they were heavily clogged with dust due to a small fan positioned above them. After this maintenance, the ship resumed electric again for two months.

<u>Period from August 2023 to March 2024</u>: No ZESpacks available for operation

- **ZESpack 3:** In November 2022, ZESpack 3 was damaged in an accident involving a reach stacker collision. Due to the impact, TNO investigated whether the battery modules inside were damaged. The conclusion of that report was that ZESpack 3 could safely be used in operations. However, it took until March 2024 before ZESpack 3 was operational again. From November 2022 to March 2024, only two battery containers were available.
- **ZESpack 2:** Since June 2023, ZESpack 2 was used to provide grid balancing services on the imbalance market under a contract with Engie. This contract ended in June 2024.
- **ZESpack 1:** In July 2023, ZESpack 1 was removed from the cargo hold at an angle, deforming the entire container structure. The container had to be replaced. Lloyd's conducted an inspection and declared it a total loss. Due to staff changes at ZES and delays between the insurer and CBOX, repairs were postponed. ZESpack 1 is currently expected to be operational again in December 2025.

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Period from July 2024 to September 2024

From April to June 2024, the Alphenaar operated again with one ZESpack on board without major issues. In June 2024, sailing resumed with two ZESpacks, but this soon led to problems. After a blackout, it was decided to temporarily suspend electric operations until all issues were resolved.

An Alphenaar Troubleshooting Workshop was organised, where all major and minor problems and shortcomings of the Alphenaar and ZES systems were identified.

Subsequently, maintenance works were carried out on 14 August, 15 August, 31 September, and 1 October on both the Alphenaar and the ZESpacks, to resolve these issues. On 1 October 2024, a successful test voyage took place with Oechies, Wärtsilä, CCT, and ZES present.

From October 2024, the Alphenaar has been sailing electrically again with ZESpack 2, from December 2024 ZESpack 3 was in operation again. The repair of the ZESpack 1 took longer than expected and will hopefully be operational again at the end of 2025.

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5.6 Adaptations to the system

To simplify the loading and unloading of the ZES packs, cell guides were installed in the middle of compartments 1 and 2. In addition, a reinforced bulkhead was constructed between compartments 2 and 3 to better protect the battery containers from impacts with cargo loaded in the hold. As shown in Figure 12, these bulkheads are often damaged during loading/unloading operation. In addition, this bulkhead was strengthened compared to the previous construction to place the ZESpacks in a watertight compartment. In Table 8 the modifications implemented on the system are presented, indicating the date of implementation.

12 | Damages on the protection bulkhead on the Alphenaar

8 | Modifications implemented on the system

Date	Description
Aug-23	Guide rails installed to help containers slide into the hold.
15-Aug-24	Bulkhead welded behind containers for added protection.
15-Aug-24	MQPC replaced on ship side.

5.7 Points for improvement

Over the past three years, valuable experience has been gained that ZES, and partners, must now build upon to enable the ship to operate 100 % emission-free with its current configuration.

Points for improvement:

- Establish maintenance agreements for both the battery containers and the ship's installation.
- Align the Service Level Agreement (SLA) to clearly define the division of tasks and responsibilities in case of disruptions.
- Create and formalize agreements regarding liability in the event of damage.
- Reinforce the battery structure to make it more robust for handling operations.

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5.8 Energetic efficiency validation

An important measurement is the efficiency of the system using the diesel generator compared to the efficiency of the system sailing on batteries. The route Alphen – Maasvlakte 1 has been sailed 18 times between 1 May 2024 and 30 June 2024. During this period, the route was sailed with 0, 1 and 2 ZESpacks. This allowed for an analysis of the results and a conclusion about the electricity usage of the ZESpacks compared to the diesel consumption of the vessel without batteries.

9 | Comparison of fuel and energy consumption without and with one or two ZESpacks

Alphen - Maasvlakte 1 with 1 ZESPack		
Diesel consumption without battery in the route	870	l
Average diesel consumption reduction achieved through battery operation	401.25	l
Average energy consumption from ZESpack	1456.5	kWh
Electricity consumption from ZESpack relative to diesel reduction	3.63	kWh/l

Alphen - Maasvlakte 1 with 2 ZESPacks		
Diesel consumption without battery in the route	870	l
Average diesel consumption reduction achieved through battery operation	740	l
Average energy consumption from ZESpacks	2500.2	kWh
Electricity consumption from ZESpack relative to diesel reduction	3.38	kWh/l

Given an energy density of 10 kWh per liter of diesel, the electricity required from the batteries corresponds to 35 % of the energy content of diesel used for the same sailing.

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6. | Lessons learned

The following points summarise the lessons learned from the full-scale demonstration of the application of a battery pack on an inland vessel:

- The system can be implemented relatively easily on existing vessels without requiring major modifications to their current arrangement, operation or propulsion system, especially when the vessel already has diesel-electric propulsion;
- The improvement in the connectors and the use of electronic indicators have made the system more robust, reducing physical damages and preventing the ZESpacks from being removed whilst still connected to the vessel or charging station;
- The new Megawatt Charging System (MCS) is a standardised connector with high interoperability which increases network coverage, supports terminal electrification goals, and enhances the feasibility of intermodal transport.
- Cargo owners are often reticent to pay a premium on zero-emission transportation of cargo and are generally unwilling to support shipowners through long-term contracts;
- High costs associated with the repair of the containers and the infrastructure should be minimized to avoid higher energy prices, which could make the ZES system less attractive to the users. A large part of these costs can be avoided if the staff who handle the ZESpacks are trained better to handle them.
- Even though a gradual scaling of the system to meet growing demand is possible, a quick scaling of the ZES system is currently limited by cost and capacity constraints. This could result in lost opportunities or reduced client interest in the ZES system.

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