D3.1 SPEC analyses of full scale and model scale demonstrators

Synergetics | Synergies for Green Transformation of Inland and Coastal Shipping

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Table of Contents

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List of Figures

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| List of Tables

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Release Approval

1 | Release Approval

NAME	ROLE	REMARKS
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Executive Summary

This report describes the operational analyses and the analyses of the Ship Propulsion, Power and Energy Concepts (SPEC) of the vessels used as demonstrators within SYNERGETICS. During the operational analysis, the operation and user needs and requirements were defined, and they were used to define power profiles. Depending on the quality and size of data available for each demonstrator, the operational profile was defined with a higher or lower level of detail. Once the operation, user needs and requirements were defined, a SPEC analysis was conducted for each demonstrator, showing the most suitable concepts and their impact (volume, weight, cost, etc.) on the design.

The purpose of this report is to describe a methodology that allows an objective comparison of the different propulsion, power and energy concepts that could be used to reduce the CO2 and harmful emissions for inland and coastal vessels. From this comparison the most suitable concepts can be selected for a further detailed study of their viability.

The creation of this deliverable coincided with an amendment regarding demonstrator 1, the utilisation of hydrogen in internal combustion engines. As the demonstration cannot take place on board the harbour tug HYDROTUG as originally planned, it had to be replanned for another ship whose operating profile were not yet available. The key aspects of the SPEC analysis will therefore be included in the following deliverable D3.5.

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1. | Introduction

The growing awareness in the society for the climate in the last decennia has resulted in governmental rules and regulations to reduce emissions of greenhouse gases. As a consequence of this, the development of greening technologies has grown very rapidly in relatively short time. Traditionally, the propulsion power and energy (PPE) systems of a ship were designed on a fixed contractual condition, or a design condition that often was not representative of the operation of the vessel, especially for ships with a diverse operational profile such as coasters and inland waterway vessels. As the new energy carriers and technologies have different properties, they can be more or less suitable for certain applications depending on the operational capabilities of the ship and on what the stakeholders' and users' requirements are. Therefore, it is essential to understand and analyse what is required from the ship, before diving into solutions.

The Operational Analysis represents the first stage of the design process. During this phase stakeholders' and users' requirements are collected through interviews and questionnaires, operations of the vessel are analysed and described through the developments of operational profiles and similar documents. In the Operational Analysis the power and energy demand onboard is defined, which will influence the type, size, and configuration of the PPE system. For instance, a battery electric vessel may be suitable for short voyages, but it is less practical for long trips because the required battery capacity becomes excessively large. This leads to an increase in the weight and volume of the PPE systems, making them less efficient for such applications.

As the alternative energy carriers and their associated technologies are new to the waterborne transport sector, it is still rather unclear what could be the consequences on the design of the vessel of one particular energy concept compared to another. For such, a detailed analysis of the operation must be conducted, followed by an analysis of the ship propulsion and energy concepts (SPEC analysis). With the operational analysis the power and energy demand of the vessel are defined for the whole operation of the vessel, which is later used as input for the SPEC analysis. Then, the SPEC analysis gives an indication of what could be the most suitable concepts form a technology, investment, and operational point of view. In addition, from this analysis an indication of the main parameters (weight and volume of PPE systems, equivalent CO2 emissions, etc.) of each concept is given, which allows to compare each concept and quickly evaluate its impact on the design of the ship. In chapter 2, a more detailed description of the method used for the operational and SPEC analyses is given.

In this deliverable both the operational and SPEC analyses carried out for the demonstrators within SYNERGETICS are presented.

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2. | Description of the method for conducting a SPEC analysis

2.1 Operational analysis

To build the operational profile, the operations of the vessel are analysed to understand how the retrofitted design will be operated, and what the requirements in terms of power and energy are. Generally, the operations of a vessel can be broken down into tasks. A task is defined as the combination of a reference vessel in its state (e.g. draught), environmental condition (e.g. sea state, shallow water) and a certain operation (in Dynamic Positioning (DP), anchorage, economic cruising, harbour). For each task the power is divided into propulsion power, auxiliary power and payload power. Propulsion power is the power consumed by the propulsion system. Auxiliary power is the part of the total power that does not belong to the propulsion power. Payload power is the part of the auxiliary power used for the cargo-related (payload-related) operations e.g., deep-well pumps on a tanker, deck cranes on a multipurpose coaster, etc.

A Mission is made by a combination of tasks, and it is a specific goal that the ship and crew are performing (Safe & Rescue, hydrographic survey, transport route A). It is defined based on the stakeholder needs.

In parallel to Missions, a Bunkering Independent Operation (BIO) is defined. This is defined as the accomplishment of one or multiple consecutive missions occurring between two bunkering/re-charging operations (energy intake operations). The described structure is depicted in Figure 2-1.

A Bunkering Independent Operation (BIO) is typically defined by the following:

- Required Autonomy, required range of the BIO [nm, km]
- Minimum required operational endurance between bunkering (energy input) tasks [h]
- Requirements on emissions: both for pollutants and carbon neutrality.

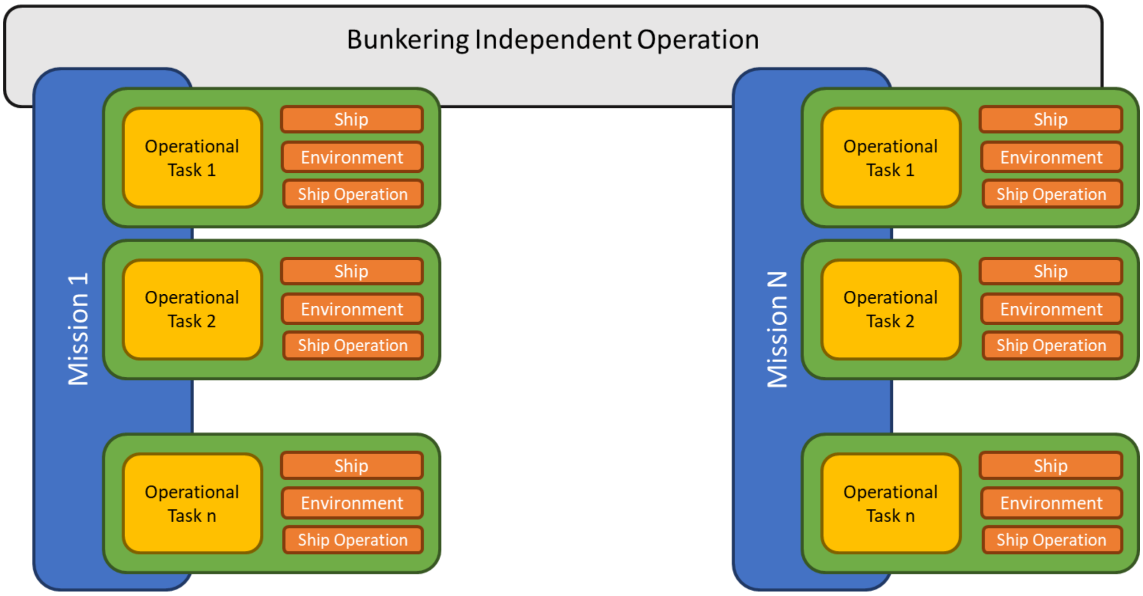

Figure 2-1: Overview of the tasks and missions that compose a Bunkering Independent Operation (BIO).

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A BIO can be described by a Task Power Time Chart (TPTC), which indicates the corresponding required power as a function of time. From the TPTC the maximum power demand and time-weighted average power are derived, which are used as input in SPEC.

It should be mentioned that the TPTCs are defined using the effective power[1] required for propulsion, payload, and auxiliary components. This effective power is defined as the power consumed by these components. Therefore, the efficiency of the system architecture is to be considered, when it comes to define the required power at the source (e.g. genset, battery, fuel cell, etc.). The power losses in the system in the SPEC analysis are taken into account in the chain efficiency. This is a parameter that is different per PPE concept, and it represents the generic energy-to-power efficiency of the ship's PPE systems. It includes the individual PPE system efficiencies (e.g. pre-treatment efficiency, energy converter efficiency, etc.).

2.2 SPEC analysis

The goal of the SPEC analysis is to evaluate what solutions (energy carrier + energy converter) are feasible within a reference vessel based on a set of operational requirements. The SPEC analysis is carried out using a MARIN in-house tool called Ship Power and Energy Concept (SPEC). The tool allows, through a weighted multi criteria analysis, to compare together different solutions and to assess what their impacts are on the design, in terms of weight, volume, efficiency and costs. The SPEC analysis uses as inputs the outputs of the operational analysis, and it is divided in three parts: Preselection, Ranking and Design Cases. (Figure 2-2). For the complete terminology used in the SPEC analysis, see the Glossary (**Fehler! Verweisquelle konnte nicht gefunden werden.**).

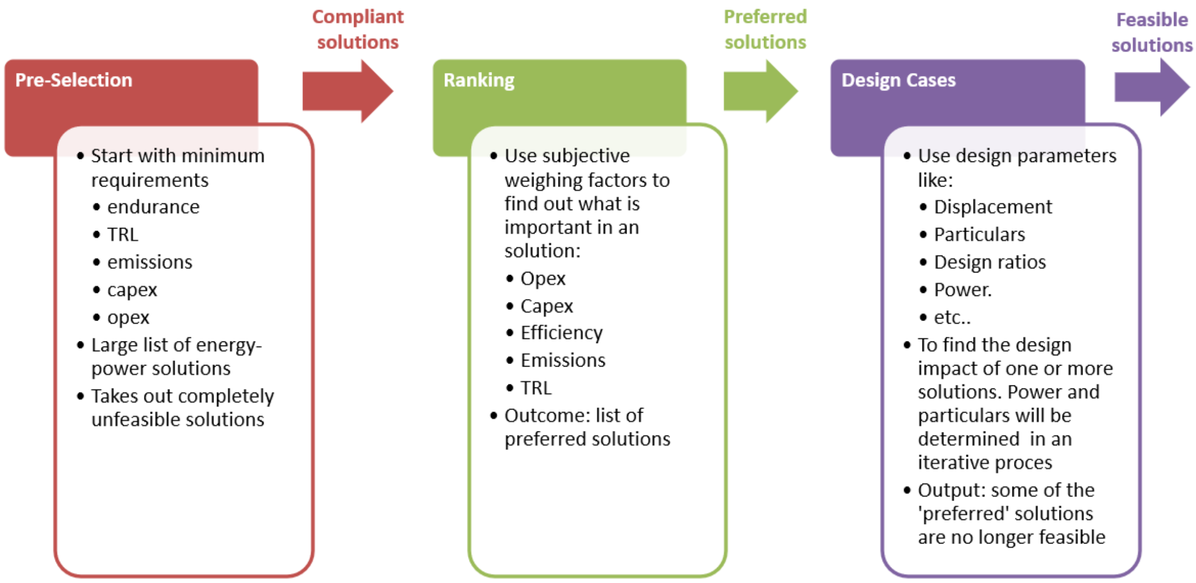

Figure 2-2: SPEC analysis – structure.

[1] Please note this is different from the hydrodynamic effective power defined as the product of the total resistance and the velocity.

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2.3 Preselection and Ranking

The Preselection phase uses requirements on a macro level to filter out solutions that are completely unfeasible. The output of this step results in a large list of energy and power solutions.

In the Ranking phase, stakeholders and users can influence the results of the analysis by weighing the different criteria based on what is more relevant for them. If no input has been given for the criteria, they are equally weighted so that all parameters are equally relevant for the solution. Based on the weights given to the technology, investment and operational parameters, SPEC ranks the concepts from 1 to 9, being these the lowest and highest score, respectively. These rankings provide an overview of what is the least and the most suitable PPE technology concept with regards to the foreseen operations of the vessel or to the type of technology and required investment to implement a solution.

Last, both the operational and technology and investment rankings are weight-averaged depending on how important they are for the client. If no input has been given, they are equally weighted so that both rankings are equally relevant. For the demonstrators within SYNERGETICS, as the PPE systems must be available in the short term to be implemented in the retrofit, only solutions with a Technology Readiness Level (TRL) 7 or above have been selected. Also, to include solutions that are relatively accepted by the society, only concepts with a Society Readiness Level (SRL) 3 or above have been considered. In the following chapters, only the overview of the preselection is presented for clarity. For the complete preselection overview see Annex 2: Complete results of the SPEC analysis.

2.3.1 Results of the SPEC analysis

With the input from the task power-time charts of the BIOs and the requirements for the vessel and the PPE system, the SPEC program sizes the PPE system. The program combines different resources, energy carriers, energy conversion systems, power distribution and drive systems to create a PPE concept defined by a pathway as shown in Figure 2-3. Each resource, energy carrier, conversion system, power distribution and drive system has its own properties per unit volume, unit weight and unit energy, based on MARIN's sustainable power database[2].

The dimensioning of the PPE systems is done by using the properties of the systems involved in a concept, the maximum and average power demand, and other relevant inputs associated with the operation of the vessel and its main particulars.

[2] https://sustainablepower.application.marin.nl/

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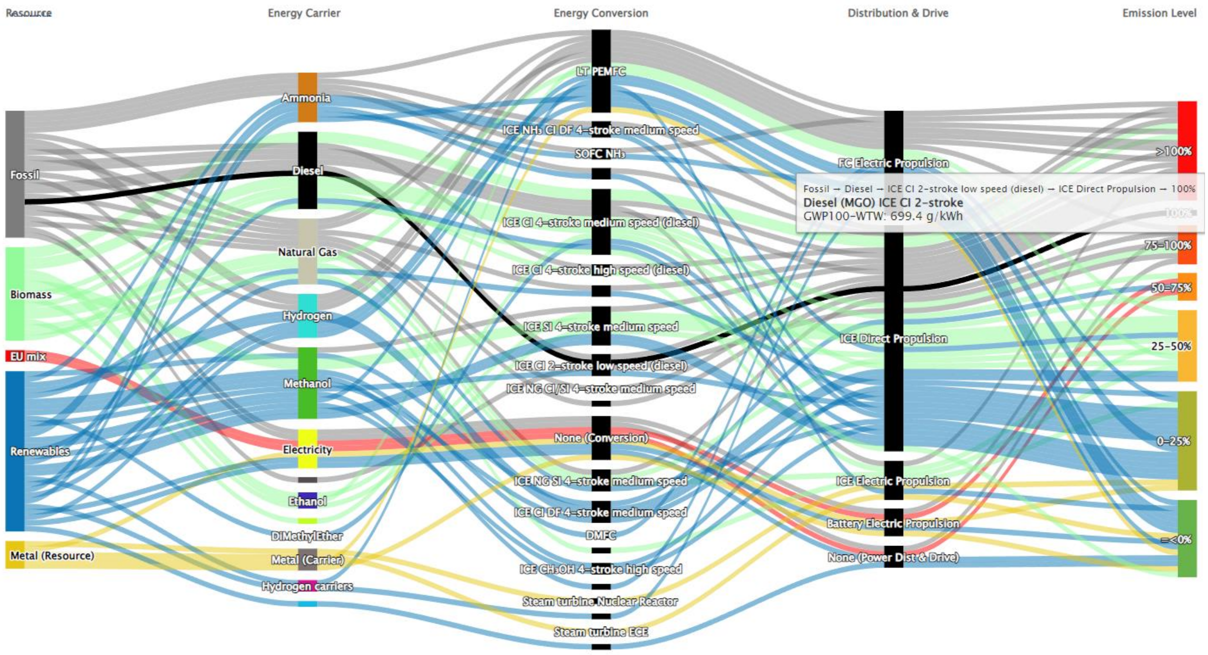

Figure 2-3: Overview of the defined pathways that define a PPE concept in SPEC. Source: https://sustainablepower.application.marin.nl/

To size the power systems, the maximum power demand derived from the BIOs is used, as the power system must be able to provide this maximum power. Similarly, the energy systems are sized based on the total required energy. In addition, other parameters such as the CO2 emissions per trip, are calculated using the time-weighted average power consumed. For such, a power profile table similar to the one showed in Table 4-2 is used as input. This table expresses for each task/operation the power ratio between the total power demanded in each operation and the maximum total power demanded. In addition, the power profile includes the percentage of time an operation is carried out with respect to the total endurance time i.e., the total time span of the BIO. With the data from the power profile, the time-weighted average power is obtained.

Once the SPEC analysis has been concluded, an overview of the required volume, weight, emissions, cost and other parameters are given for each concept. The base concept has been compared with other concepts, corresponding to the most common PPE concepts that are being implemented nowadays for the decarbonisation of the waterborne transport.

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2.3.2 | Pre-selection of technologies

Based on the requirements that were set by the project, a pre-selection of investigated technologies is made for all demo cases. This is firstly done based on requirements that can be set in SPEC:

- The Technical Readiness Level (TRL) of 7 for SYNERGETICS.
- Societal Readiness Level (SRL) of 3

This threshold TRL applies to all components within a SPEC technology (energy storage, pre-treatment, conversion, after-treatment and distribution). The SRL threshold applies to the energy carrier, and a SRL of 3 was adopted as a minimum, to avoid the selection of technologies that will have significant risks in terms of their potentially negative impact. A SRL scale is provided in Table 2-1. The excluded energy carriers due to a low SRL are:

- Ammonia
- Uranium
- Biodiesel produced from soybean or palm oil

It must be noted that Ammonia and Uranium are also filtered out due to a low technical readiness level.

Table 2-1 Societal readiness level scale used in SPEC

SRL	Description
9	Fully accepted by society
8	Widely accepted but has minor issues
7	Accepted but has significant shortcomings
6	Normally accepted with awareness of some negative impact
5	Accepted because production, storage, and/or handling are well arranged
4	Accepted provided that production, storage, and/or handling are well arranged
3	Only accepted when the negative impact is fully mitigated
2	Only accepted in limited specialist applications
1	Not accepted by society, leads to resistance

The resulting compliant technologies are given in Annex 2:|Complete results of the SPEC analysis.. This annex lists 25 different technologies (with specific fuel production pathways). These 25 technologies include both fuels produced from fossil, renewables and bio-feedstock. As the goal is to reduce emissions, a greenhouse gas emission threshold was added. All technologies that emit 25% or less, compared to the Diesel (EN-590) ICE Direct technology are included. This is based on a CO_{2eq} calculation for a Global Warming Potential of 100 years on the well-to-wake basis. With this included, the following technologies remained from the-preselection:

1. Diesel (HVO from UCO, POME) ICE CI 4-stroke high speed (diesel)
2. e-CH3OH 95%vol + Diesel 5%vol ICE CH3OH 4-stroke high speed
3. e-CH3OH (renewable electricity + flue gas CO2) ICE CH3OH 4-stroke high speed
4. e-LNG (renewables + flue gas CO2) ICE NG SI 4-stroke high speed
5. Electricity (renewable) stored in Li-NMC battery
6. e-CH3OH (Renewable electricity + DAC CO2) ICE CH3OH 4-stroke high speed
7. e-CompH2 300 bar in ISO container (Renewable) LT PEMFC
8. e-CompH2 300 bar integrated tanks (Renewable) LT PEMFC

As the above list contains three methanol technologies and two hydrogen storage systems, a limited selection will be applied in the different Demo cases.

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3. | Operational and SPEC analyses of Demo 1 (HYDROTUG)

When the SYNERGETICS project started, the harbour tug HYDROTUG owned by CMB.TECH was assigned as Demo 1 to demonstrate the application of dual-fuel hydrogen-diesel technology in internal combustion engines. However, the vessel is no longer available for the retrofit within SYNERGETICS and the creation of this deliverable coincided with an amendment regarding the demonstration of the utilisation of hydrogen in internal combustion engines. When the details on the new demo vessel including its operational profile are known, the key aspects of the SPEC analysis will therefore be included in the following deliverable D3.5.

4. | Operational and SPEC analyses of Demo 2 (Stolt IJssel)

4.1 Introduction of Demo 2

The Demo 2 reference vessel is the Stolt IJssel, owned by Mercurius Shipping Group and operated by Stolt-Nielsen Limited. The Stolt IJssel is a type C inland chemical tanker, which transports chemical cargo in liquid form between Amsterdam, Rotterdam, and Antwerp (ARA), and other smaller ports nearby.

Beside sailing in the ARA area, the vessel also operates along the Rhine, sailing up to Ludwigshafen near Mannheim in Germany. The main bunkering location is in Dordrecht.

Figure 4-1: Photo of the vessel Stolt IJssel.

The ship is equipped with a double hull. The cargo area is divided into fourteen holds with a total capacity of about 5000 m^3. Each cargo hold is equipped with heating coils to heat the cargo, and a deep well pump for unloading.

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The vessel has a diesel-electric propulsion system, with the engine room located at the foreship, and propulsion is provided by means of three ducted thruster units. The stakeholders intend lowering the carbon footprint of the vessel by exploring different solutions that would use methanol as energy carrier, alone or combined with diesel.

4.2 Sailing route

The vessel mainly operates between the cities of Antwerp, Rotterdam, and Amsterdam (ARA). This can be seen in the geospatial distribution presented in Figure 4-2. This representation was made using AIS data from the ship.

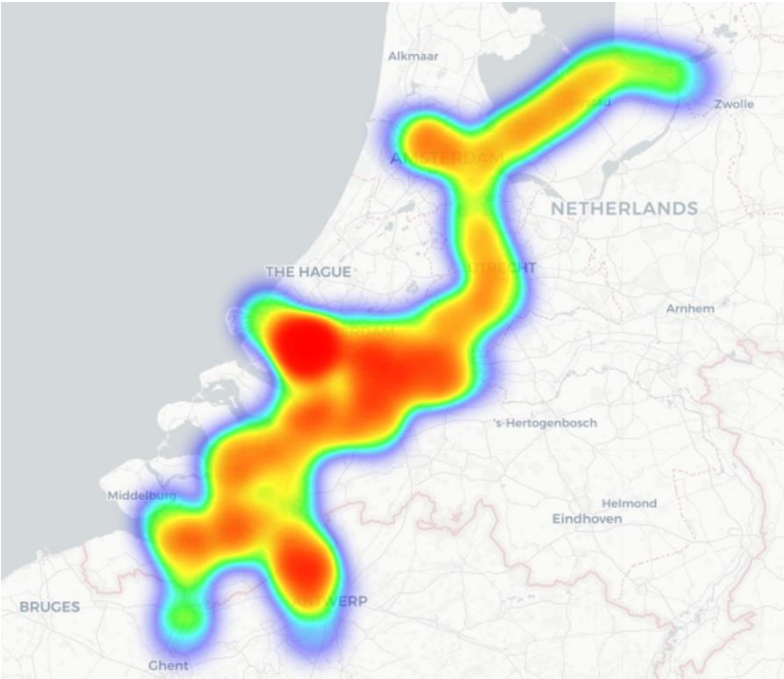

Figure 4-2: Geospatial operational distribution of the Stolt Ijssel.

Further analysis has been conducted to find out the most energy demanding operation of the vessel. This resulted to be the mission of sailing up the Rhine to Ludwigshafen and back.

This operation starts at the bunkering location in Dordrecht, continues with the first trip to Antwerp followed by a second trip up to Ludwigshafen, near Mannheim in Germany. Then, the vessel sails back on the same route without bunkering in Ludwigshafen. The total mission extends over 1468 km. An overview of the route is presented in Figure 4-3.

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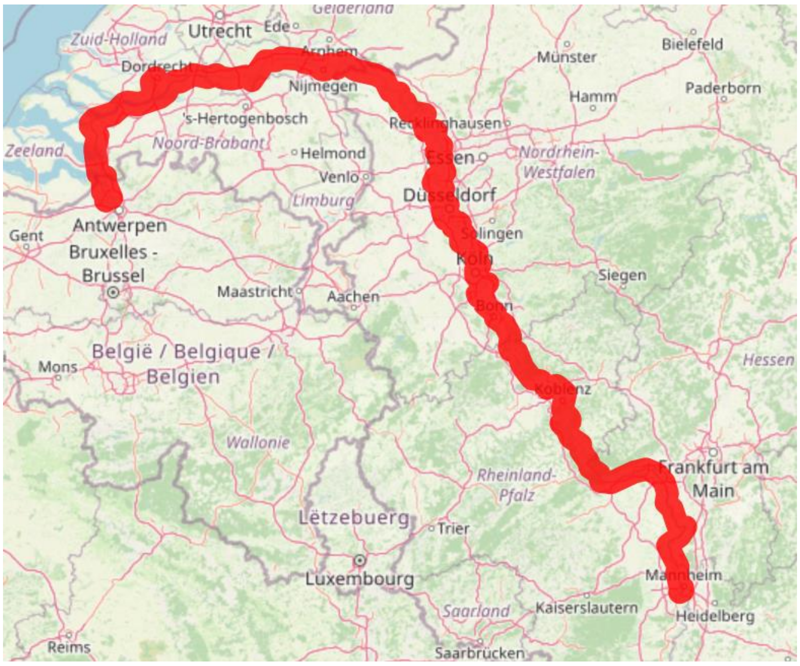

Figure 4-3: Route of the Stolt Ijssel.

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4.3 Operational Analysis

The Operational Analysis was carried out using measured operational data of the reference ship provided by Shipping Technology, thanks to the concession of Stolt-Nielsen.

The data covered the operations of the vessel from the 27th of March 2023 to the 11th of March 2024, with a sample rate of one minute. The registered parameters were the GPS datetime and location, the GPS speed, the power of the bow thruster, the propulsion power, the generated power and the hotel & auxiliary power. Other parameters were derived from the registered data, such as the energy consumption. After a statistical analysis and filtering of the data, the latter has been used to obtain representative values to describe the most critical Bunker Independent Operation. Table 4-1 summarises the main findings.

Table 4-1 Stolt IJssel data overview.

Parameter	Value	Unit
Sailing distance (one way)	734	km
Total sailing distance	1468	km
Design speed (in calm water)	18	km/h
Average speed sailing upstream	11	km/h
Average speed sailing downstream	24	km/h
Upstream endurance	60-64	h
Downstream endurance	24-30	h
Total endurance (including stops)	4	days
Maximum generated power by the gensets	1840	kW
Maximum propulsion power	1530	kW
Maximum power at bow thruster	410	kW
Installed auxiliary power	400	kW

Based on the analysed data, the following operational profile was developed. The 'Power Percentage' refers to a percentage of the maximum installed power, in this case called 'Max generated power'.

Table 4-2 Demo 2, operational profile.

Task	Power Percentage [% of max. power]	Time Percentage [% of BIO time]
Sailing upstream	70	30
Sailing downstream	50	30
Sailing (no current)	60	30
Waiting	10	10

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4.4 SPEC analysis of Demo 2

4.4.1 Preselection and ranking

The results from the operational analysis and the stakeholders’ requirements have been used as inputs for the next step of the analysis. An overview of the inputs used in the preselection can be seen in Table 4-3. The selection of the most suitable/feasible technology is performed using the Ship Power and Energy Concept (SPEC) tool, which, through a weighted multi criteria analysis, allows to assess what solutions (energy carrier + energy converter) are feasible within the reference ship and its operations, and what are their impacts on the design, in terms of weight, volume, efficiency and costs. The stake-holders and users can influence the results of the analysis by weighing the different criteria based on what is more relevant for them.

In the Annex A2.2, the full output of the ranking of this demonstrator is presented.

Table 4-3: Preselection input Demo 2.

Parameter	**Value**	
Max Effective Power *[kW]*	1840	
Endurance *[d]*	4	
Estimated downtime *[%]*	10	
Expected lifespan *[yr]*	25	
Average power delivered *[kW]*	814	
Minimum TRL	7	
CO_2 price/ton emission *[EUR/t]*	73	
Zero emission only?	Yes	No X
Minimum SRL	3	

For this demonstrator, no preference was given by the stakeholders, therefore the criteria have been weighted equally, as it can be seen in Table 4-4 and Table 4-5.

Table 4-4: Demo 2, "Technology & Investment" criteria. Weight factors.

Ranking – Technology & Investment	
Criteria	Weight [%]
Contained energy density volume	8.3
Contained energy density weight	8.3
CapEx energy carrier	8.3
TRL energy carrier	8.3
SRL energy carrier	8.3
Specific volume on board power systems	8.3
Specific weight on board power systems	8.3
CapEx on board power systems	8.3
Chain efficiency systems	8.3
TRL on board power systems	8.3
Harmful exhaust emission	8.3
Green House Gas emission	8.3

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Table 4-5: Demo 2, "Operations" criteria. Weight factors.

Ranking – Operations	
Criteria	Weight [%]
Contained energy density volume	16.7
Contained energy density weight	16.7
OpEx energy carrier	16.7
Chain efficiency systems	16.7
Harmful exhaust emission	16.7
Green House Gas emission	16.7

For this demonstrator, the diesel-electric case has been used as a benchmark to compare the other solutions. In Table 4-6 an overview of the total ranking can be seen. It should be noted that as the base concept of this demonstrator was a vessel with diesel-electric architecture, the concepts included in the ranking as well as in the SPEC results are for ships with electric propulsion. For instance, the solution #16 is the benchmark case, and it refers to a diesel-electric solution.

Table 4-6: Ranking overview of Demo 2.

Concept	**Ranking**		
	Overall	**Technology & Investment**	**Operations**
#16 = Diesel (EN590) CI ICE (hi-speed)	8.2	8.1	8.5
#4 = Diesel (POME, UCO) CI ICE	9	9	9
#8 = e-CH3OH (CO2 PTS)/Dsl 65/35%vol CI ICE	6.1	5.7	6.6
#9 = e-CH3OH (CO2 PTS)/Dsl 95/5%vol CI ICE	5.8	6	5.5
#19 = e-LNG (CO2 PTS) SI ICE	6.8	6.8	6.7
#21 = Battery-electric (renewable)	7.7	8.8	6.5
#36 = e-H2 300b ISO LT PEMFC	3.3	2.2	4.3

4.4.2 Overview of the SPEC results

The results of the SPEC analysis are presented in Annex A2.2. In Figure 4-4, Figure 4-5 and Figure 4-6 a comparison in weight, volume and CO_2 emissions of some concepts is shown. It should be noted that in the solution with batteries, the term "fuel" used in SPEC refers to the weight and volume of batteries, as for a battery electric PPE system these are the energy carriers instead of fuel.

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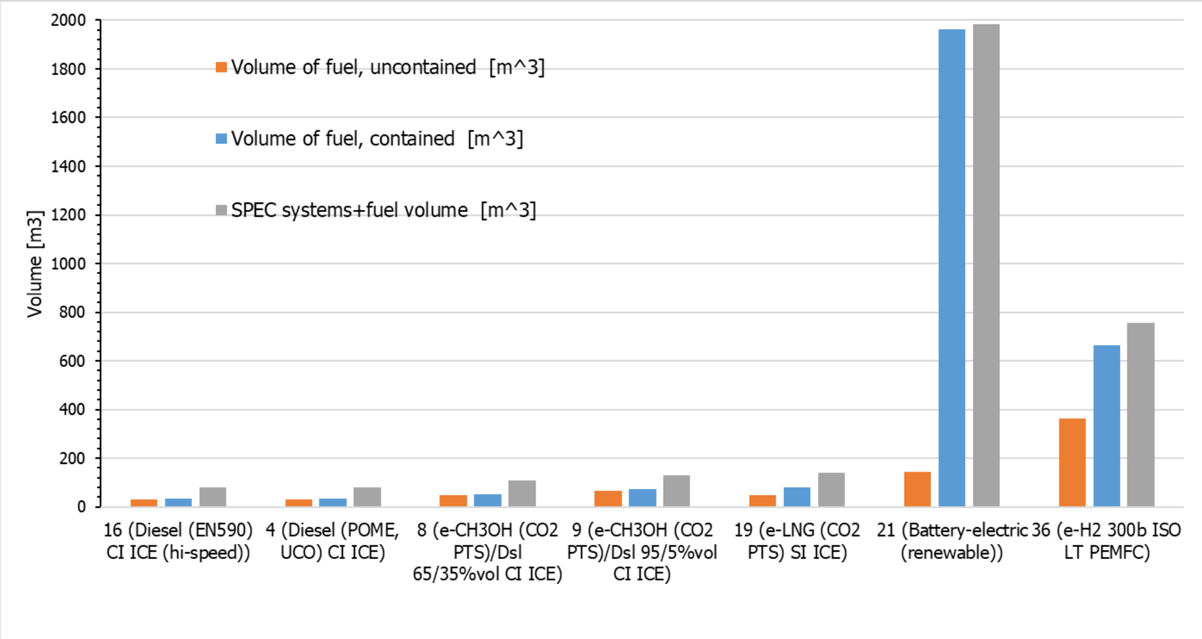

Figure 4-4 Overview of the fuel and systems volume for each concept resulting from the SPEC analysis of Demo 2.

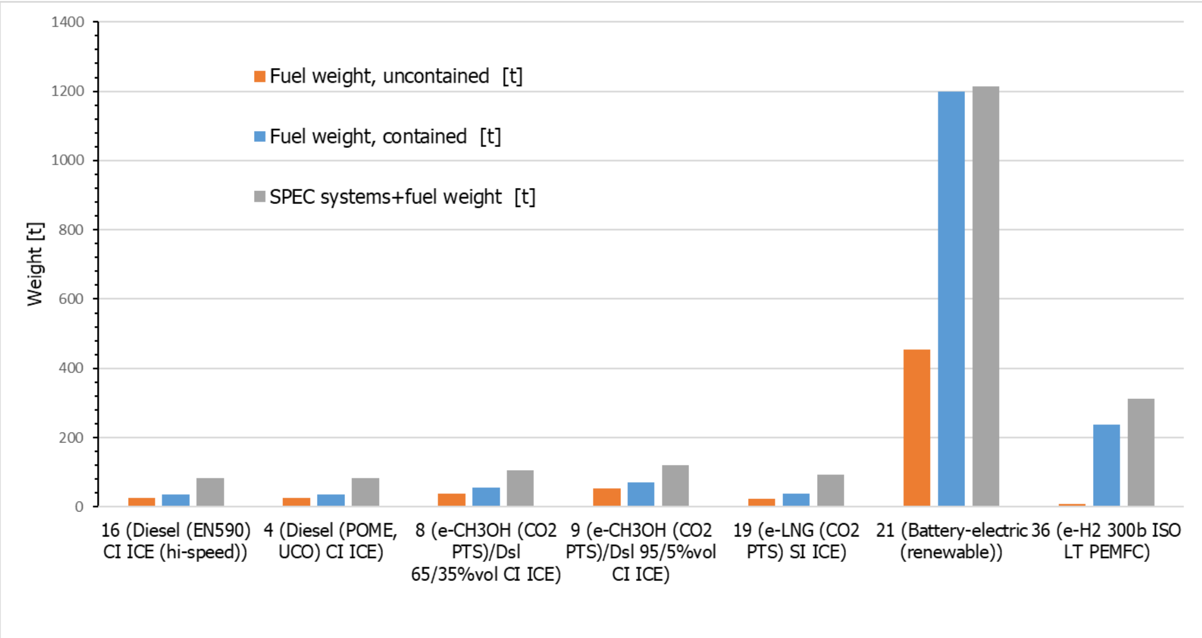

Figure 4-5: Overview of the fuel and systems weight for each concept resulting from the SPEC analysis of Demo 2.

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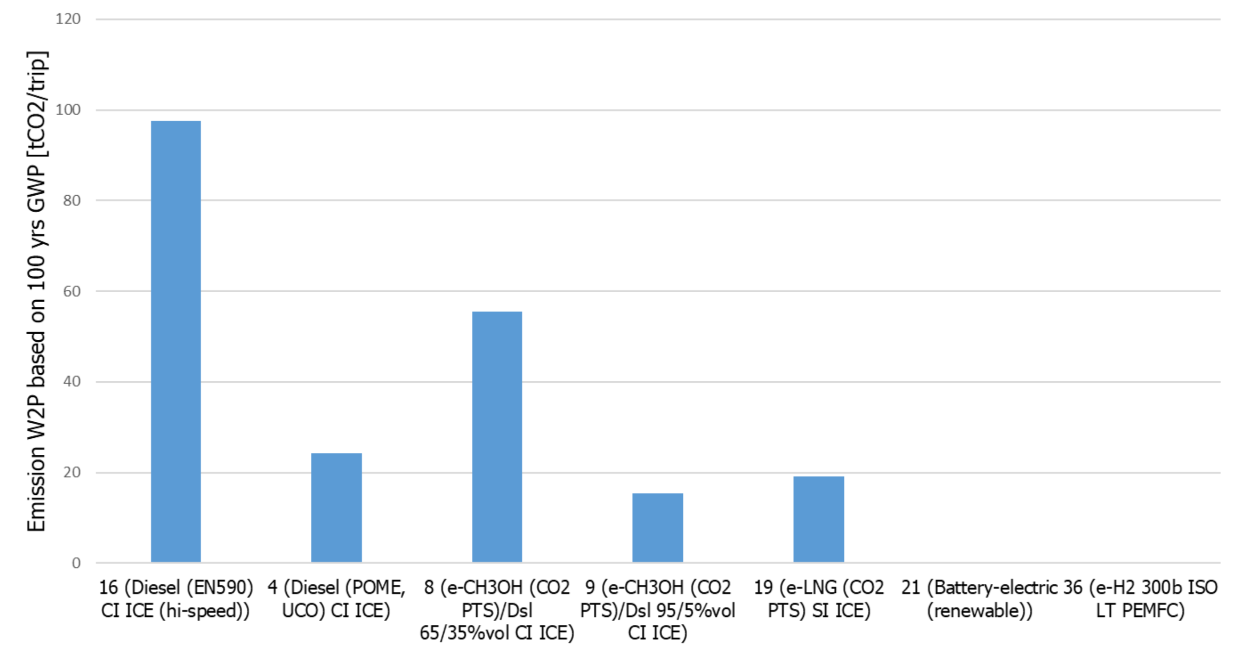

Figure 4-6: Overview of the CO2 equivalent emissions (well to propulsion) per trip for each concept resulting from the SPEC analysis of Demo 2.

In Figure 4-6 only the CO2 emissions from the production, transportation, and use of the fuel are considered, while those from the creation of the supporting infrastructure, such as the construction of wind or solar farms and engine manufacturing, are excluded.

4.4.3 Conclusions of the SPEC analysis

For the Stolt IJssel, operating as described in the operational analysis, the following conclusions summarise the findings of the SPEC analysis:

- The battery-electric and compressed hydrogen concepts (#21 and #36) have the best performance in terms of emissions. The electricity used to charge the batteries and to produce hydrogen is derived from a renewable source. However, these concepts require a very large volume and weight on board, making them less attractive for the Stolt IJssel. It has to be noted that for the battery concept, the term "uncontained" refers to the volumetric and gravimetric energy densities of the battery cells only, while the term "contained" refers to the volumetric and gravimetric energy densities of the whole battery system, including, for example, the support structure and the support systems of the battery such as cooling and ventilation.

- The methanol concepts offer a different range of emission reduction depending on the methanol share in the fuel blend. Concept #8 is considered to be the most conservative DF methanol concept in terms of volume share in the fuel blend for the future methanol Dual Fuel Internal Combustion Engines, while concept #9 refers to the most optimistic one. The reduction in CO2 equivalent emissions is dependent on the methanol share in the blend, and it is due to the fact that methanol is produced by carbon capture at a point source (CO2 PTS) and therefore it has a negative CO2 Well to Tank emissions value.

- The bio-Diesel concept (#4) offers a substantial reduction in emissions. This is due to the negative CO2 Well to Tank emissions value, and it is very dependent on the pathway from source to production and transportation of the fuel.

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- Concepts #16 and #4 have similar costs in terms of volume and weight, as they refer to the same technology and similar fuel types.
- The methanol concepts (#8 and #9) require a relatively small increase in volume and weight. This is mostly due to the lower energy density (volumetric and gravimetric) of methanol compared to Diesel.

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5. | Operational and SPEC analyses of Demo 3 (Alphenaar)

5.1 Introduction of Demo 3

The Alphenaar is an inland container vessel dedicated to transport beer between the Dutch towns Alphen aan den Rijn and Moerdijk. The vessel is operated by the beer producer Heineken, which loads the beer from its brewery in the town of Zouterwoude and then transports it by lorry to a nearby town, Alphen aan den Rijn. Here, at the Alpherium terminal, the containers are loaded on the Alphenaar.

From Alphen aan den Rijn, the Alphenaar sails South to Moerdijk, where the beer containers are unloaded. At Moerdijk the beer containers are loaded onto container feeder ships which carry the cargo to the deep-sea terminals of the port of Rotterdam. From here they are further loaded onto large container vessels, that carry the beer overseas, mainly to the US.

Figure 5-1: Photo of vessel Alphenaar.

The ship has a diesel-electric propulsion system with an aft and a forward engine room, where the main gensets are located in the latter. Despite having diesel-electric propulsion, for most of its normal operation the Alphenaar uses battery packs, making it possible for the ship to sail in zero-emission mode. The battery packs are part of a system developed by Zero Emission Services (ZES) which works as follows:

1) Battery packs are installed in a 6-foot containerised module that is charged in the harbour at Alphen aan den Rijn. The module is owned by ZES, and leased to the operator who pays for the use of the energy.
2) The battery modules are loaded on board and subsequently connected to the ship's grid. At the moment, two containers are loaded at the harbour, used for the round trip to and from Moerdijk. When the vessel returns to Alphen aan den Rijn, the battery containers are placed on their

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charging location at the Alpherium terminal, where they are charged as the vessel is unloaded or waiting.

3) When the vessel is loaded anew, the battery modules are placed again on board, and steps 1 and 2 are repeated.

In addition, the containers are used as energy storage, which allows to return power to the grid. At the moment only two containers and a charging location is available at Alphen aan den Rijn, but ZES aims to add new charging stations at other ports and increase the number of battery containers in the future.

5.2 Sailing route

The Alphenaar sails most of its time a fixed route between Alphen aan den Rijn and Moerdijk, located from each other at a sailing distance of 63 km. Thus, the total distance sailed in a round trip is 126 km. In Figure 5-2 the route of the Alphenaar can be seen on a map. Consequently, only the following route has been used for the operational analysis of this vessel:

1. **Alphen aan de Rijn → Moerdijk** (typical route). Ship departs fully loaded from Alphen aan de Rijn and then discharges the full containers at Moerdijk. At Moerdijk the ship is loaded with other containers, and then sails back to Alphen aan de Rijn. Once the ship arrives at Alphen an de Rijn, the containers are unloaded, and the ship is loaded again with new containers.

Figure 5-2: Route of the Alphenaar shown on a map.

5.3 Operational analysis

The operational analysis of the Alphenaar was carried out using data received from ZES. ZES provided data recordings of their battery packs similar to the one shown in Figure 5-4. These recordings represent the state of charge of a battery pack and the vessel speed for every 5-minute time step within a day. The data belongs to only one of the ZES battery units, while typically two ZES battery pack container units are stowed on board.

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Since occasionally the vessel does not sail using power from the battery packs, the power derived from the consumed battery energy is not a full representation of the power demand during the operation. For instance, in Figure 5-5 it can be seen that at after 10:00 no power is consumed. This is because the power is derived from the consumed energy of the batteries and, as at 10:00 the battery pack was empty, the derived power is zero. Still, from the ship speed data it can be seen the ship is sailing at 10:00, therefore probably the other battery pack was put in use, or perhaps the diesel generators. Nevertheless, the ship speed from the data recordings gives a good indication of the operation of the vessel, and of the power consumption to be expected at certain conditions. From all data recordings a similar trend in ship speed is observed in all days, indicating that the vessel mostly follows this pattern:

- Ship departs at 5:30 from Alphen aan de Rijn and sails south at low speed (≈4 kn) for 2 hours.
- Around 7:30 the speed is increased up to 6 kn, and it sails at this speed for about 2.5 hours.
- At around 10:30 the speed is further increased, and the Alphenaar sails at about 8-9 kn until it approaches Moerdijk. At around 11:15 the vessel reduces speed and manoeuvres when approaching the port and calls at Moerdijk container terminal at 11:30.
- Containers are loaded and unloaded from the ship for about 3 hours, and then the ship departs Moerdijk at 14:30.
- The Alphenaar sails at high speed (8-9 kn) until 16:30; then the speed is reduced to 6-7 kn.
- The ship continues at medium speed until around 17:30, and sails at low speed (3 kn) until 18:30. Sometimes the vessel even stops within this period, probably due to dinner time.
- After 18:30 the vessel increases speed and continues sailing north at medium speed until 19:30, where it approaches Alphen aan de Rijn. Then the ship reduces speed and manoeuvres, arriving at the Alpherium terminal at 20:00. There the containers are loaded and unloaded while the battery packs are charged.

Based on the sequence of operations described above, the time distribution presented in Figure 5-3 was identified for the Alphenaar. It should be noted that the time spent for loading and unloading in Alphen aan de Rijn is not included in the time distribution as for such operations the shore power connection is used and therefore will not be part of the bunkering independent operation. Once the data recordings were analysed, the average values presented in Table 5-1 were obtained.

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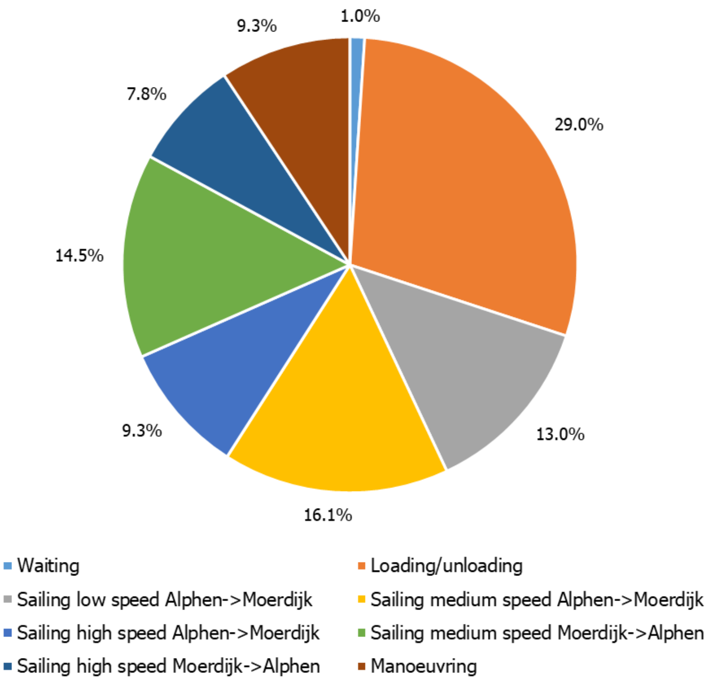

Figure 5-3: Time distribution of the operational profile of the Alphenaar.

Table 5-1: Summary of the derived values from the data recording of the Alphenaar.

	Unit	**Date**				**Average**
		5-Jan-24	15-Apr-24	28-Jun-24	25-Apr-24	
Recorded time	h	24.0	24.0	23.8	23.9	23.9
Total energy consumed	kWh	3289	3335	3138	3099	3215
Total time sailing	h	7.8	6.6	9.3	7.6	7.8
Total distance sailed	km	104	85	117	102	102
Average sailing speed	kn	7.2	7.0	6.8	7.3	7.1
Average total power[3] consumed	kW	241	371	325	214	284
Max. power consumed	kW	546	693	573	639	613

[3] i.e., the sum of propulsion and auxiliary power.

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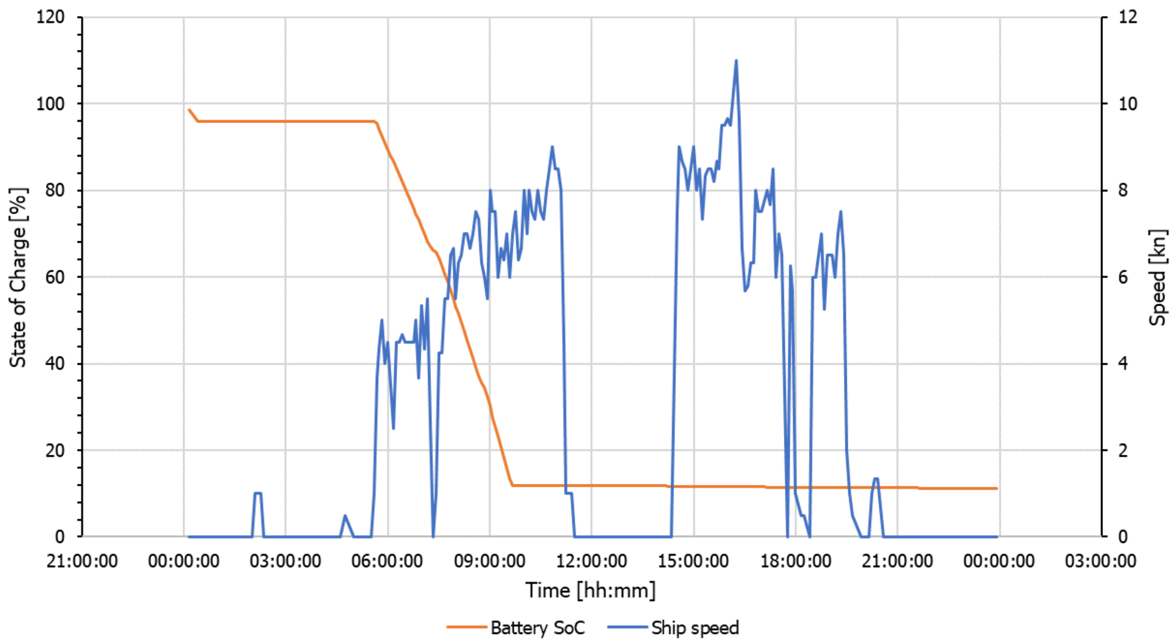

Figure 5-4: Example of the data recordings of one of the ZES battery packs used by the Alphenaar.

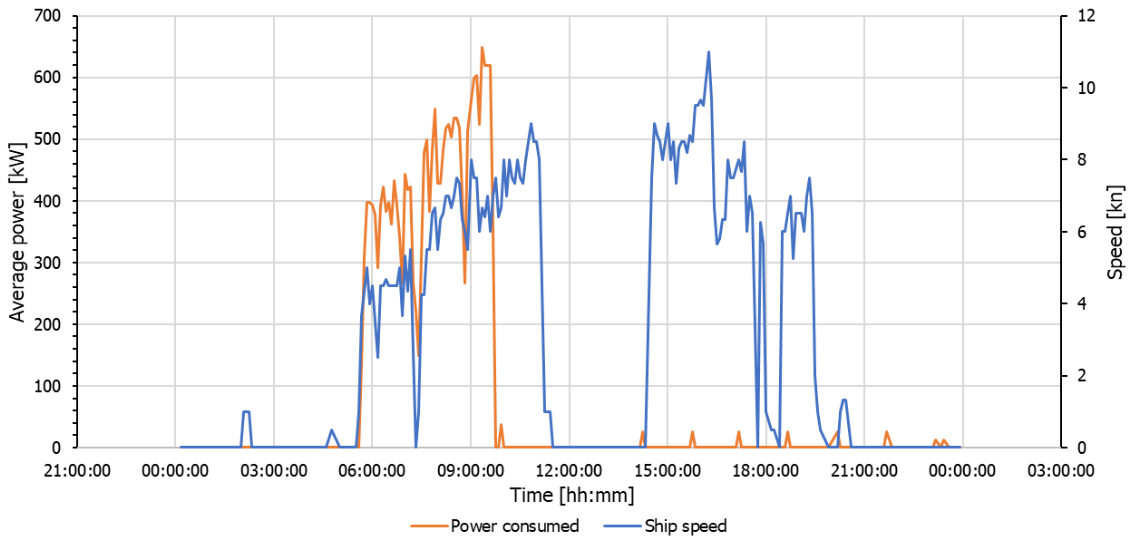

Figure 5-5: Example of a power distribution derived from a data recording of the Alphenaar.

5.3.1 Definition of Bunkering Independent Operations

Since the Alphenaar sails a fixed route and the battery charging station is located in Alphen aan de Rijn, only the following bunkering independent operation (BIO) was defined for this vessel:

1) **BIO I:**

   Alphen aan de Rijn → Moerdijk → Alphen aan de Rijn

Based on the patterns observed in the data recordings, combined with input about the operation provided by ZES, the following tasks/operations were identified:

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1. **Waiting:** Ship is waiting in harbour, but not connected to the shore power supply. Main consumers are auxiliary systems which are part of the hotel load.
2. **Loading/unloading:** Containers are being loaded/unloaded on the ship. This operation is carried out by the terminal cranes, so no power from the vessel is used for the loading/unloading of containers. Therefore, only the auxiliary power to cover the hotel load needs to be supplied during this operation.
3. **Sailing low speed Alphen -> Moerdijk:** Ship sails between Alphen aan de Rijn and Moerdijk fully loaded (2.8 m draught) at a speed of 4 knots. In addition to the propulsive power, the auxiliary load in sailing condition needs to be supplied.
4. **Sailing medium speed Alphen -> Moerdijk:** Ship sails between Alphen aan de Rijn and Moerdijk fully loaded (2.8 m draught) at a speed of 6 knots. In addition to the propulsive power, the auxiliary load in sailing condition needs to be supplied.
5. **Sailing high speed Alphen -> Moerdijk:** Ship sails between Alphen aan de Rijn and Moerdijk fully loaded (2.8 m draught), at a speed of about 9 knots. In addition to the propulsive power, the auxiliary load in sailing condition needs to be supplied.
6. **Sailing medium speed Moerdijk -> Alphen:** Ship sails between Moerdijk and Alphen aan de Rijn half loaded (1.3 m draught) at a speed of 6 knots. In addition to the propulsive power, the auxiliary load in sailing condition needs to be supplied.
7. **Sailing high speed Moerdijk -> Alphen:** Ship sails between Moerdijk and Alphen aan de Rijn half loaded (1.3 m draught) at a speed of approximately 9 knots. In addition to the propulsive power, the auxiliary load in sailing condition needs to be supplied.
8. **Manoeuvring:** Ship is manoeuvring and/or sailing at low speed (3 kn or less).

To estimate the required propulsion power for each task, a speed-power prediction was carried out using MARIN's power prediction program DESP. The main particulars and hydrostatics of the vessel were used as input, and propulsive factors of similar vessels were used to arrive at the required shaft power. As a result, the propulsion power values presented in Table 5-2 were obtained.

The auxiliary power used during loading/unloading was derived from the energy consumed from the energy pack at Moerdijk. In all data recordings no energy was consumed from the batteries at harbour in Alphen aan de Rijn, suggesting that there the vessel is always connected to the shore power connection. In some of the data recordings, such as the one shown in Figure 5-6, it can be seen the battery pack was used during loading/unloading. From the energy consumption at Moerdijk the power consumption during loading/unloading was derived, resulting in a chart similar to the one shown in Figure 5-5. From this figure it can be seen that the power consumed during this operation was about 25 kW.

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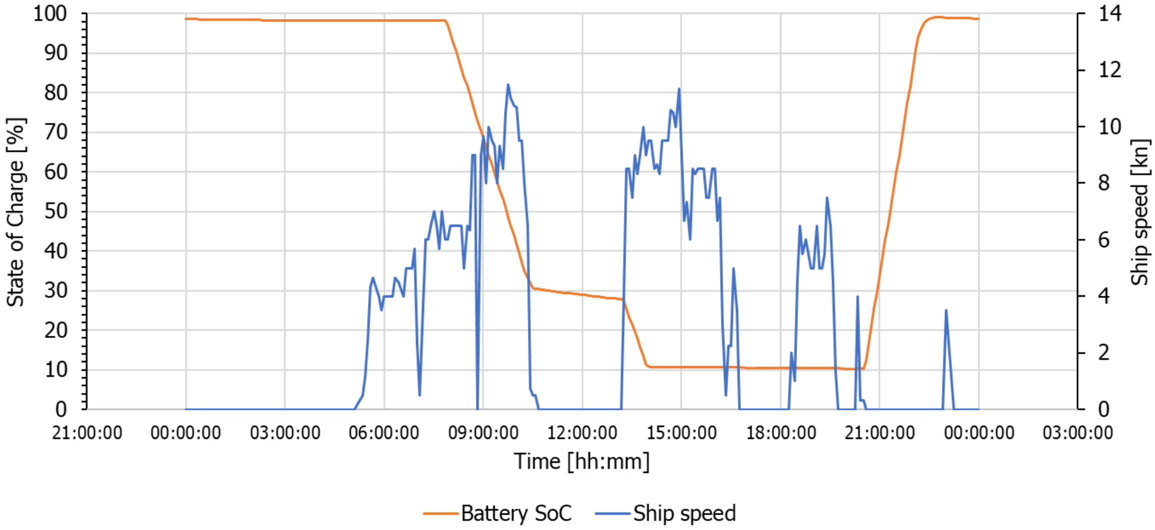

Figure 5-6: Example of a data recording of the Alphenaar where energy is consumed while loading/unloading at Moerdijk (between 10:30-13:00)

In addition, the auxiliary power consumed during sailing was obtained from the electric load balance provided by ZES.

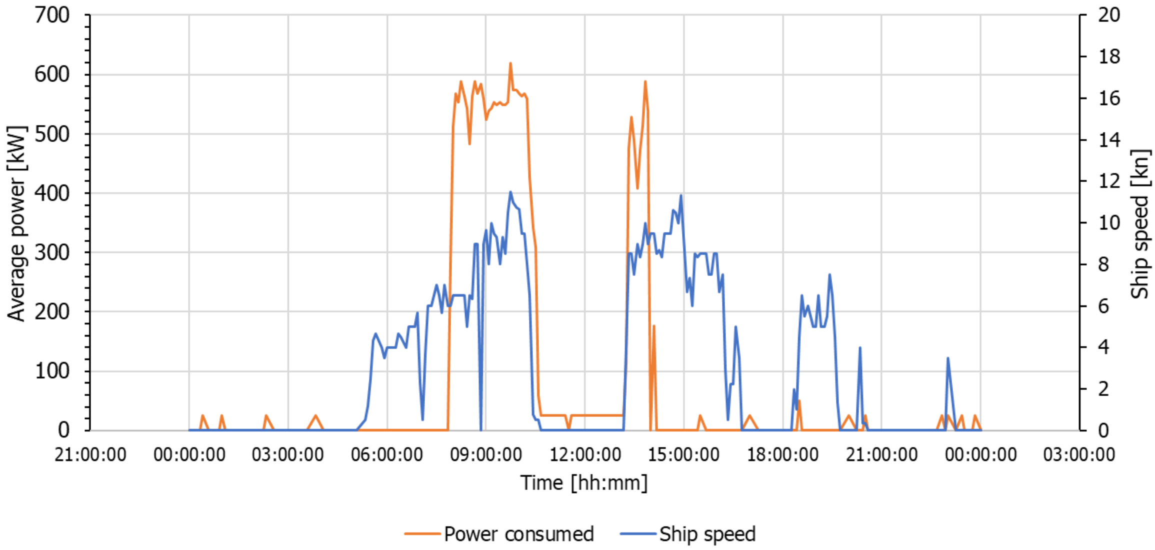

Figure 5-7: Example of power derived from a data recording of the Alphenaar where power is consumed while loading/unloading at Moerdijk (between 10:30-13:00)

Once the tasks and their corresponding power demand were defined, BIO I was constructed. This was done by setting a sequence of tasks that represent the pattern observed in the data recording. Then, these tasks were assigned with the power demand values from Table 5-2, resulting in the power-time chart (PTC) from Figure 5-8.

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Table 5-2: Overview of the speed and required power for each of the tasks carried out by the Alphenaar.

Task/operation	SOG [kn]	SOG [km/h]	Propulsion power (shaft power) [kW]	Auxiliary power [kW]	Total power [kW]
Waiting	0.0	0.0	0	15	15
Loading/unloading	0.0	0.0	0	22	22
Sailing low speed Alphen->Moerdijk	4.0	7.4	53	89	142
Sailing medium speed Alphen->Moerdijk	6.0	11.1	168	89	257
Sailing high speed Alphen->Moerdijk	9.0	15.7	626	89	715
Sailing medium speed Moerdijk->Alphen	6.0	11.1	127	89	216
Sailing high speed Moerdijk->Alphen	9	15.7	436	89	525
Manoeuvring	3.0	5.6	100	89	189

In Table 5-3 a comparison between the average values from the data recordings and those from the power-time chart of BIO I are presented. It can be seen that some parameters, such as the energy consumed and the average sailing speed, match very well. On the other hand, a significant difference in sailed distance is observed. The reason for this difference can be due to the method used to determine the distance sailed from the data recordings. For instance, by looking at the values from Table 5-1, on one day the sailed distance was 85 km an another day it was 120 km, closest to the actual distance of 124 km, whereas the energy consumption for both days is almost identical. In addition, the distance of 126 km sailed in BIO I is very close to the actual round trip between Alphen aan de Rijn and Moerdijk (124 km), therefore is it considered the sequence of tasks defined for BIO I represent properly the operation of the Alphenaar.

Also, in Table 5-3 a difference in maximum and average power consumed is observed between BIO I and the average from the data recordings. It should be noted that the maximum power is very sensitive to the way the vessel is operated on a particular day. For instance, if the captain starts sailing at low speed and then increases the speed significantly to reach port in time, the maximum power will be higher than for another day where the ship sails at a more even speed during the whole route. This can also be observed in Table 5-1, where the maximum power ranges between 620 and 785 kW.

Table 5-3: Comparison between the average values from data recordings and the task power-time chart (TPTC) of BIO I of the Alphenaar.

	Unit	Average from data recordings	Average from TPTC of BIO I
Total energy consumed	kWh	3215	3578
Total distance sailed	km	102	124.2
Average sailing speed	kn	7.1	6.9
Average power consumed	kW	284	222
Max. power consumed	kW	693	715

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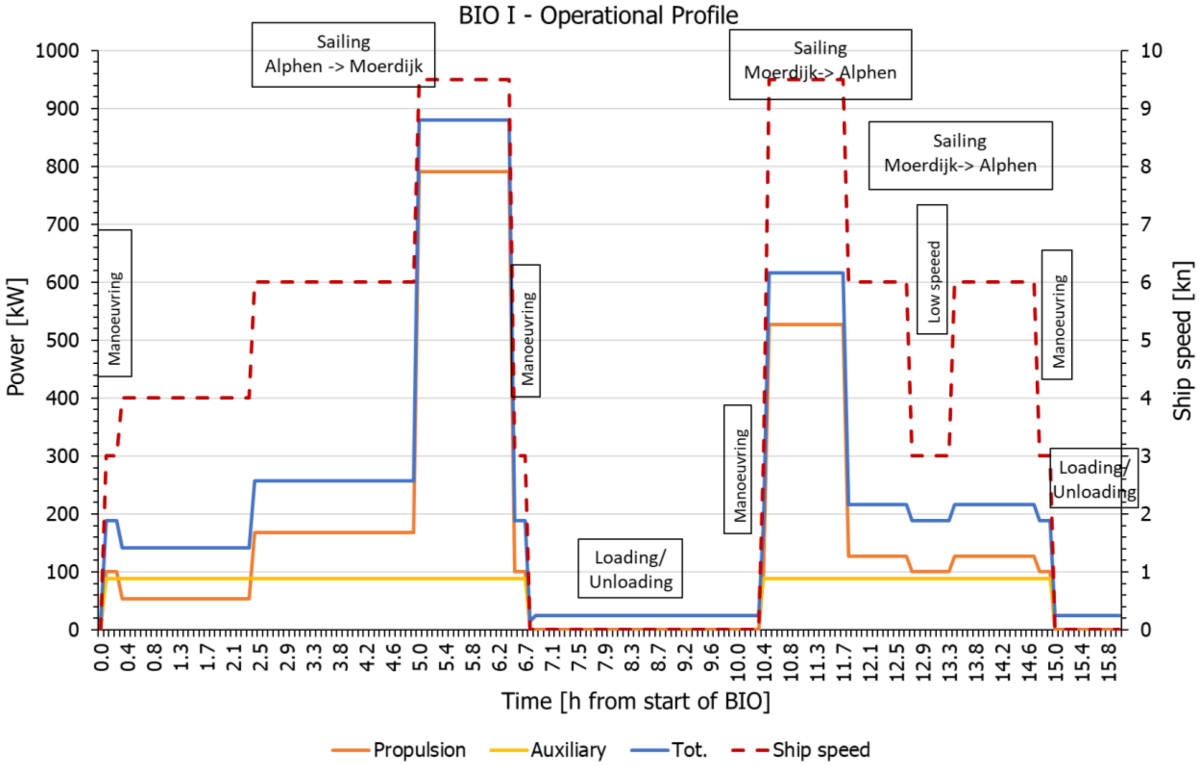

Figure 5-8: Task power-time chart of BIO I of the Alphenaar.

In general, despite the slight differences between the values from Table 5-3, it can be seen how the total energy consumed during BIO I is in line with that of the data recordings. Thus, it can be concluded that the operational profile described by BIO I represents properly the operation of the vessel and therefore the energy demand for the dimensioning of the energy carrier. The power-time chart for this BIO was used to extract the maximum and average power demand, used for the subsequent SPEC analysis described in next section.

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5.4 SPEC analysis of Demo 3

5.4.1 Preselection and ranking

A preselection of the most suitable technologies was made using the combination of ship- and client-related inputs (Table 5-4). Next, the relevance of technology-, investment- and operations-related criteria were weighted and subsequently ranked. The full ranking is given in Annex A2.3.

Table 5-4: Inputs used in the SPEC preselection of Demo 3.

Parameter	**Value**	
Max Effective Power *[kW]*	715	
Endurance *[d]*	0.67	
Estimated downtime *[%]*	10	
Expected lifespan *[year]*	25	
Average power delivered *[kW]*	222	
Minimum TRL	7	
Zero emission only?	Yes	No X
CO2 price/ton emission *[EUR/t]*	73	
Minimum SRL	3	

For this demonstrator, no preference was given by the stakeholders (see Table 5-5 and Table 5-6).

Table 5-5: Demo 3, "Technology & Investment" criteria. Weight factors.

Criteria	**Weight [%]**
Contained energy density volume	8.3
Contained energy density weight	8.3
CapEx energy carrier	8.3
TRL energy carrier	8.3
SRL energy carrier	8.3
Specific volume on board power systems	8.3
Specific weight on board power systems	8.3
CapEx on board power systems	8.3
Chain efficiency systems	8.3
TRL on board power systems	8.3
Harmful exhaust emission	8.3
Green House Gas emission	8.3

Table 5-6: Demo 3, "Operations" criteria. Weight factors.

Criteria	**Weight [%]**
Contained energy density volume	16.7
Contained energy density weight	16.7
OpEx energy carrier	16.7
Chain efficiency systems	16.7
Harmful exhaust emission	16.7
Green House Gas emission	16.7

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The base concept (diesel electric with high speed ICE) was compared with five other solutions, resulting in the weighted ranking presented in Table 5-7. It should be noted that as the base concept of this demonstrator was a vessel with diesel-electric architecture, the concepts included in the raking as well as in the SPEC results are for ships with electric propulsion. For instance, concept #16 corresponds to a diesel-electric concept that uses a diesel (EN590) genset to generate electricity. From Table 5-7, it can be seen that the concepts that use batteries as energy carrier are very suitable for the Alphenaar from a operational, technological and investment point of view.

Table 5-7: Results of the SPEC system ranking for the preselection of a system for Demo 3. Base concept is Diesel (EN590) CI ICE (hi-speed).

System	Ranking		
	Overall	**Technology & Invest-ment**	**Operations**
#16 = Diesel (EN590) CI ICE (hi-speed)	8.2	8.1	8.4
#9 = e-CH3OH (CO2 PTS)/Dsl 95/5%vol CI ICE	5.8	6	5.5
#19 = e-LNG (CO2 PTS) SI ICE	6.8	6.8	6.7
#21 = Battery-electric (renewable)	7.7	8.8	6.5
#36 = e-H2 300b ISO LT PEMFC	3.3	2.2	4.3
#48 = Battery-electric (fossil)	7.6	8	7.2

5.4.2 Overview of the SPEC results

From the power time chart developed for BIO I, the power profile from Table 5-8 was developed for the SPEC analysis. With the data from the power profile, the time-weighted average power was obtained and then used as input in SPEC to dimension the PPE system.

Table 5-8: Power profile used as input in SPEC.

Type of operation	**Power** [% of max. power]	**Time** [% of endurance time]
Waiting	2.1	1.0
Loadin/unloading	3.1	29.0
Sailing low speed Alphen->Moerdijk	19.8	13.0
Sailing medium speed Alphen->Moerdijk	35.9	16.1
Sailing high speed Alphen->Moerdijk	100.0	9.3
Sailing medium speed Moerdijk->Alphen	30.2	14.5
Sailing high speed Moerdijk -> Alphen	73.4	7.8
Manoeuvring	26.4	9.3
Time-weighted average	**31.13**	

Once the SPEC analysis was carried out, the results presented in Annex A2.3 were obtained for this demonstrator. From these results, the charts presented in Figure 5-9, Figure 5-10 and Figure 5-11 were generated. It should be noted that in the solution with batteries, the term "fuel" used in SPEC refers to the weight and volume of batteries, as for a battery electric PPE system these are the energy carriers instead of fuel.

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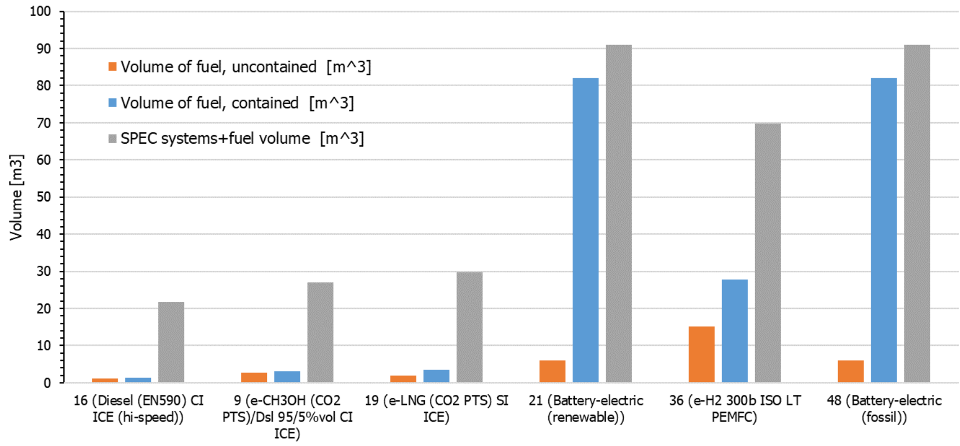

Figure 5-9: Overview of the fuel and systems volume for each concept resulting from the SPEC analysis of Demo 3.

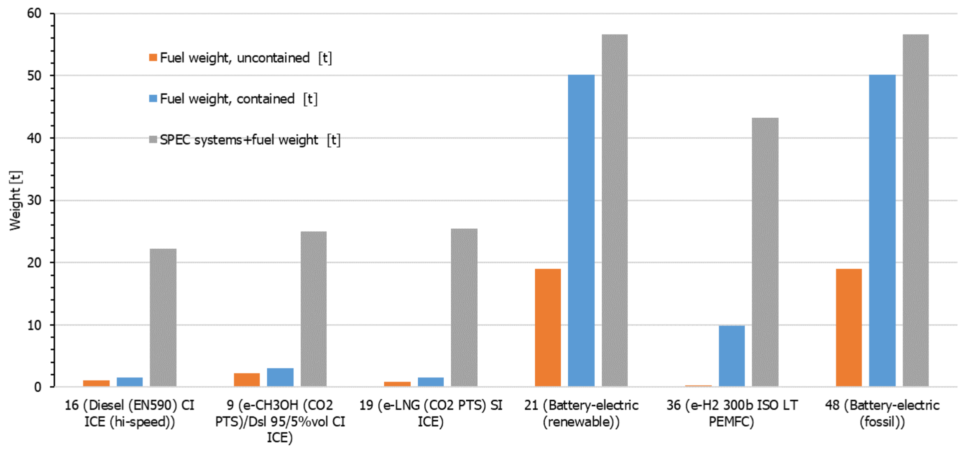

Figure 5-10: Overview of the fuel and systems weight for each concept resulting from the SPEC analysis of Demo 3.

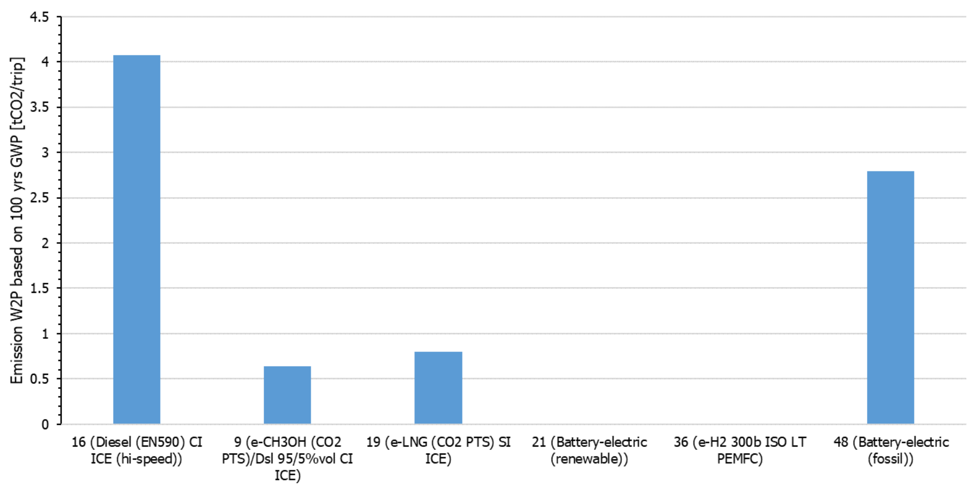

Figure 5-11: Overview of the CO2 equivalent emissions (well to propulsion, W2P) per trip for each concept resulting from the SPEC analysis of Demo 3.

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5.4.3 Conclusions of the SPEC analysis

For the vessel Alphenaar, operating as described in the operational analysis, the following conclusions summarise the findings of the SPEC analysis:

- The concept with battery-electric PPE system display the largest reduction in CO2 emissions when renewable sources are employed to generate the electricity (concept #21), together with the renewable hydrogen concept (concept #36). However, when fossil fuels are used to generate electricity for the batteries (concept #48), other concepts become more attractive in terms of CO2 emissions reduction (such as concept #9 and concept #19).

- The battery electric concepts (#21 and # 48) require a significant greater amount of weight and volume of energy carrier than the other concepts. It has to be noted that for the battery concept, the term "uncontained" refers to the volumetric and gravimetric energy densities of the battery cells only, while the term "contained" refers to the volumetric and gravimetric energy densities of the whole battery system, including, for example, the support structure and the support systems of the battery such as cooling and ventilation.

- The e-methanol and the e-LNG concepts (#9 and #19) require a relatively small increase in volume and weight, due to the relatively lower energy density of methanol with respect to diesel and have comparable CO2 emissions.

- The compressed hydrogen concept (#36) turns out as an intermediate solution in terms of volume and weight, positioned between the methanol and LNG options and the fully battery-powered systems.

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6. | Operational and SPEC analyses of Demo 4 (Le Sandre)

6.1 Introduction of Demo 4

Le Sandre is an inland cement carrier vessel dedicated to the transport of cement from Gennevilliers, located at the north of Paris, to Ivry sur Seine, located at the south of Paris. During its route along the Seine river, the vessel calls at several ports, where cement is discharged.

Figure 6-1: Photo of vessel Le Sandre sailing on the Seine river.

The cement is loaded at the port of Gennevilliers by gravity in combination with a screw conveyor located on deck. Unloading is conducted by liquifying cement using pressurized air and then discharged with flexible hoses. Discharge occurs typically at Issy les Moulineaux or Port-Victor.

Le Sandre has a diesel-electric propulsion system consisting of two main gensets plus one harbour generator. Propulsion is provided by two ducted thrusters each connected to an electric motor via a Z-drive.

As the vessel spends most of its time waiting or loading/unloading in the harbour, shore power could be used to provide the required power for unloading the cargo, which is one of the most power demanding activities. In addition to supplying the required power in the harbour (including loading/unloading), the shore power could be used to charge the batteries that will be installed on board after the retrofit. Also, the current unloading harbour, Port Victor, is located in an industrial zone. Therefore, installing a shore connection would be reasonably feasible.

In principle, no major changes would be needed to install batteries. A problem is that the current shore connection is not designed for the load required to charge the battery packs, so it needs to be dimensioned again. Additional weight may also limit the application of batteries, as the payload should not be reduced. In addition, Class requirements may also require additional space to divide the main source of power, the space for ventilation of the battery room, etc. If a fully electric propulsion is not an option, a hybrid propulsion can be an alternative.

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6.2 Sailing routes

As shown in Figure 6-3, Le Sandre sails between ports located within or in the vicinity of Paris. The cement is loaded at Gennevilliers port, and afterward the vessel sails upstream to discharge in other ports. The typical routes of Le Sandre are the following:

1. **Gennevilliers ↔ Issy les Moulineaux/Port-Victor** (most preferred route). The ship departs fully loaded from Gennevilliers and then discharges at Issy-les-Moulineaux or Port Victor. Once the ship is unloaded, it sails back to Gennevilliers. The ship sails fully loaded upstream and empty downstream.
2. **Gennevilliers → Clichy → Issy les Moulineaux/Port-Victor → Ivry sur Seine** (longest route). The ship departs fully loaded from Gennevilliers and then discharges at Clichy, Issy-les-Moulineaux /Port Victor and Ivry. Then it returns to Issy les Moulineaux /Port Victor to discharge again, and then sails empty to Gennevilliers.

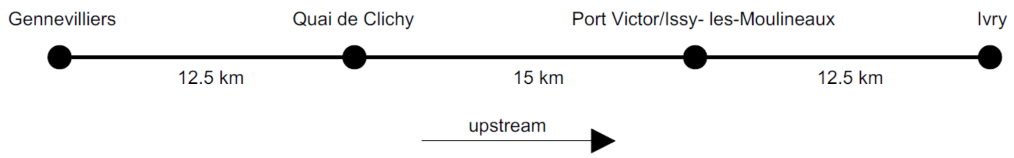

Figure 6-2: Overview of the route of Le Sandre.

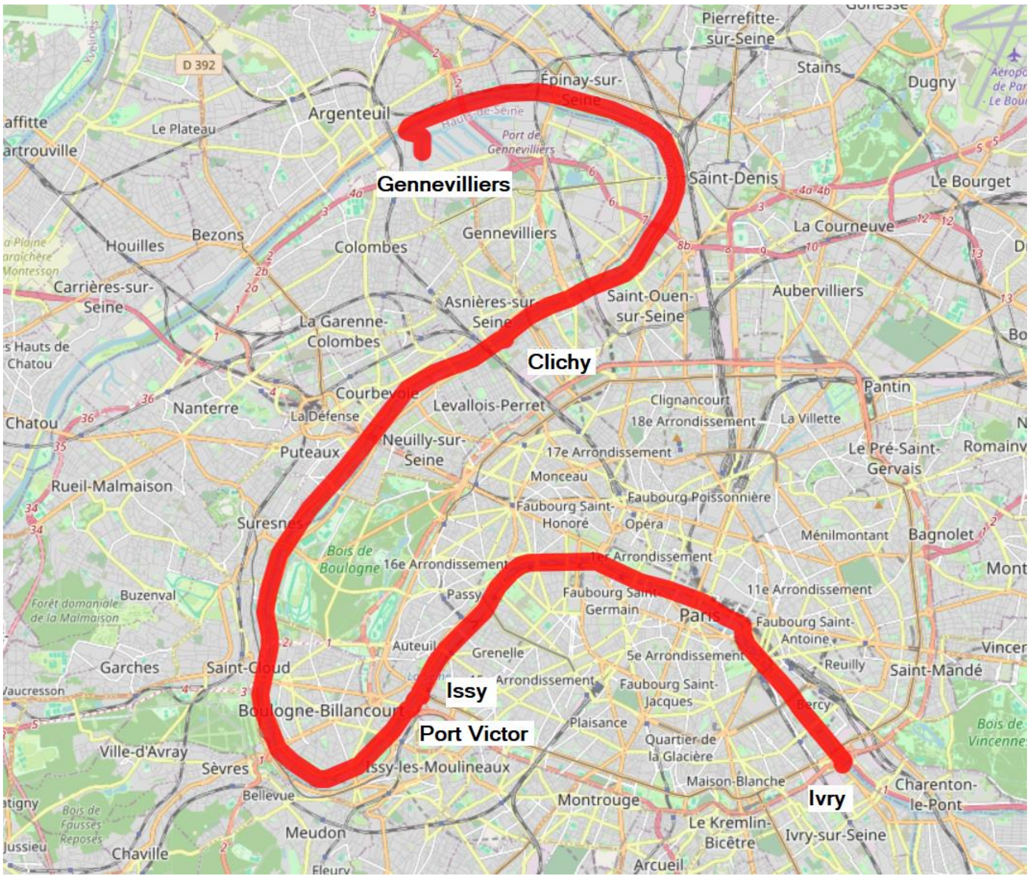

Figure 6-3: Route of Le Sandre shown on a map.

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6.3 Operational analysis

The operational analysis of Le Sandre was built based primarily on data recordings, measured on the electrical busbar, taken during a period of 14 days, excluding the weekends where the ship was not operating, making a total of about 200 hours recorded. These data recordings, provided by Sogestran, detailed the type of operation and total energy consumed at a particular time when the ship was operating. In Figure 6-4 the cumulative energy consumed from the recordings is shown. From the cumulative energy distribution, the average power consumed at each operation was derived, resulting in the power-time chart presented in Figure 6-5.

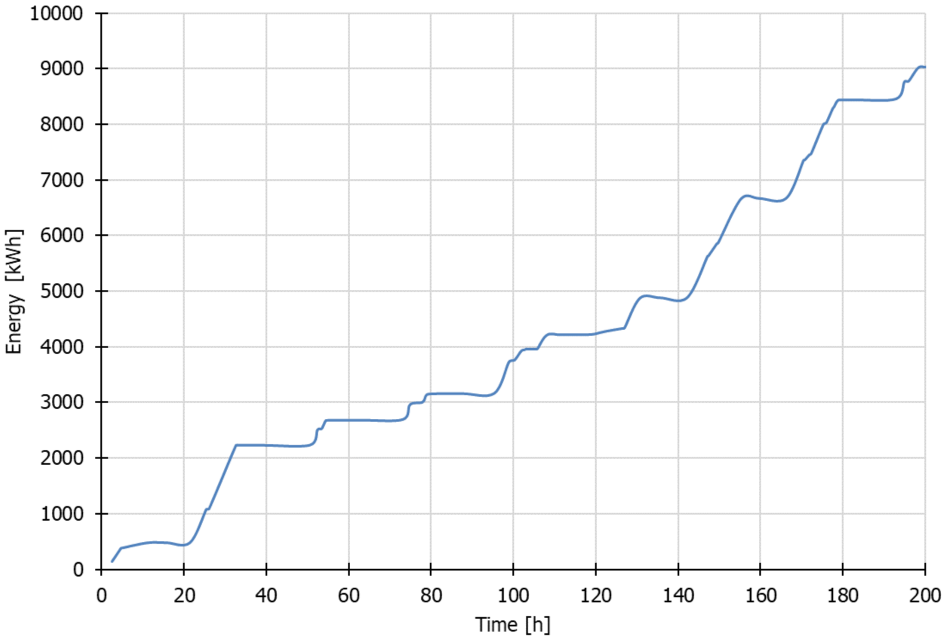

Figure 6-4: Total cumulative energy consumed from the 14-day data recording of Le Sandre

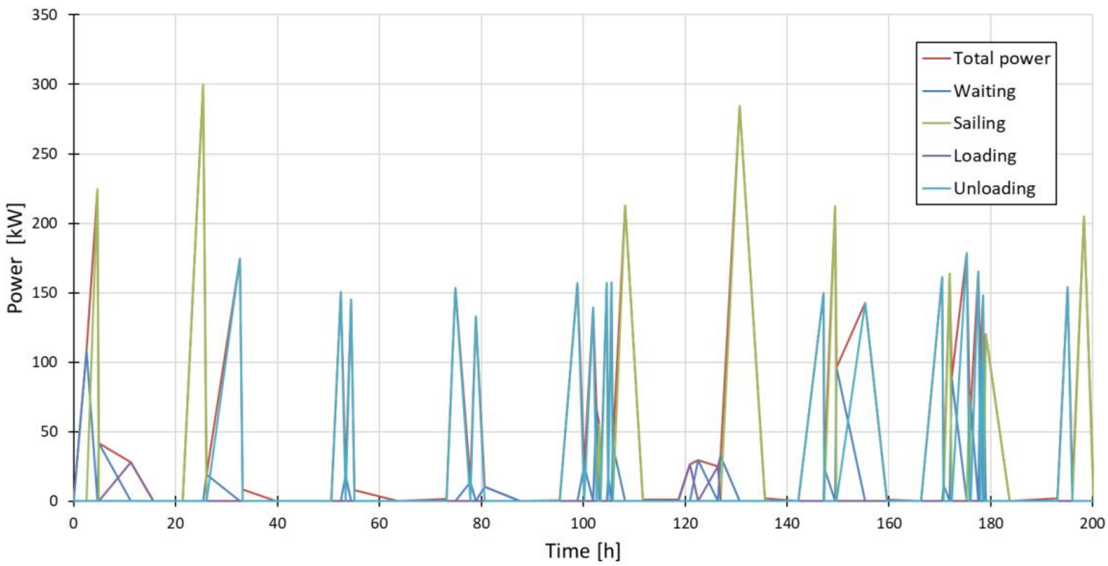

Figure 6-5: Power-time chart derived from the 14-day data recording of Le Sandre.

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6.3.1 Definition of Bunkering Independent Operations of current vessel

The data recordings included several voyages combining the routes presented in section 6.2. In order to dimension the PPE system, the bunkering independent operations (BIOs) were identified. This was done by grouping the recorded operations into bunkering intervals. As the vessel bunkers at Gennevilliers, the BIOs were defined by a sequence of operations between two consecutive calls at Gennevilliers. From the recorded data, two BIOs with the following routes were identified:

1) **BIO I:**

   Gennevilliers → Port-Victor → Issy → Gennevilliers

2) **BIO II:**

   Gennevilliers → Port-Victor → Ivry → Port-Victor → Issy → Port-Victor → Gennevilliers

In addition the following tasks/operations were identified:

1. **Sailing upstream:** Ship sailing against the current i.e., in the direction Gennevilliers → Ivry
2. **Sailing downstream:** Ship sailing with the current i.e., in the direction Ivry → Gennevilliers
3. **Loading:** Cement is loaded on board. Main power consumers are the screw conveyors on deck and other auxiliary equipment.
4. **Unloading:** Cement is unloaded from the ship. Main power consumers are the air compressor units used to liquify the cargo, and the pumps to blow the cement.
5. **Waiting:** Ship is waiting in harbour. Main consumers are auxiliary systems which are part of the hotel load.
6. **Economic waiting:** Ship is waiting in harbour with a minimum power consumption, e.g., at night.

After analysing the recorded data, it was found that the tasks carried out by Le Sandre demanded the average power showed in Table 6-1.

Table 6-1: Average power consumption (in kW) for each of the BIOs of Le Sandre before the retrofit.

Task/operation	**BIO I**	**BIO II**
Sailing upstream	300	259
Sailing downstream	213	191
Waiting	22	45
Loading	28	26
Unloading	159	155
Economic waiting	1	1

Once the tasks and the route of each BIO were identified, power-time charts were constructed by establishing a sequence of tasks that describe the operation of the vessel. This was done based on the recorded data in combination with the input from Sogestran. By doing so, it was possible to determine the power demand as a function of time for each BIO, resulting in the power-time charts presented in Figure 6-6 and Figure 6-7.

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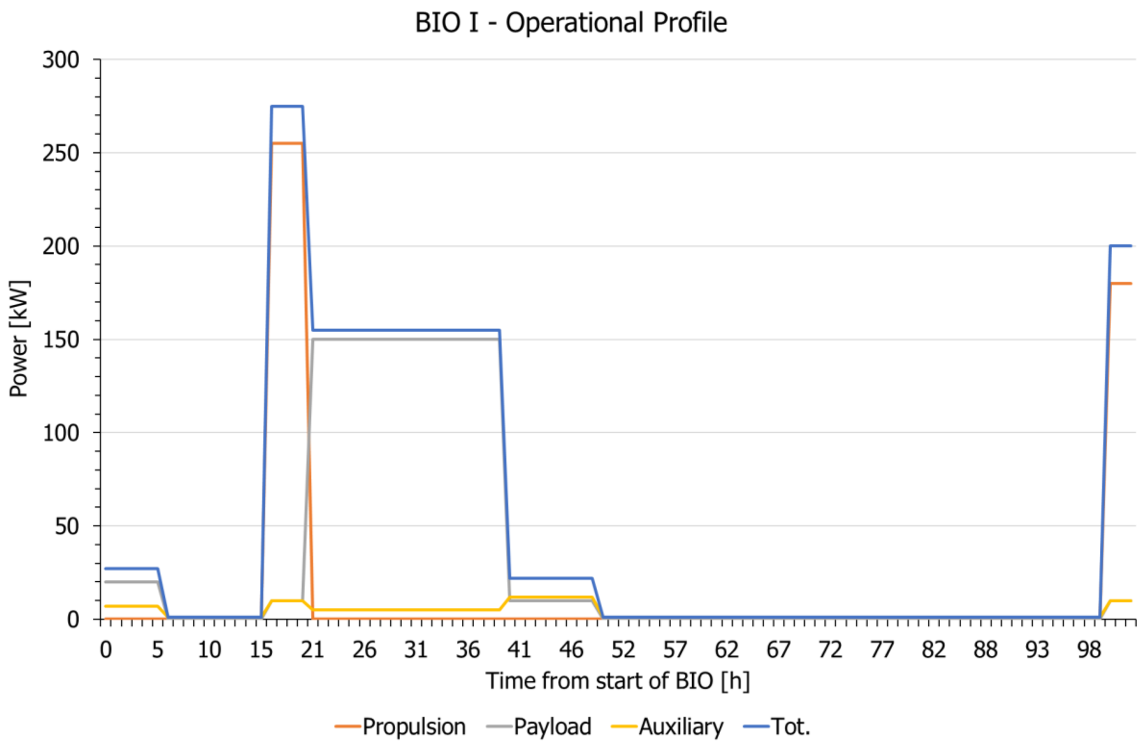

Figure 6-6: Power-time chart of BIO I of Le Sandre before the retrofit.

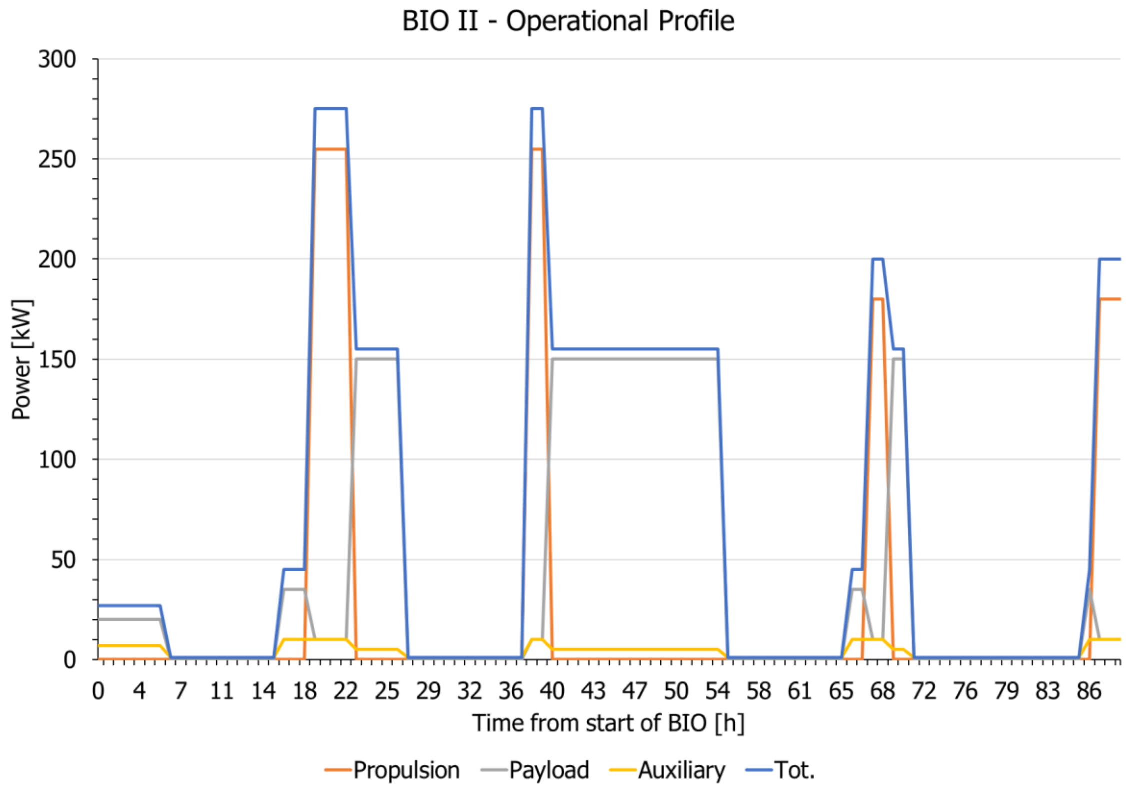

Figure 6-7: Power-time chart of BIO II of Le Sandre before the retrofit.

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Next, from the power-time charts the energy demand of each BIO was calculated, and then compared with the recorded data. It was observed that the energy demand calculated from the power-time charts matched very well (within 2%) with the energy from the recorded data, which proved that the defined tasks were a realistic representation of the power demand to be expected during the operation of Le Sandre.

6.3.2 Definition of Bunkering Independent Operations after the retrofit

After the retrofit, Le Sandre will be equipped with batteries that will be charged at a shore power connection located at Port Victor. Thus, as Port Victor will be the new "bunkering" location, the BIOs for the retrofitted ship will start and end at Port Victor instead of Gennevilliers. Using the recorded data as reference, only the long stops (time at port more than 10 hours) at Port Victor were used as a start of a new BIO, as this is the expected time required to charge the batteries. In addition, Sogestran communicated that for the future operation it do not plan to sail up to Issy, therefore this port was not included in the new operational profile. Based on this, the two following BIOs were defined:

1) **BIO I:**

   Port-Victor → Gennevilliers → Port-Victor

2) **BIO II:**

   Port-Victor → Issy → Gennevilliers → Port-Victor

For these BIOs the average power values from Table 6-2 were used for each task, resulting in the power-time charts presented in Figure 6-8 and Figure 6-9. The power values defined in each task, are derived from the energy provided in the measured data by Sogestran. This suggests that certain environmental conditions, such as water level and stream speed, are implicitly affecting the propulsion power but are not directly available in the data. Consequently, the propulsive power might be higher when the vessel is sailing at a given speed than when it is moving at a higher speed It should be noted that in contrast with the old BIOs before the retrofit, the unloading event which is carried out at Gennevilliers requires zero power from the PPE system as the ship is connected to the shore power connection. Also, the task 'Sailing PV-Issy' was introduced to describe the operation when the vessel sails at very low speed between Port Victor and Issy, located only a few hundred meters away.

Table 6-2: Average power consumption (in kW) for each of the BIOs of Le Sandre after the retrofit.

Tasks	SOG [kn]	SOG [km/h]	Propulsion power [kW]	Payload power [kW]	Auxiliary power [kW]	Total power [kW]
Sailing upstream BIO I	3.7	6.9	280	10	10	300
Sailing upstream BIO II	4.0	7.3	265	10	10	285
Sailing downstream BIO I	6.9	12.7	205	10	10	225
Sailing downstream BIO II	6.4	11.8	190	10	10	210
Economic Waiting	0.0	0.0	0	0	1	1
Loading	0.0	0.0	0	20	7	27
Unloading	0.0	0.0	0	150	7	157
Waiting BIO I	0.0	0.0	0	22	20	42
Waiting BIO II	0.0	0.0	0	8	20	28
Sailing PV - Issy	0.7	1.3	45	0	10	55

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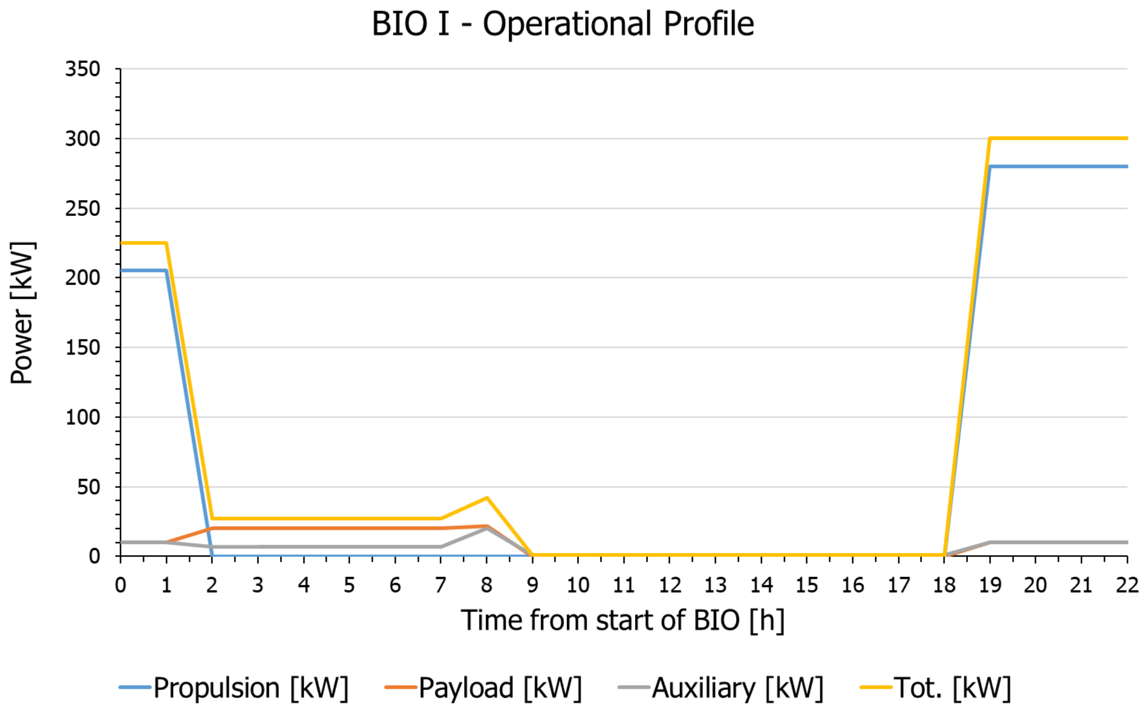

Figure 6-8: Power-time chart of BIO I of Le Sandre after the retrofit.

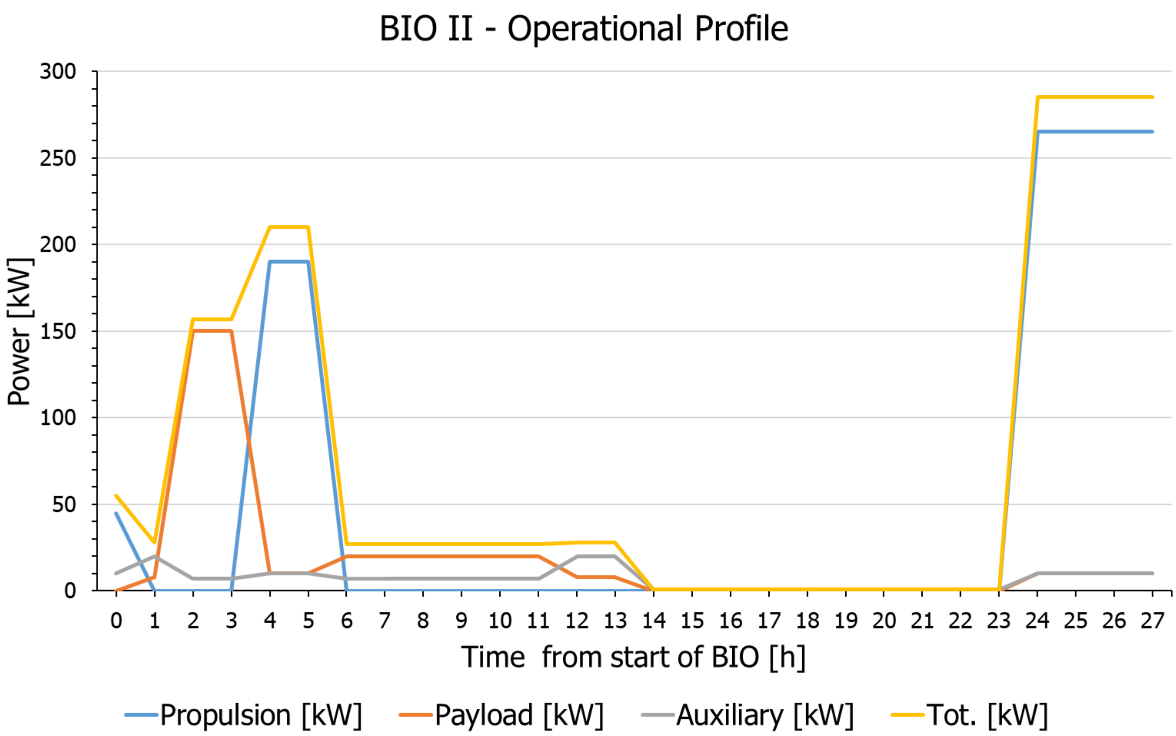

Figure 6-9: Power-time chart of BIO II of Le Sandre after the retrofit.

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6.4 SPEC analysis of Demo 4

6.4.1 Preselection and ranking

A preselection of the most suitable technologies was made using the combination of ship- and client-related inputs (Table 6-3). Next, the relevance of technology-, investment- and operations-related parameters were weighted and subsequently ranked. The full ranking is given in Annex A2.4.

Table 6-3: Inputs used in the SPEC preselection of Demo 4.

Parameter	Value	
Max Effective Power *[kW]*	300	
Endurance *[d]*	1.17	
Estimated downtime *[%]*	30	
Expected lifespan *[year]*	25	
Average power delivered *[kW]*	78	
Minimum TRL	7	
CO_2 price/ton emission *[EUR/t]*	73	
Zero emission only?	Yes	No X
Minimum SRL	3	

For this demonstrator, Table 6-4 and Table 6-5 show the preference that was given by the stakeholders.

Table 6-4: Demo 4, "Technology & Investment" criteria. Weight factors

Criteria	Weight [%]
Contained energy density volume	0
Contained energy density weight	0
CapEx energy carrier	13.0%
TRL energy carrier	0
SRL energy carrier	0
Specific volume on board power systems	13.0%
Specific weight on board power systems	13.0%
CapEx on board power systems	13.0%
Chain efficiency systems	8.0%
TRL on board power systems	0
Harmful exhaust emission	20.0%
Green House Gas emission	20.0%

Table 6-5: Demo 4, "Operations" criteria. Weight factors

Criteria	Weight [%]
Contained energy density volume	10%
Contained energy density weight	10%
OpEx energy carrier	20%
Chain efficiency systems	10%
Harmful exhaust emission	25%
Green House Gas emission	25%

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The base concept (diesel-electric with high speed ICE) has been compared with five other solutions, resulting in the ranking presented in Table 5-7. These five solutions correspond with the most common PPE concepts that are being implemented at the moment for the decarbonisation of the waterborne transport. It should be noted that as the base concept of this demonstrator was a vessel with diesel-electric architecture, the concepts included in the ranking as well as in the SPEC results, are for ships with electric propulsion. For instance, concept #41 from Table 5-7 corresponds with a diesel electric concept that uses dual fuel (LNG-MGO) gensets to generate electricity.

From the ranking from Table 6-6 it can be seen that the concepts that use batteries as energy carrier are the most suitable for Le Sandre from an operational, technological and investment point of view.

Table 6-6: Results of the SPEC concept ranking for the preselection of a system for Demo 4. Base concept is Diesel (EN590) CI ICE (hi-speed).

Concept	**Ranking**		
	Overall	**Technology & Invest-ment**	**Operations**
#16 = Diesel (EN590) CI ICE (hi-speed)	4.1	2.5	5.6
#9 = e-CH3OH (CO2 PTS)/Dsl 95/5%vol CI ICE	5	4	5.9
#19 = e-LNG (CO2 PTS) SI ICE	5.8	5.1	6.5
#21 = Battery-electric (renewable)	8.9	9	8.8
#36 = e-H2 300b ISO LT PEMFC	5.4	3.5	7.4
#48 = Battery-electric (fossil)	8.3	7.6	9

6.4.2 Overview of the SPEC results

Using the power-time chart developed for BIO II, the power profile from Table 6-7 was used for the SPEC analysis. With the data from the power profile, the time-weighted average power was obtained and then used as input in SPEC to dimension the PPE system.

Table 6-7: Power profile used as input in SPEC.

Type of operation	**Power** [% of max. power]	**Time** [% of endurance time]
Sailing upstream BIO II	95.0	14.2
Sailing downstream BIO II	70.0	7.1
Economic Waiting	0.3	35.6
Waiting BIO II	9.3	10.7
Loading	9.0	21.4
Unloading	52.3	7.1
Sailing PV - Issy	18.3	3.6
Time-weighted average	**25.61**	

Once the SPEC analysis was carried out, the results presented in Annex A2.4 were obtained for this demonstrator. From these results, the charts presented in

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Figure 6-10, Figure 6-11 and Figure 6-12 were generated. It should be noted that in the solution with batteries, the term "fuel" used in SPEC refers to the weight and volume of batteries, as for a battery electric PPE system these are the energy carriers instead of fuel.

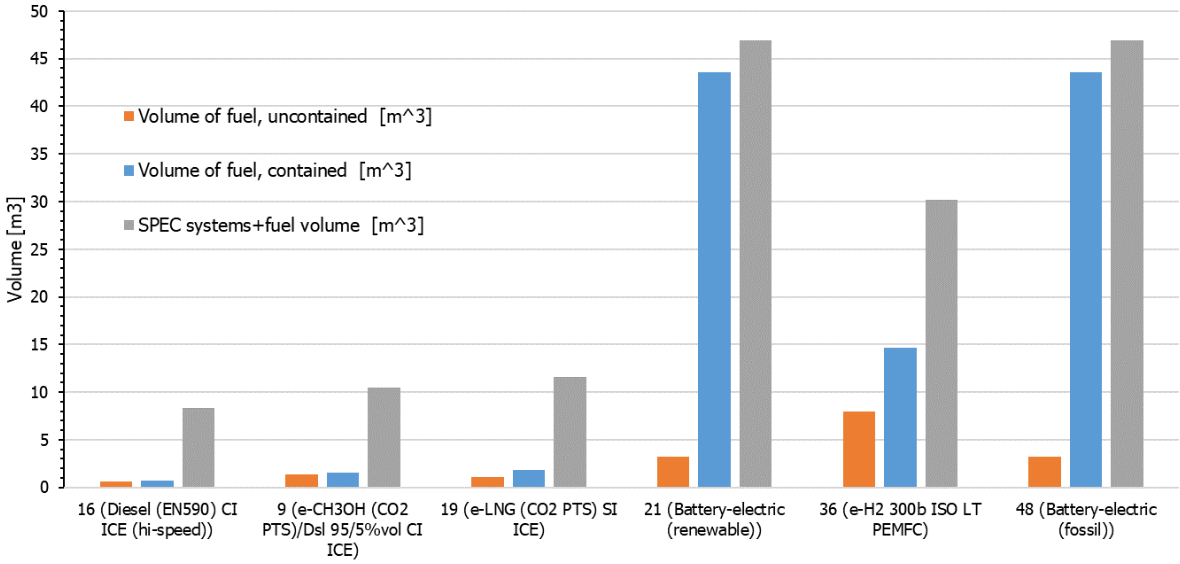

Figure 6-10: Overview of the fuel and systems volume for some concepts resulting from the SPEC analysis of Demo 4.

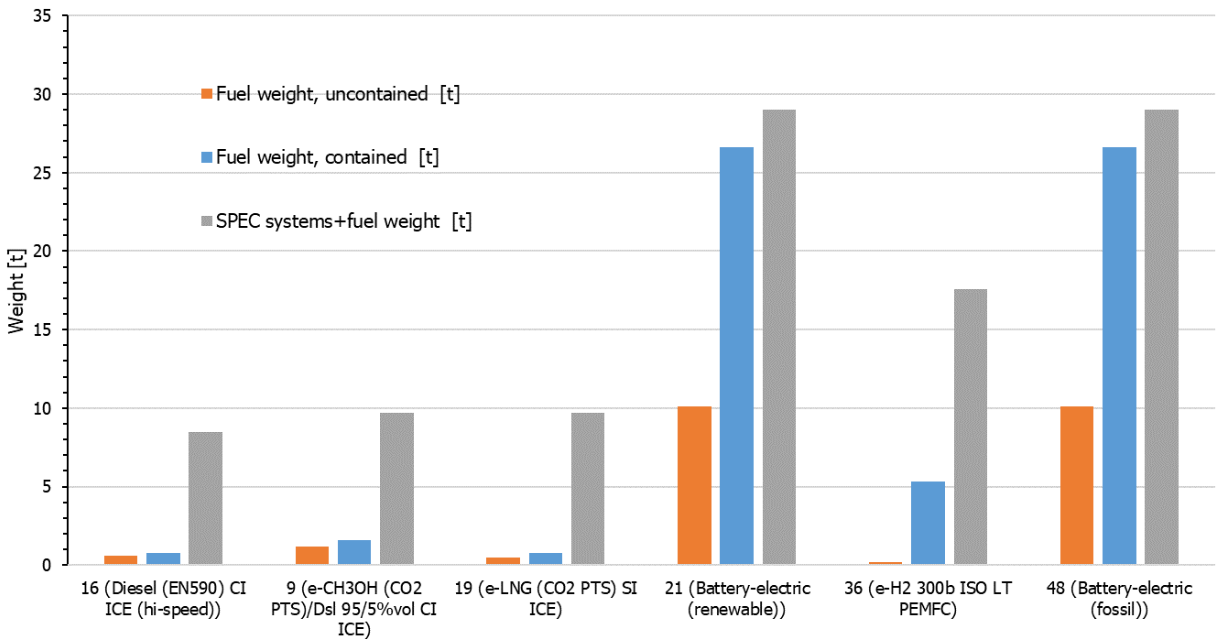

Figure 6-11: Overview of the fuel and systems weight for some concepts resulting from the SPEC analysis of Demo 4.

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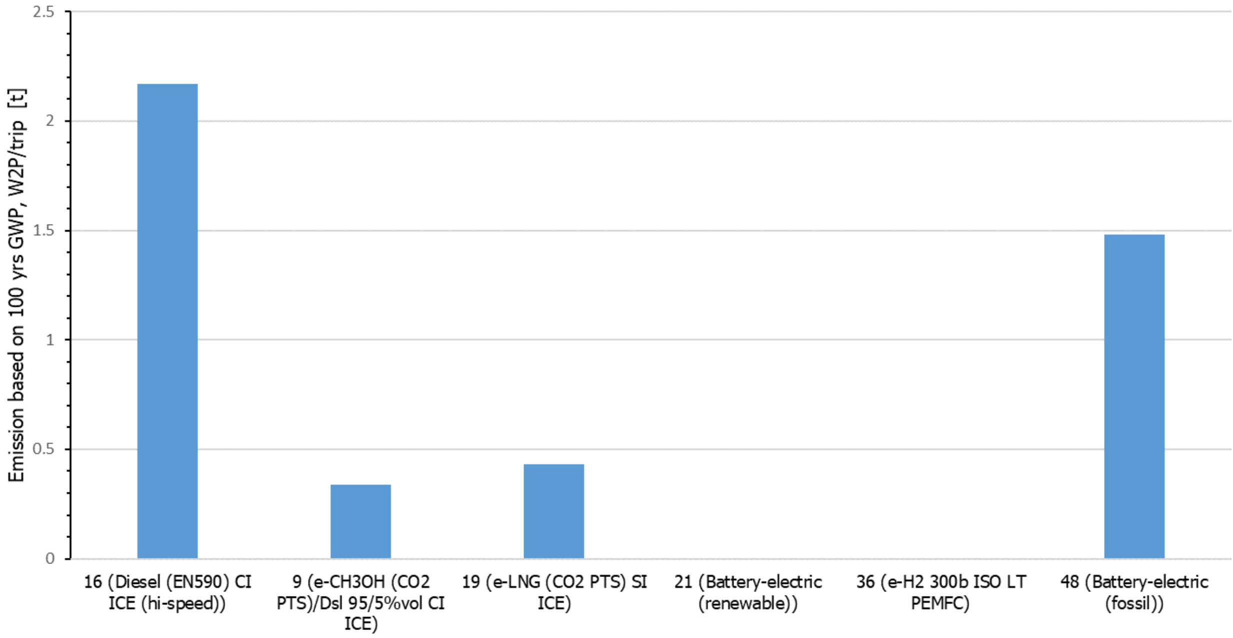

Figure 6-12: Overview of the CO2 equivalent emissions (well to propulsion, W2P) per trip for each solution concept resulting from the SPEC analysis of Demo 4.

6.4.3 Conclusions of the SPEC analysis

For the vessel Le Sandre, operating as described in the operational analysis, the following conclusions summarise the findings of the SPEC analysis:

- The concept with battery-electric PPE system display the largest reduction in CO2 emissions when renewable sources are employed to generate the electricity (concept #21), together with the renewable hydrogen concept (concept #36). However, when fossil fuels are used to generate electricity for the batteries (concept #48 other concepts become more attractive in terms of CO2 emissions reduction (such as concept #9 and concept #19).

- The battery electric concepts (#21 and # 48) require a significant greater amount of weight and volume of energy carrier than the other concepts. It has to be noted that for the battery concept, the term "uncontained" refers to the volumetric and gravimetric energy densities of the battery cells only, while the term "contained" refers to the volumetric and gravimetric energy densities of the whole battery system, including, for example, the support structure and the support systems of the battery such as cooling and ventilation.

- The e-methanol and the e-LNG concepts (#9 and #19) require a relatively small increase in volume and weight, due to the relatively lower energy density of methanol with respect to diesel and have comparable CO2 emissions.

- The compressed hydrogen concept (#36) turns out as an intermediate solution in terms of volume and weight, positioned between the methanol and LNG options and the fully battery-powered systems.

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7. | Operational and SPEC analyses for Demo 5

7.1 Introduction of Demo 5

The Ernst Kramer is a nearly 50-year-old inland dry cargo vessel belonging to shipping company Rhenus. The vessel is operated mainly on the river Rhine, carrying dry cargo in bulk.

To achieve a reduction in emissions, the deskstudy with scale tests and computational optimisation considers the replacement of the aftship to improve the hydrodynamic efficiency and thus the fuel consumption. In addition, to further improve the emission performances, a replacement of the propulsion and power system is considered.

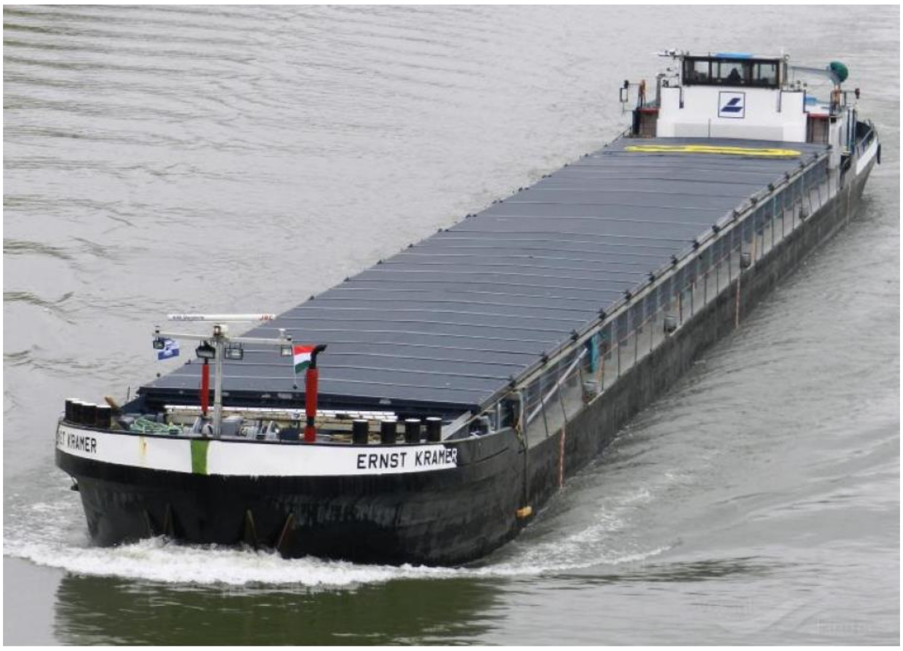

Figure 7-1: Photo of the Ernst Kramer.

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7.2 Sailing routes

The Ernst Kramer operates along the following routes through canals and through the Rhine River:

1) Canal route:
The vessel departs from Duisburg and sails eastwards through several canals until it reaches its final destination, Brandenburg an der Havel. Along the route, the vessel calls at some intermediate ports.

- Duisburg to Brandenburg an der Havel

  Duisburg → Herne → Kreis Steinfurt → Landkreis Schaumburg → Wolfsburg → Jerichower Land → Brandenburg an der Havel

- Brandenburg an der Havel to Duisburg

  Brandenburg an der Havel → Börde → Hannover → Landkreis Osnabrück → Münster → Duisburg

2) Rhine route:
The ship sails first upstream from Duisburg to Mannheim and then back downstream, calling at several ports in between.

- Upstream

  Duisburg → Bonn → Landkreis Mainz-Bingen → Mannheim

- Downstream

  Mannheim → Koblenz → Duisburg

Figure 7-2: Overview of the canal route followed by the Ernst Kramer.

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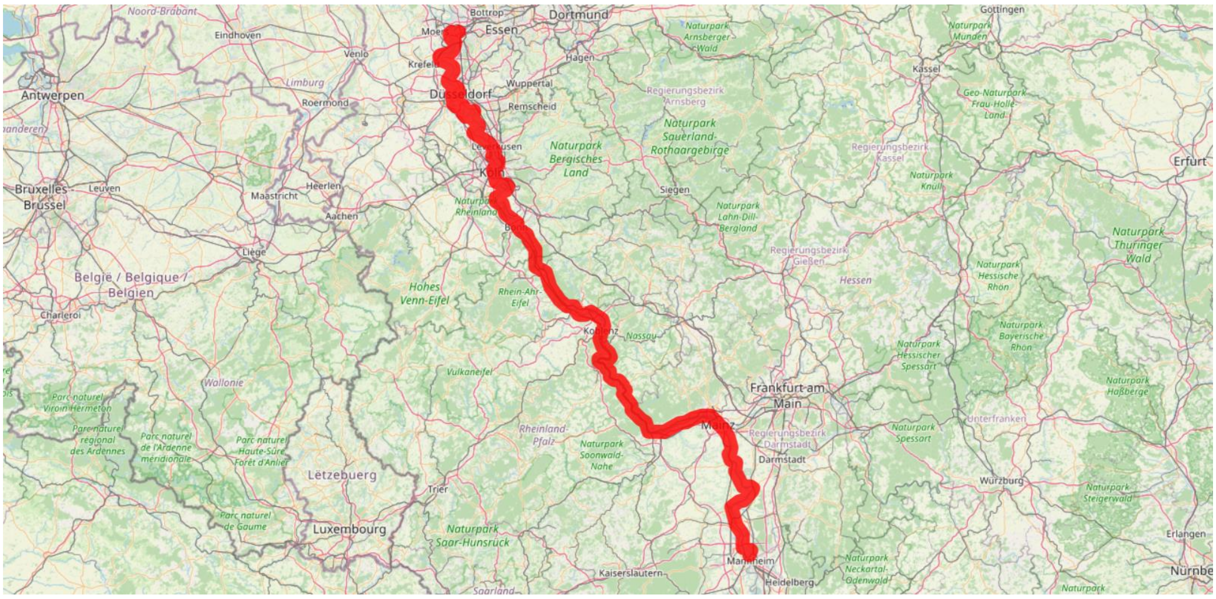

Figure 7-3 Route on the Rhine river of the Ernst Kramer

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7.3 Operational analysis

The operational analysis of this demonstrator was carried out by DST. Based on the fuel consumption measured on board and the specific fuel consumption of the main engine, the required effective propulsion power was derived. In Figure 7-4 and Figure 7-5 the required propulsion power of the Ernst Kramer is shown for the canal and Rhine route, respectively.

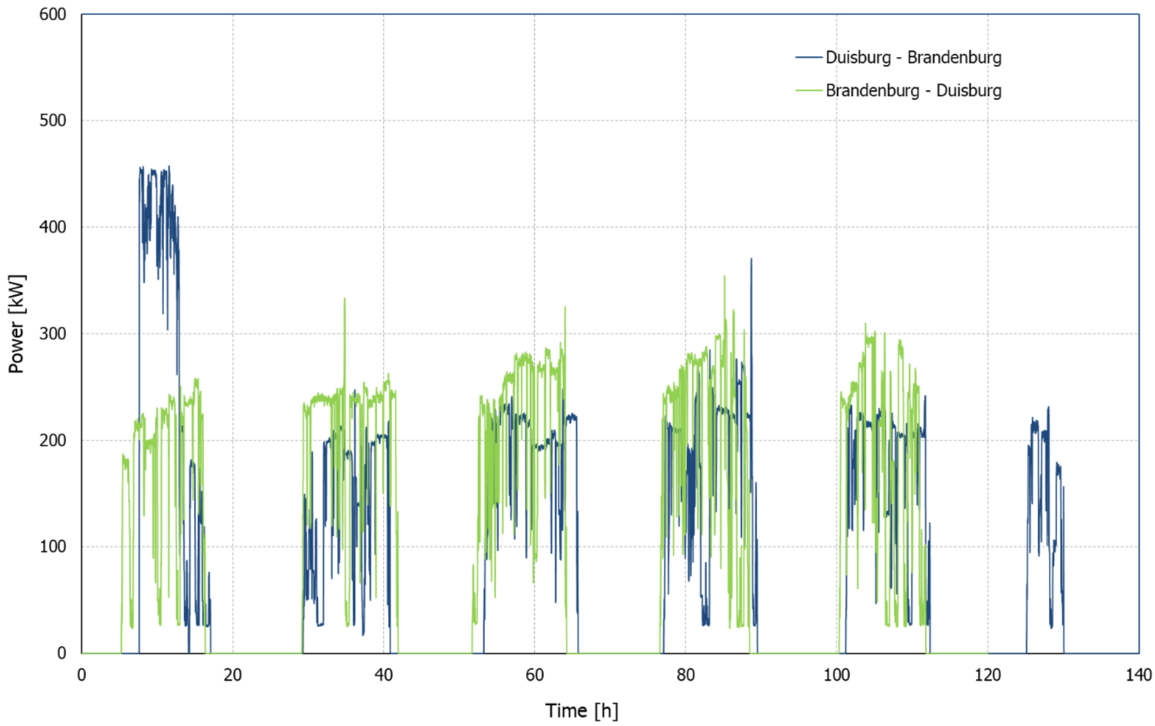

Figure 7-4: Propulsion power utilized by the Ernst Kramer during its trip along the canal route.

Using the propulsion power data the average power consumed for propulsion was obtained for both legs of the Canal and the Rhine routes. In Table 7-1 and Table 7-2 a summary of the calculation of the average propulsion power is presented for the canal and Rhine routes, respectively.

In addition to the propulsion power, the auxiliary power was included in the calculation of the total power. As no measurements of the auxiliary power were conducted on the Ernst Kramer, the average and maximum auxiliary power were estimated based on reference ships of similar size to the Ernst Kramer.

Next, by averaging the propulsion power for both directions of the canal and Rhine routes over the time during which the power was used, and by incorporating both the maximum and average auxiliary power, the total power values shown Table 7-3 were derived.

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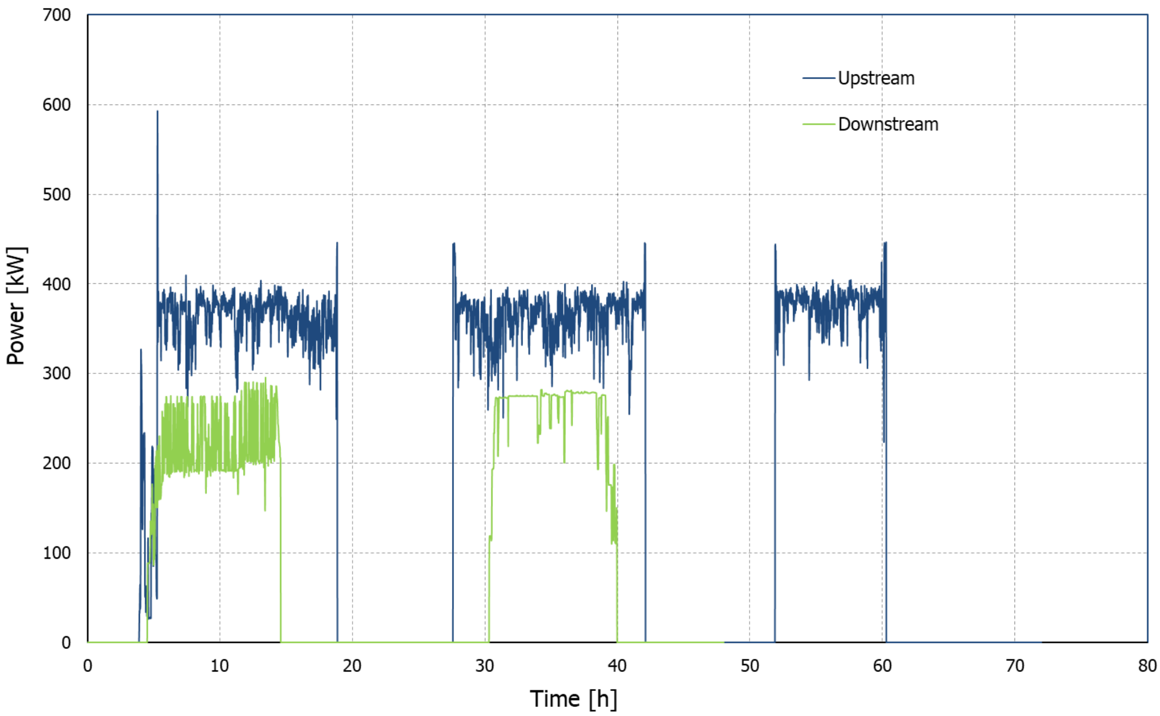

Figure 7-5: Propulsion power utilized by the Ernst Kramer during its trip along the Rhine route.

Table 7-1: Overview of the propulsion power utilized by the Ernst Kramer during the canal route.

Canal route Duisburg -> Brandenburg							
Parameter	Unit	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
Average propulsion power	kW	278	143	196	183	179	150
Maximum propulsion power	kW	458	247	248	370	242	232
Time the ship is using propulsion power	min	560	692	749	744	669	296
	h	9.3	11.5	12.5	12.4	11.2	4.9

Total weighted-average propulsion power	189	kW
Total duration of trip	61.8	h
Maximum propulsion power	458	kW

Canal route Brandenburg -> Duisburg						
Parameter	Unit	Day 1	Day 2	Day 3	Day 4	Day 5
Average propulsion power	kW	181	215	220	214	190
Maximum propulsion power	kW	258	334	325	355	309
Time the ship is using propulsion power	min	667	765	751	712	689
	h	11.1	12.8	12.5	11.9	11.5

Total weighted-average propulsion power	205	kW
Total duration of trip	59.7	h
Maximum propulsion power	355	kW

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Table 7-2: Overview of the propulsion power utilized by the Ernst Kramer during the Rhine route.

Rhine route upstream (Duisburg -> Mannheim)				
Parameter	Unit	Day 1	Day 2	Day 3
Average propulsion power	kW	341	364	377
Maximum propulsion power	kW	592	445	446
Time the ship is using propulsion power	min	898	872	504
	h	15.0	14.5	8.4

Total weighted-average propulsion power	358	kW
Total duration of trip	37.9	h
Maximum propulsion power	592	kW

Rhine route downstream (Mannheim -> Duisburg)			
Parameter	Unit	Day 1	Day 2
Average propulsion power	kW	215	257
Maximum propulsion power	kW	294	282
Time the ship is using propulsion power	min	604	579
	h	10.1	9.7

Total weighted-average propulsion power	236	kW
Total duration of trip	19.7	h
Maximum propulsion power	294	kW

From Table 7-3 it can be seen that the River route is the most power demanding, whereas the Canal route is the most energy demanding.

Table 7-3: Summary of the maximum and average power for the canal and Rhine route of the Ernst Kramer.

Parameter	**Unit**	**Canal route**	**Rhine route**
Maximum propulsion power	kW	458	592
Maximum auxiliary power	kW	100	100
Maximum total power	kW	558	692
Average propulsion power	kW	61	32
Average auxiliary power	kW	70	70
Total average power	kW	528	662
Total duration	h	121.6	57.6
Total energy consumed	kWh	64135	38131

7.3.1 Definition of Bunkering Independent Operations

For this demonstrator, the BIOs were constructed using the existing routes established to measure the fuel consumption. Therefore, the two following BIOs were identified:

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1) **BIO I (canal route):**
Navigation from Duisburg to Brandenburg an der Havel through several canals.

Duisburg → Herne → Kreis Steinfurt → Landkreis Schaumburg → Wolfsburg → Jerichower Land → Brandenburg an der Havel → Börde → Hannover → Landkreis Osnabrück → Münster → Duisburg

2) **BIO II (Rhine route):**
Navigation upstream from Duisburg to Mannheim through the Rhine river and then downstream in the opposite direction.

Duisburg → Bonn → Landkreis Mainz-Bingen → Mannheim → Koblenz → Duisburg

As the BIOs used for this demonstrator coincided with the routes defined to measure the fuel consumption, the power and energy data from Table 7-3 was sufficient to conduct the SPEC analysis.

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7.4 SPEC analysis of Demo 5

7.4.1 Preselection and ranking

The data of the most energy demanding BIO was used as a starting input for the SPEC analysis, as it can be seen in Table 7-4. In particular, the maximum and average effective powers were obtained from the measured data, the endurance was calculated as the time in which the engine was being used, while the downtime and the expected lifespan were estimated based on similar ships, as this information were not available.

A preselection of the most suitable technologies was made in SPEC. Next, the relevance of technology-investment- and operations-related parameters were weighted and subsequently ranked. In Annex A2.5 the full output of the ranking of this demonstrator is presented.

Table 7-4: Inputs used in the SPEC preselection of Demo 5.

Parameter	**Value**	
Max Effective Power *[kW]*	692	
Endurance *[d]*	5.01	
Estimated downtime *[%]*	10	
Expected lifespan *[year]*	25	
Average effective power *[kW]*	267	
Minimum TRL	7	
CO_2 price/ton emission *[EUR/t]*	73	
Zero emission only?	Yes	No X
Minimum SRL	3	

For this demonstrator, no preference was given by the stakeholders, therefore the criteria have been weighted equally, as it can be seen in Table 7-5 and Table 7-6.

Table 7-5: Demo 5, "Technology & Investment" criteria. Weight factors

Criteria	**Weight [%]**
Contained energy density volume	8.3
Contained energy density weight	8.3
CapEx energy carrier	8.3
TRL energy carrier	8.3
SRL energy carrier	8.3
Specific volume on board power systems	8.3
Specific weight on board power systems	8.3
CapEx on board power systems	8.3
Chain efficiency systems	8.3
TRL on board power systems	8.3
Harmful exhaust emission	8.3
Green House Gas emission	8.3

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Table 7-6: Demo 5, "Operations" criteria. Weight factors

Criteria	Weight [%]
Contained energy density volume	16.7
Contained energy density weight	16.7
OpEx energy carrier	16.7
Chain efficiency systems	16.7
Harmful exhaust emission	16.7
Green House Gas emission	16.7

The base concept (diesel-direct with high speed ICE) has been compared with five other solutions, resulting in the ranking presented in Table 7-7.

From the ranking from Table 7-7 it can be seen that the diesel direct base concept as well as concepts that use batteries as energy carrier are the most suitable for the Ernst Kramer from an operational, technological and investment point of view.

Table 7-7: Results of the SPEC system ranking for the preselection of a system for Demo 5. Base concept is Diesel (EN590) CI ICE (hi-speed) Direct.

Concept	Ranking		
	Overall	Technology & Invest-ment	Operations
#52 = Diesel (EN590) CI ICE (hi-speed) Direct	9	9	9
#21 = Battery-electric (renewable)	6.9	7.4	6.5
#48 = Battery-electric (fossil)	6.9	6.7	7.2
#41 = LNG DF ICE CI	6.3	4.1	8.5
#36 = e-H2 300b ISO LT PEMFC	3.2	2.1	4.3
#9 = e-CH3OH (CO2 PTS)/Dsl 95/5%vol CI ICE	5.3	5.1	5.5

7.4.2 Overview of the SPEC results

Using the power and time values from Table 7-3, the power profile from Table 7-8 was used for the SPEC analysis. With the data from the power profile, the time-weighted average power was obtained and then used as input in SPEC to dimension the PPE system.

Table 7-8: Power profile used as input in SPEC.

Type of operation	Power [% of max. power]	Time [% of endurance time]
Sailing Duisburg -> Brandenburg	37	51
Sailing Brandenburg -> Duisburg	40	49
Time-weighted average	**38.47**	

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Once the SPEC analysis was carried out, the results presented in Annex A2.5 were obtained for this demonstrator. From these results, the graphs presented in Figure 7-6, Figure 7-7 and Figure 7-8 were made.

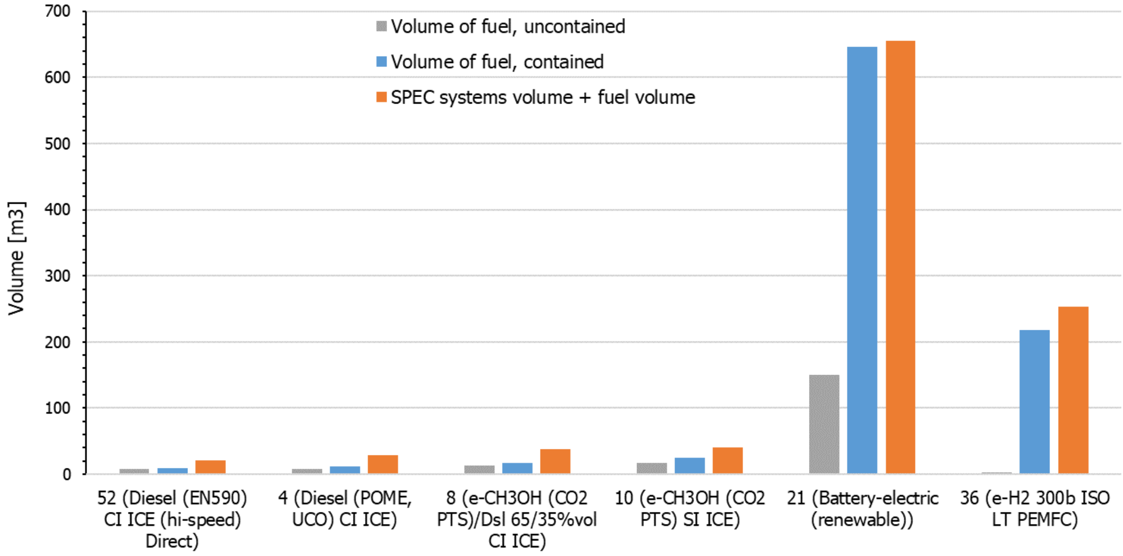

Figure 7-6: Overview of the fuel and systems volume for some concepts resulting from the SPEC analysis of Demo 5.

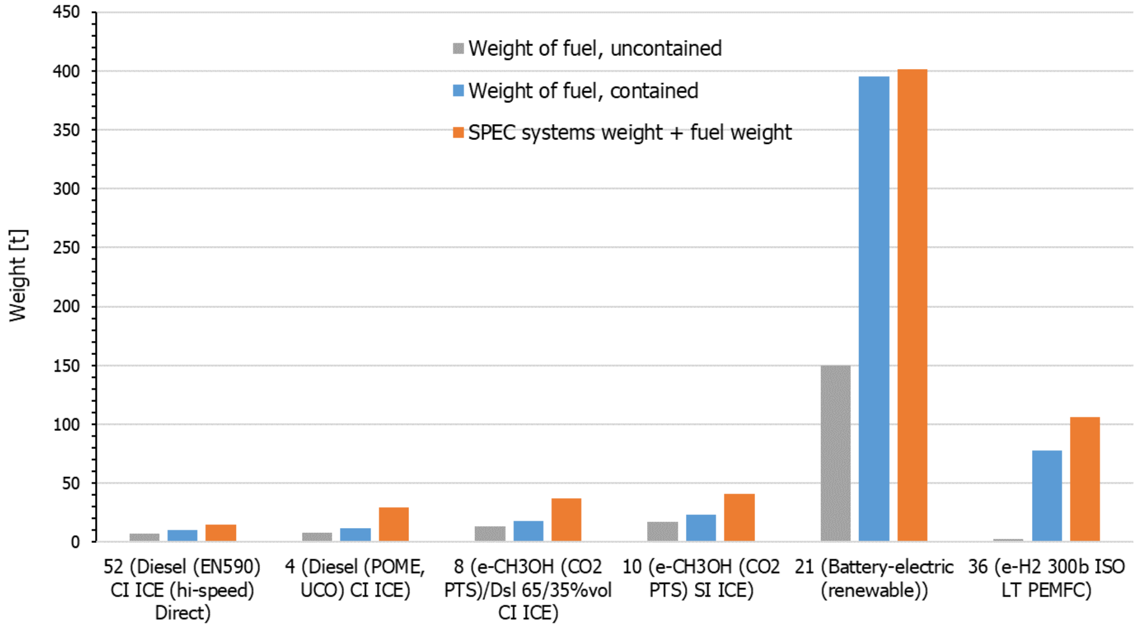

Figure 7-7: Overview of the fuel and systems weight for some concepts resulting from the SPEC analysis of Demo 5.

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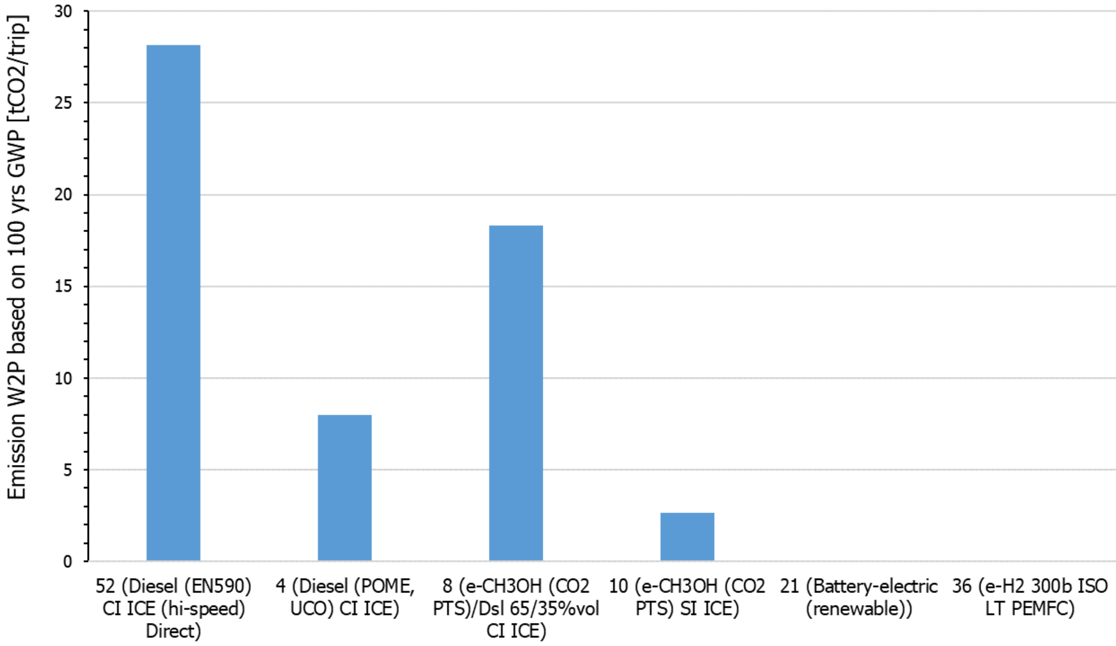

Figure 7-8: Overview of the CO2 equivalent emissions (well to propulsion, W2P) per trip for each solution concept resulting from the SPEC analysis of Demo 5.

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7.4.3 Conclusions of the SPEC analysis

For the vessel Ernst Kramer, operating as described in the operational analysis, the following conclusions summarise the findings of the SPEC analysis:

- The concept with battery-electric PPE system displays the largest reduction in CO2 emissions when renewable sources are employed to generate the electricity (concept #21). However, this concept requires a significantly greater amount of weight and volume of energy carriers than the other concepts. It has to be noted that for the battery concept, the term "uncontained" refers to the volumetric and gravimetric energy densities of the battery cells only, while the term "contained" refers to the volumetric and gravimetric energy densities of the whole battery system, including, for example, the support structure and the support systems of the battery such as cooling and ventilation.

- Concept #36 consisting of compressed hydrogen from a renewable source and fuel cells, results in a zero-emission solution that requires significantly less weight and volume than the battery-electric concept. If zero emission has to be achieved, this concept is a better alternative than that the battery-electric concept.

- The methanol concepts offer a different range of emission reduction depending on the methanol share in the fuel blend. Concept #8 is considered to be the most conservative in terms of volume share in the fuel blend for the future methanol Dual Fuel Internal Combustion Engines. Concept #10 refers to a methanol-only, therefore spark-ignited (SI), Internal Combustion Engine. The reduction in emissions is due to the fact that methanol is produced by carbon capture at a point source (CO2 PTS) and therefore it has a negative CO2 Well-to-Tank emissions value. The concept requires a relatively small increase in volume and weight. This is mostly due to the lower energy density (volumetric and gravimetric) of methanol compared to Diesel. It can be noted, in fact, that the methanol-only concept (#10) has slightly higher costs in terms of volume and weight compared to concept #8, because of the higher fuel capacity required.

- The bio-diesel concept (#4) offers a significant reduction in emissions with respect to the base concept, requiring a similar volume and weight for the fuel. Nevertheless, it requires a slightly larger volume and weight of the SPEC systems compared to the base concept, due to the lower efficiency of the diesel-electric configuration compared to the diesel direct of the reference case.

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8. | Operational and SPEC analyses of Demo 6 (Bad Deutsch-Altenburg)

8.1 Introduction of Demo 6

The Bad Deutsch-Altenburg is a push boat dedicated to the maintenance of the river Danube, owned by the Austrian waterway operator viadonau. Its capabilities include marking of waterways and maintenance of buoys and other aids to navigation to ensure the safe passage of vessel traffic on the Danube.

Despite being a low-emission vessel fitted with main engines compliant with EU Stage V emission regulations that can run on HVO100, viadonau is interested in exploring new concepts to reach lower emission levels for its future push boats.

The new push boat should carry out the same tasks as the Bad Deutsch-Altenburg, and in addition be able to push a barge with an excavator used for waterway maintenance. The new pusher would be similar to the Bad Deutsch-Altenburg, but viadonau is open to modifications of the main particulars to allow for alternative fuels to reach a solution as close as possible to zero emission, at a reasonable cost. In addition, the new push boat shall be able to replace the Bad Deutsch-Altenburg in seldom cases when the vessel is out of order, e.g. due to maintenance or technical malfunctions.

The Bad Deutsch-Altenburg does not have a fixed route, and current fuel autonomy allows for about 100 hours of operation.

Figure 8-1: Photo of vessel Bad Deutsch-Altenburg sailing on the Danube.

The Bad Deutsch-Altenburg has a diesel-direct propulsion system consisting of two high-speed diesel engines. Each engine is connected to a shaft line by means of a gearbox, and each shaft line has a ducted propeller. In addition, a generator set located in the engine room is used to provide auxiliary power.

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8.2 Sailing routes

The vessel operates on the river Danube. The typical operation consists of pushing a barge carrying buoys and other equipment used for waterway marking. In the future the boat is intended to push also pontoons with a crane, used to carry out maintenance work.

Depending on the conditions of the waterway, the ship is in operation one or a few days a week. After high water events and floods, it may be in operation all days of a week for approximately two weeks in the worst case, corresponding to an operational range of 350 km covering the entire Austrian Danube. In addition, the vessel to be built will serve as back up for the first pusher in cases it has to be maintained or repaired. Therefore, it has to be able to sail between Krems and Bad Deutsch-Altenburg. Whereas the main operational area will be the free flowing section west of Vienna close to Krems (Service Center Wachau), displaying similar, but a little less severe conditions like the section east of Vienna. As the vessel will sail occasionally also east of Vienna, it has to cope with the conditions present there.

Figure 8-2: The Bad Deutsch-Altenburg pushing a barge carrying waterway marking equipment.

Figure 8-3: Austrian Danube. Bad Deutsch-Altenburg is located at river km 1873, i.e., east of Vienna close to Bratislava.

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To analyse the operation of the vessel, viadonau provided data recordings of the Bad Deutsch-Altenburg for some representative trips occurred between October 2023 and February 2024. The data recordings contained information about location, course over ground, speed over ground, but unfortunately no power data was available. The GPS coordinates of the data recordings were plotted, resulting in the routes shown in Figure 8-4. From this figure it can be seen that the vessel operates in the vicinity of its main port Bad Deutsch-Altenburg[4], between Vienna and Bratislava. Besides the routes shown in Figure 8-4, a sailing trip covering the operational range between Bad Deutsch-Altenburg and Krems an der Donau was included in the operational analysis (Figure 8-5).

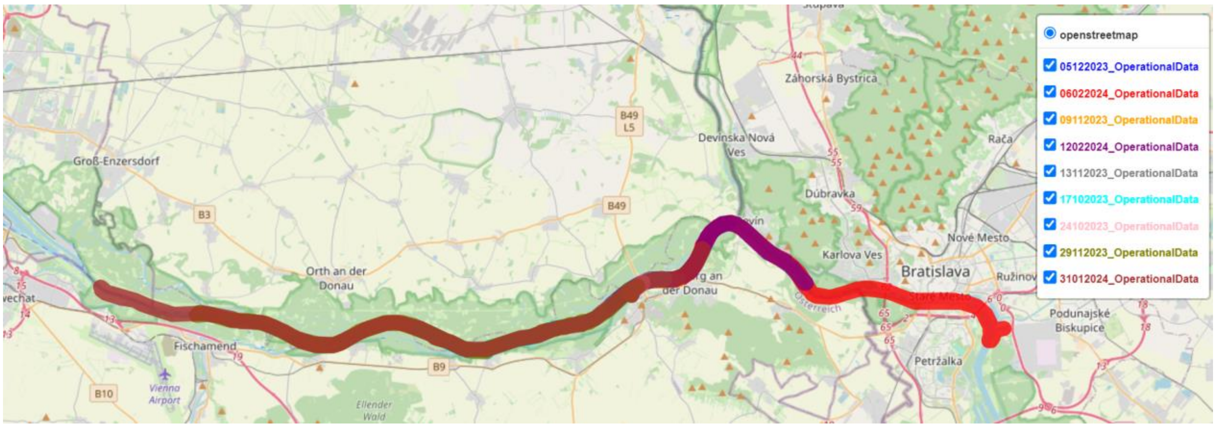

Figure 8-4: Overview of the routes sailed by the Bad Deutsch-Altenburg provided by viadonau.

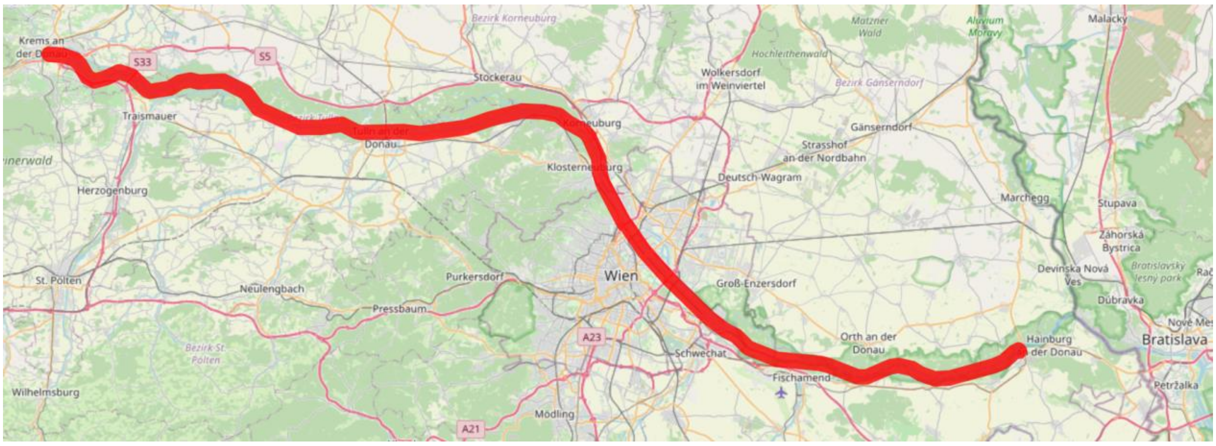

Figure 8-5: View of the route between Bad Deutsch-Altenburg to Krems an der Donau (sailed in BIO I).

[4] Homeport has the same name as the vessel.

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8.3 Operational analysis

As no power or energy data was available in the data recordings, the power had to be calculated. The auxiliary power was based on the electric load balance of the vessel, provided by viadonau. To calculate the propulsion power, a statistical speed-power prediction in deep water was carried out, and then corrected for shallow water effects using the Lackenby method.

As the vessel will sail in varying water depths, the average water depth of 4 m was selected for the required propulsion power. This water depth value represents the average depth value during the days of the operational data provided by viadonau (source: https://www.doris.bmk.gv.at/en/fairway-information/water-levels/annual-courses). For barge-pushing operations (tasks), the additional resistance of the barge was included in the speed-power prediction. The dimensions of the barge considered in the power prediction were provided by viadonau and are summarized in Table 8-1.

Table 8-1: Barge main dimensions

Parameter	Value
Length	19.74 m
Beam	6.04 m
Draught (full)	0.80 m
Depth	3.06 m

8.3.1 Definition of Bunkering Independent Operations

To fully describe the operations of the vessel, a Bunker Independent Operation per operational capability has been defined. The main operational capabilities are sailing a round trip from Bad Deutsch-Altenburg to Krems an der Donau, performing maintenance operations and waterway markings along the river, and performing a bathymetric survey. All the BIOs start and finish in Bad Deutsch-Altenburg, where the bunkering facility is located. The defined BIOs are:

1) **BIO I (round trip from Bad Deutsch-Altenburg to Krems an der Donau)**
Ship sails, without the barge, from Bad Deutsch-Altenburg to viadonau's Servicecenter Wachau at Krems an der Donau. There, the vessel spends the night and sails next day from Krems an der Donau back to Bad Deutsch-Altenburg, without bunkering. During the analysis this BIO has been split into two Missions:

   Mission I: Bad Deutsch-Altenburg → Krems an der Donau;
   Mission II: Krems an der Donau → Bad Deutsch-Altenburg.

2) **BIO II (maintenance of Danube river/waterway marking)**
Ship departs with the barge from Bad Deutsch-Altenburg towards the west (upstream). After sailing 4 km, the vessel stops. There, using the barge waterway maintenance tasks are carried out for 30 minutes. Then the vessel with the barge sail upstream for another 5 km to arrive to another location to carry out task related to waterway marking, for a period of time of 30 minutes. After these tasks are performed, the ship with the barge continues sailing 8 km upstream to another location where waterway maintenance tasks are performed for another 30 minutes. When these tasks are concluded, the ship and the barge sail downstream 8 km to another location where waterway markings are deployed/retrieved. This operation lasts for about 30 minutes. Ultimately, after this task has ended, the ship and the barge sail for another 10 km downstream to come back to Bad Deutsch-Altenburg.

   Bad Deutsch-Altenburg → River location 1 → River location 2 → River location 3 → River location 4 → Bad Deutsch-Altenburg

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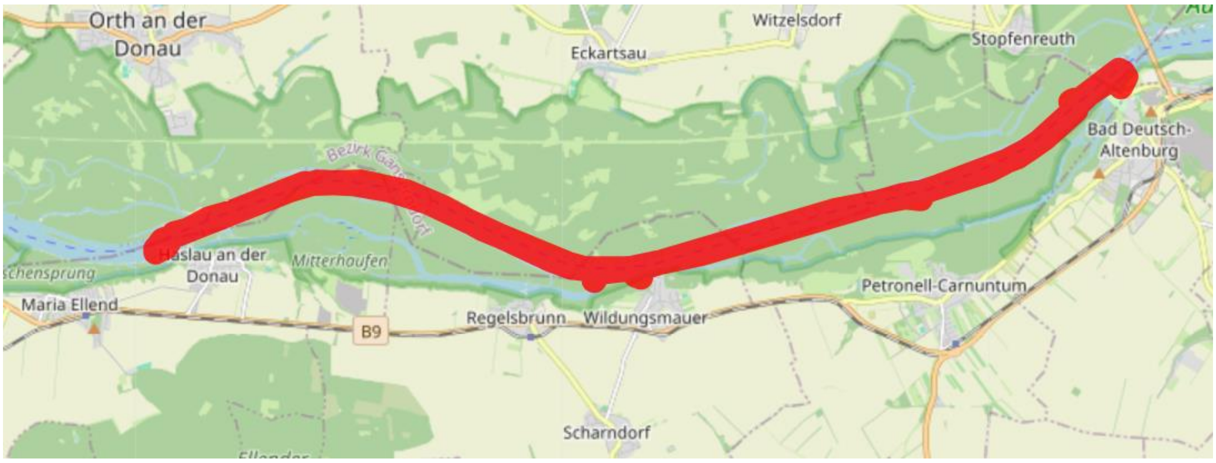

Figure 8-6: Route travelled during BIO II of Demo 6.

3) BIO III (Bathymetric survey)

Ship departs, without the barge, from Bad Deutsch-Altenburg towards the east (downstream). After sailing 10 km, the bathymetric survey starts. The survey is carried out at 2 km/h for an hour. Then the ship sails 4 km upstream, followed by another bathymetric survey carried out for a distance of 1 km, at 2 km/h speed over ground. After the second bathymetric survey, the vessel returns to its homeport.

Bad Deutsch-Altenburg → Bathymetry location 1 → Bathymetry location 2→ Bad Deutsch-Altenburg

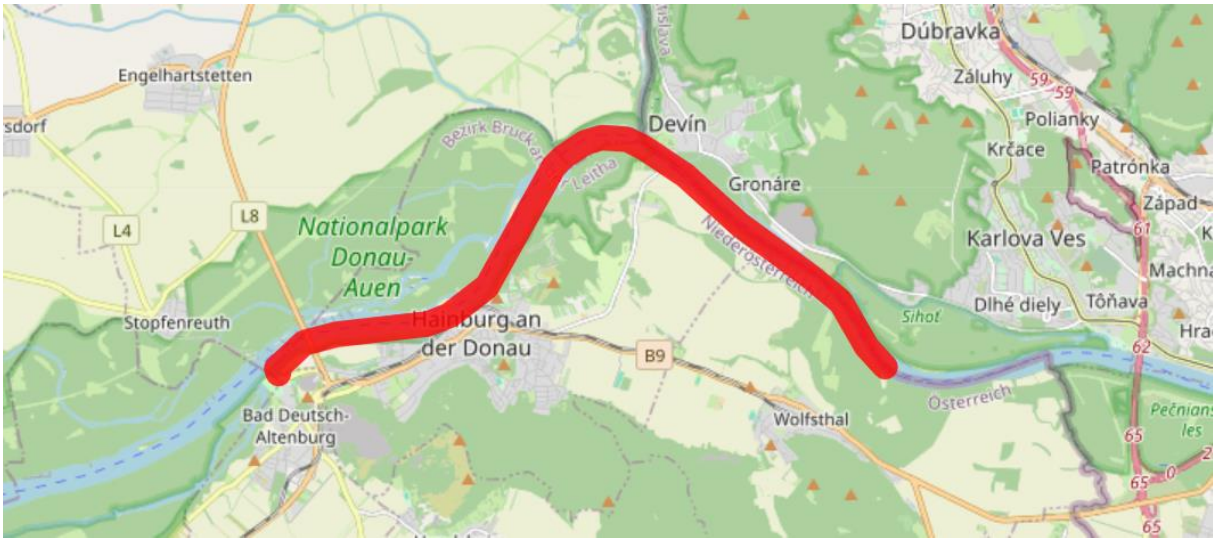

Figure 8-7: Route travelled during BIO III of Demo 6.

Based on the operations of the vessel, the operational tasks in Table 8-2 were defined. The "speed (through water)" was calculated using an average current speed of 5.6 km/h.

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Table 8-2: Demo 6, operational tasks overview

Tasks	SOG [km/h]	Speed (through water) [km/h]	Propulsion power (shaft power) [kW]	Auxiliary power [kW]	Total power [kW]
Waiting (idling in lock, port, berth, constr. site)	0.0	0.0	0.0	9.4	9.4
Navigation upstream (no barge)	8.5	14.1	71.3	9.4	80.7
Navigation downstream (no barge)	20.0	14.4	81.9	9.4	91.3
Manoeuvring (no barge)	4.0	4.0	1.5	15.9	17.4
Waterway marking (buoy deploying operation)	0.0	5.6	3.4	21.6	25.1
Navigation upstream with barge	8.0	13.6	155.2	15.9	171.1
Navigation downstream with barge	12.0	6.4	9.9	15.9	25.8
Navigation upstream high speed (no barge)	12.0	17.6	300.3	15.9	316.2
Navigation downstream high speed (no barge)	20.0	14.4	81.9	15.9	97.8
Waterway bathymetric survey (no barge)	2.0	7.6	7.6	21.6	29.2

Through the combination of tasks, a Task-Power Time Chart was created to describe the vessel's operations for each BIO. The results are presented in Figure 8-8, Figure 8-9, Figure 8-10, and Figure 8-11.

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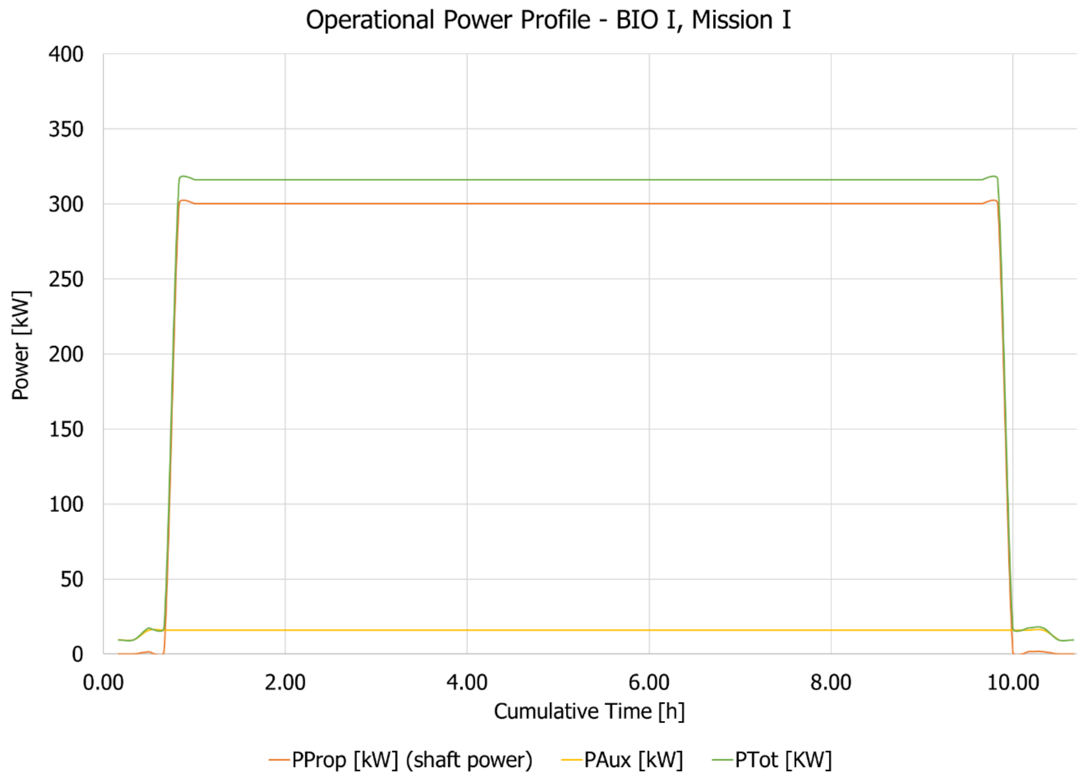

Figure 8-8: Demo 6. Task Power Time Chart, Mission I, BIO I. Sailing from Bad Deutsch-Altenburg to Krems an der Donau.

Figure 8-9: Demo 6. Task Power Time Chart, Mission I, BIO I. Sailing from Krems an der Donau to Bad Deutsch-Altenburg.

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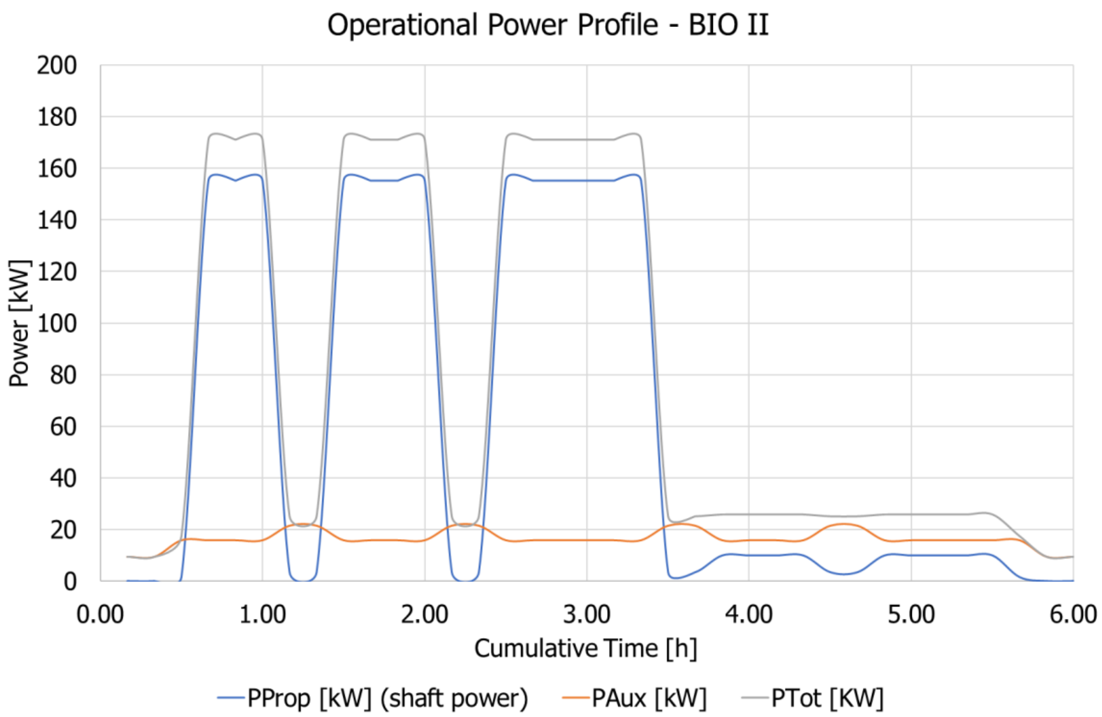

Figure 8-10: Demo 6, BIO II. Performing maintenance of Danube river/waterway marking

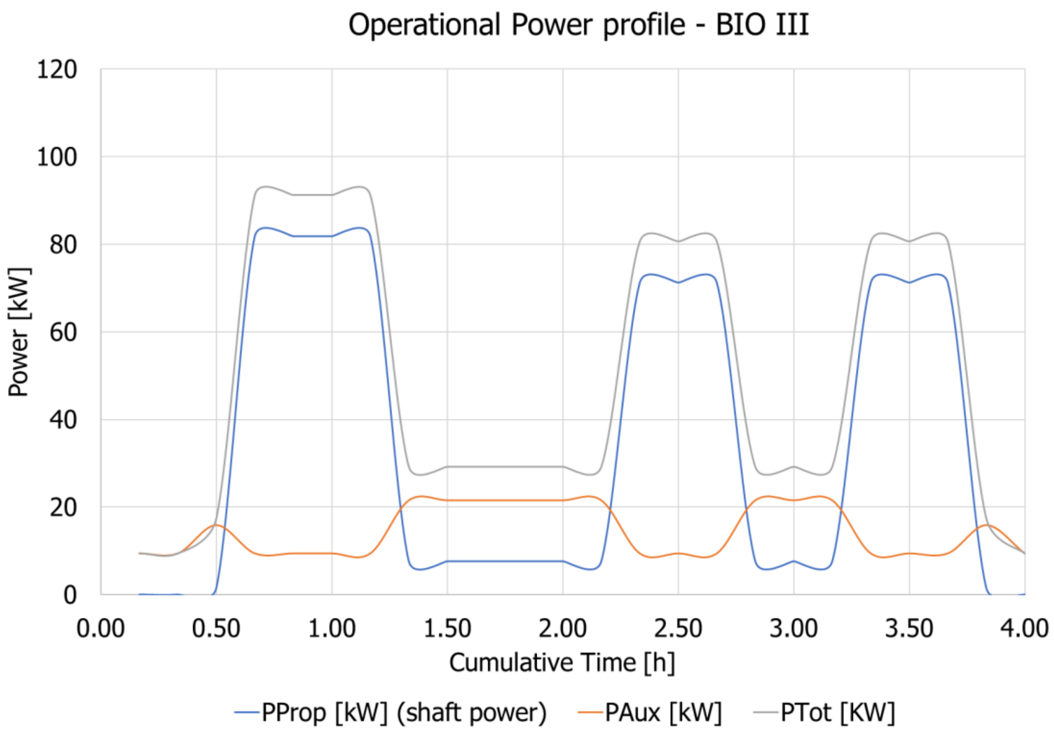

Figure 8-11: Demo 6, BIO III. Performing bathymetric survey

Table 8-3 shows an overview of the operational analysis results. From the table, it can be seen that BIO I, representing a good starting point for the evaluation of the technical and operational capabilities of

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the vessel, allowing for a greater number of possible technology solutions which would fall out of scope in the worst-case scenario (flood event). is the most energy and power demanding BIO.

Table 8-3: Demo 6, overview of the results of the operational analysis.

	BIO I	BIO II	BIO III
Autonomous range [km]	227	36.7	26.2
Endurance [h]	17.3	6	4
Total Energy [kWh]	3486	455	196
Average power [kW]	201.1	75.8	49
Max power [kW]	316.2	171.1	91.3

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8.4 SPEC analysis of Demo 6

8.4.1 Preselection and ranking

The results from the operational analysis and the stakeholders' requirements have been used as inputs for the next step of the analysis. An overview of the inputs used in the preselection can be seen in Table 8-4. The selection of the most suitable/feasible technology is performed using the Ship Power and Energy Concept (SPEC) tool, which, through a weighted multi criteria analysis, allows to assess what solutions (energy carrier + energy converter) are feasible within the reference ship and its operations, and what are their impacts on the design, in terms of weight, volume, efficiency and costs. The stake-holders and users can express influence the results of the analysis by weighing the different criteria based on what is more relevant for them.

Table 8-4: Preselection input Demo 6

Parameter	Value	
Max Effective Power [kW]	500	
Endurance [d]	0.72	
Estimated downtime [%]	57.3	
Expected lifespan [year]	30	
Average power delivered [kW]	201	
Minimum TRL	7	
CO2 price/ton emission [EUR/t]	148[5]	
Zero emission only?	Yes	No X
SRL	3	

For this demonstrator, the diesel-direct case has been used as a benchmark to compare the other solutions.

In Table 8-5 an overview of the ranking can be seen. It should be noted that the base concept of this demonstrator is diesel-direct architecture (concept #52).

Table 8-5: Ranking overview of Demo 6

Concept	Ranking		
	Overall	Technol-ogy & In-vestment	Opera-tions
#16 = Diesel (EN590) CI ICE (hi-speed)	7.4	7.8	7
#4 = Diesel (POME, UCO) CI ICE	9	9	9
#9 = e-CH3OH (CO2 PTS)/Dsl 95/5%vol CI ICE	6.4	6.6	6.2
#19 = e-LNG (CO2 PTS) SI ICE	7.4	7	7.8
#21 = Battery-electric (renewable)	8.1	8.4	7.9
#36 = e-H2 300b ISO LT PEMFC	4.5	2.8	6.2

[5] Source: https://ec.europa.eu/newsroom/cipr/items/722278/, as requested by viadonau

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8.4.2 Results of the SPEC analysis

From the task power time chart developed for BIO I, the power profile from Table 8-6 was developed as input for the SPEC analysis. With the data from the power profile, the time-weighted average power was obtained and then used as input in SPEC to dimension the PPE system.

Table 8-6: Power profile used as input in SPEC for Demo 6.

Type of operation	**Power** [% of max. power]	**Time** [% of endurance time]
Waiting	1.9	8.0
Manoeuvring	3.5	7.0
Navigation upstream high speed	63.2	53.0
Navigation downstream high speed	19.6	33.0
Time-weighted average	**39.96**	

Once the SPEC analysis was carried out, the results presented in Annex A2.6 were obtained for this demonstrator. From these results, the charts presented in Figure 8-12, Figure 8-13, and Figure 8-14 were generated.

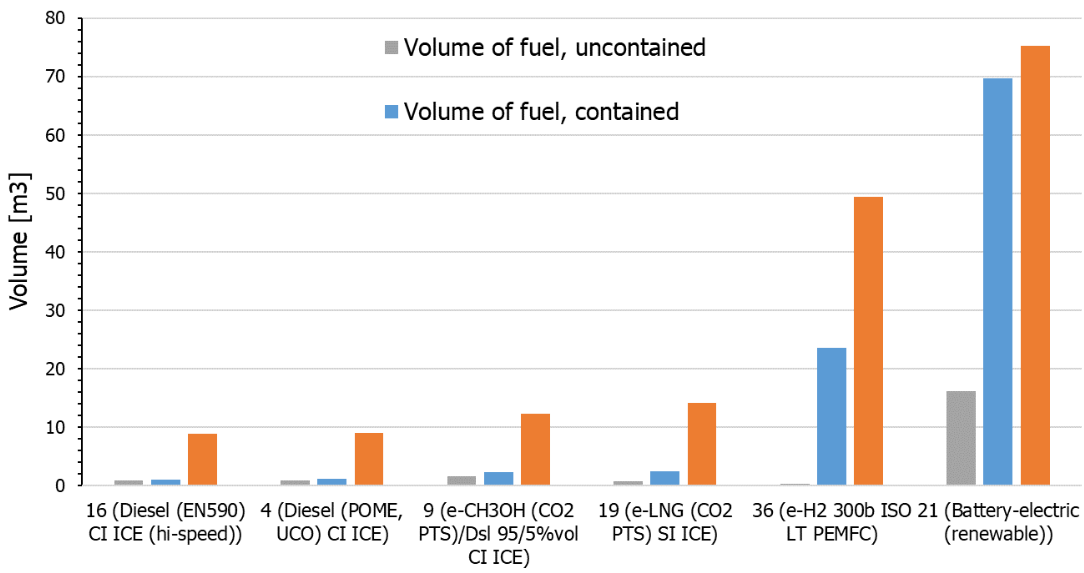

Figure 8-12: Overview of the fuel and systems volume for some concepts resulting from the SPEC analysis of Demo 6.

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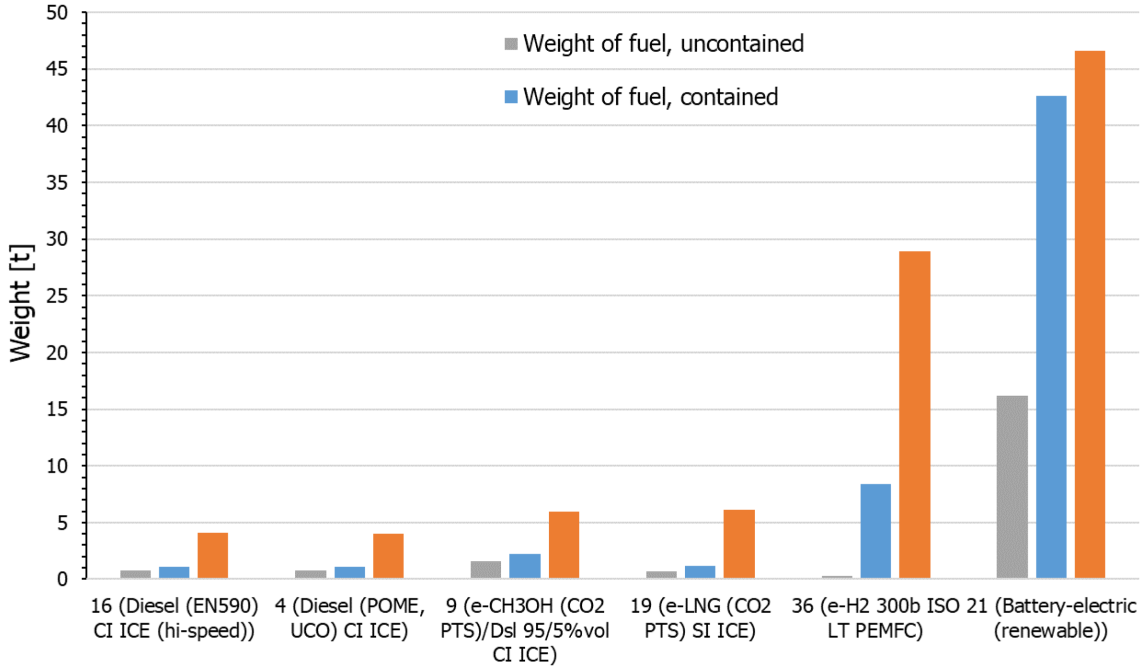

Figure 8-13: Overview of the fuel and systems weight for some concepts resulting from the SPEC analysis of Demo 6.

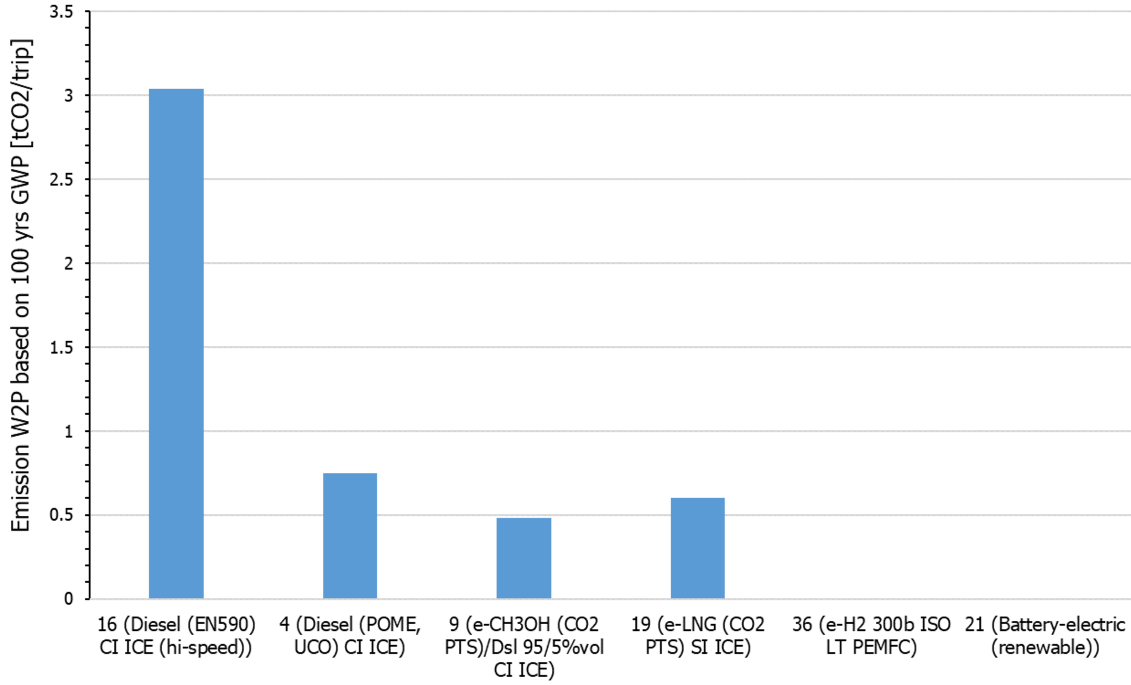

Figure 8-14: Overview of the CO2 equivalent emissions (well to propulsion) per trip for some concepts resulting from the SPEC analysis of Demo 6.

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8.4.3 Conclusions of the SPEC analysis

For the vessel Bad Deutsch Altenburg, operating as described in the operational analysis, the following conclusions summarise the findings of the SPEC analysis:

- The battery-electric and compressed hydrogen concepts (#21 and #36) have the best performance in terms of emissions. The electricity used to charge the batteries and to produce hydrogen is derived from a renewable source. However, these concepts require a very large volume and weight on board, making them less attractive compared to the other concepts. It has to be noted that for the battery concept, the term "uncontained" refers to the volumetric and gravimetric energy densities of the battery cells only, while the term "contained" refers to the volumetric and gravimetric energy densities of the whole battery system, including, for example, the support structure and the support systems of the battery such as cooling and ventilation.

- The methanol concept (#9) results in a reduction of about 80% of the well to propulsion emissions, but it requires approximately twice the volume and weight of fuel compared with the base case, due to the lower energy density (volumetric and gravimetric) of methanol compared to Diesel. In addition, the methanol concept requires about 50% extra weight and volume of the PPE systems with respect to the base concept.

- The e-LNG concept (#19) turns out as an intermediate solution in terms of CO2 equivalent emissions reduction, positioned between the methanol and biodiesel options. It also requires comparable volume and weight relative to these aforementioned concepts.

- The bio-Diesel concept (#4) offers a significant reduction in emissions with respect to the base concept, requiring a similar volume and weight for the fuel.

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9. | Conclusions

Based on the operational and SPEC analyses carried out for the demonstrators in SYNERGETICS, the following conclusions are made:

- The propulsion power and energy (PPE) concepts with battery-electric power are not suitable for vessels with an operational profile with a high energy demand, due to the large volume and weight.

- The bio-Diesel concepts offer a significant reduction in emissions with respect to the base concept, requiring a similar volume and weight for the fuel. However, if the system architecture changes from direct to (bio)diesel-electric, the volume and weight of PPE systems increase significantly.

- Concepts with a battery-electric PPE system display the largest reduction in CO2 emissions when renewable sources are employed to generate the electricity. However, when the source of electricity is not renewable, the CO2 well to propulsion emissions increase significantly, performing worse than other concepts in terms of emissions.

- The battery-electric and compressed hydrogen concepts display the best performance in terms of emissions. It has to be noted that the electricity used to charge the batteries and to produce hydrogen has to be derived from a renewable source. However, these concepts require a very large volume and weight on board, making these concepts less suitable for retrofitting.

- The methanol concepts result in a significant reduction of the well to propulsion CO2 emissions but require approximately the double of volume and weight of fuel compared with the Diesel concept, due to the lower energy density (volumetric and gravimetric) of methanol compared to Diesel. Consequently, the implementation of these concepts may be challenging for a retrofit in ships with limited volume available.

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Annex 1: | Glossary of terms used for the SPEC analysis

Term	Unit	Definition
Average power percentage	%	Percentage of the total power that is used on average within a BIO.
BIO	-	Bunker Independent Operation (sequence of tasks carried out within two consecutive bunkering events)
CO2 price/ton emission	EUR/tCO2	Price per ton of emitted CO2
Emission based on 100 years GWP, W2P/trip	t	CO2 emissions (GWP) from well to propulsion per trip. Emissions of methane
Endurance	day	Total time the vessel can operate for a particular PPE concept and a certain amount of energy carrier
Fuel weight, contained	t	Weight of the energy carrier including the weight of the container required to contain it.
Fuel weight, uncontained	t	Weight of the energy carrier excluding the weight of the container required to contain it.
Generic efficiency	-	Total efficiency between a power consumer and the energy carrier
Lifespan	year	Expected time the vessel will be operative considering the lifespan, downtime
Lifetime emission based on 100 years GWP	t	Global warming potential (GWP) is the heat absorbed by any greenhouse gas in the atmosphere, as a multiple of the heat that would be absorbed by the same mass of carbon dioxide (CO2). GWP is 1 for CO2. For other gases it depends on the gas and the time frame.
Max. effective power	kW	Maximum total power (propulsion, payload, and auxiliary) consumed during the operation of the vessel.
Payload power	kW	Cargo-related auxiliary power
Propulsion power	kW	Power consumed by the propulsors
SPEC systems volume	m^3	Volume of the propulsion system and energy converters
SPEC systems weight	t	Weight of the propulsion system and energy converters
Total cost of ownership	MEUR	Sum of Capital Expenditure (CAPEX) and Operational Expenditure (OPEX)
Volume of fuel, contained	m^3	Volume of the energy carrier including the volume of the container required to contain it.
Volume of fuel, uncontained	m^3	Volume of the energy carrier excluding the volume of the container required to contain it.

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Acronyms used in SPEC

Acronym	Definition
CH3OH	Methanol
CI ICE	Compress Ignited Internal Combustion Engine – Diesel cycle engine.
CNG	Compressed Natural Gas
CO2 DAC	Carbon Dioxide Direct Air Capture
CO2 PTS	Corbon Dioxide Point Source capture - CO_2 sourced from a so-called "point source", where it is present in high concentrations. For instance, at an industrial process outlet.
EN590	EN 590 is a standard published by the European Committee for Standardization that describes the physical and chemical properties that all automotive diesel fuel must meet if it is to be sold in the European Union and several other European countries.
LNG	Liquid Natural Gas
LT PEMFC	Low Temperature Proton Exchange Membrane Fuel Cell
POME	Palm Oil Mill Effluent - is a regenerated blend of crude palm oil and Palm Fatty Acid Distillate (PFAD) after the washing process of the fruits, making this a good alternative to the fossil fuel, using this as a component for bio heating oil or even processing it into a 2nd generation bio diesel.
SI ICE	Spark Ignited Internal Combustion Engine – Otto cycle engine
UCO	Used Cooking Oil

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Annex 2: | Complete results of the SPEC analysis

A2.1. Overview of concepts considered in the SPEC analyses

(TRL ≥ 7 and SRL ≥ 3)

Concept	Description
#4 = Diesel (POME, UCO) CI ICE	Diesel (HVO from UCO, POME) ICE CI 4-stroke high speed (diesel)
#5 = Diesel (20% UCO) CI ICE	Diesel (20% FAME UCO) ICE CI 4-stroke high speed (diesel)
#6 = Diesel (50% UCO/rapeseed) CI ICE	Diesel (20% FAME UCO, 30% HVO rapeseed) ICE CI 4-stroke high speed (diesel)
#8 = e-CH3OH (CO2 PTS)/Dsl 65/35%vol CI ICE	e-CH3OH 65%vol + Diesel 35%vol ICE CH3OH 4-stroke high speed
#9 = e-CH3OH (CO2 PTS)/Dsl 95/5%vol CI ICE	e-CH3OH 95%vol + Diesel 5%vol ICE CH3OH 4-stroke high speed
#10 = e-CH3OH (CO2 PTS) SI ICE	e-CH3OH (renewable electricity + flue gas CO2) ICE CH3OH 4-stroke high speed
#12 = CNG SI ICE	CNG ICE NG SI 4-stroke medium speed
#16 = Diesel (EN590) CI ICE (hi-speed)	Diesel (EN590) ICE CI 4-stroke high speed (diesel)
#19 = e-LNG (CO2 PTS) SI ICE	e-LNG (renewables + flue gas CO2) ICE NG SI 4-stroke high speed
#21 = Battery-electric (renewable)	Electricity (renewable) stored in Li-NMC battery None
#22 = LNG SI ICE	LNG ICE NG SI 4-stroke medium speed
#29 = CH3OH (glycerin) SI ICE	CH3OH (glycerin) ICE CH3OH 4-stroke high speed
#30 = Diesel (palm oil) CI ICE	Diesel (HVO from palm oil) ICE CI 4-stroke high speed (diesel)
#31 = Diesel (soybean oil) CI ICE	Diesel (HVO from soybean oil) ICE CI 4-stroke high speed (diesel)
#35 = e-CH3OH (CO2 DAC) SI ICE	e-CH3OH (Renewable electricity + DAC CO2) ICE CH3OH 4-stroke high speed
#36 = e-H2 300b ISO LT PEMFC	e-CompH2 300 bar in ISO container (Renewable) LT PEMFC
#37 = CH3OH SI ICE	CH3OH (Natural gas) ICE CH3OH 4-stroke high speed
#38 = H2 300b intg. LT PEMFC	CompH2 300 bar (natural gas) LT PEMFC
#40 = Diesel (MGO) CI ICE	Diesel (MGO) ICE CI 4-stroke high speed (diesel)
#41 = LNG DF ICE CI	LNG ICE NG CI/SI 4-stroke medium speed
#44 = e-H2 300b intg. LT PEMFC	e-CompH2 300 bar integrated tanks (Renewable) LT PEMFC
#47 = H2 300b/Dsl 96/4%vol CI ICE	CompH2 300 bar (natural gas) ICE CI DF H2 4-stroke high speed
#48 = Battery-electric (fossil)	Electricity (fossil) stored in Li-NMC battery
#51 = GTL (natural gas) CI ICE	GTL (natural gas) ICE CI 4-stroke high speed (diesel)
#52 = Diesel (EN590) CI ICE (hi-speed) Direct	Diesel (EN590) ICE CI 4-stroke high speed (diesel)

Note: Concepts preceded by 'e-' indicate the resource is obtained using electricity from renewable sources.

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A2.2. Full SPEC output of Demo 2

Table A2.1 SPEC technology & investment ranking of Demo 2

System	Technology & Investment	Cont. energy density on volume, scaled	Cont. energy density on weight, scaled	Capex based on energy, scaled	TRL for energy carrier	SRL	Specific volume of power systems, scaled	Specific weight of power systems, scaled	Capex based on power, scaled	Generic efficiency, scaled	TRL	W2P GHG emission, scaled	Harmful emissions, scaled
#16 = Diesel (EN590) CI ICE (hi-speed)	8.1	8.7	8.6	9	9	5	6.2	4.8	8.2	4.2	9	4.3	1
#4 = Diesel (POME, UCO) CI ICE	9	8.4	9	9	9	5	6.2	4.8	8.2	4.2	9	7.8	1
#5 = Diesel (20% UCO) CI ICE	8.3	9	8.5	9	9	5	6.2	4.8	8.2	4.2	9	5.1	1
#6 = Diesel (50% UCO/rapeseed) CI ICE	8.4	8.4	9	9	9	5	6.2	4.8	8.2	4.2	9	5.8	1
#8 = e-CH3OH (CO2 PTS)/Dsl 65/35%vol CI ICE	5.7	5.8	6.1	9	7	5	5.4	4.3	6.2	4.2	7	6.3	2.6
#9 = e-CH3OH (CO2 PTS)/Dsl 95/5%vol CI ICE	6	4.4	4.9	9	7	7	5.4	4.3	6.2	4.2	7	8.3	2.6
#10 = e-CH3OH (CO2 PTS) SI ICE	7.5	4.1	4.7	9	7	8	7	4.8	7.2	4.4	7	8.6	4.2
#12 = CNG SI ICE	5	2.9	2.1	8.9	8	5	4.8	3	8.6	5	8	5.6	4.2
#19 = e-LNG (CO2 PTS) SI ICE	6.8	4	8.3	9	7	4	4.8	3.8	8.6	4.3	7	8.1	4.2
#21 = Battery-electric (renewable)	8.8	1	1	1	9	6	9	9	9	9	9	9	9
#22 = LNG SI ICE	5.7	4	8.3	9	8	4	2.3	1.9	8.4	5	8	5.8	4.2
#29 = CH3OH (glycerin) SI ICE	6.1	4.1	4.7	9	7	4	7	4.8	7.2	4.4	7	7.1	4.2
#30 = Diesel (palm oil) CI ICE	6.7	8.4	9	9	9	3	6.2	4.8	8.2	4.2	9	1	1
#31 = Diesel (soybean oil) CI ICE	7	8.4	9	9	9	3	6.2	4.8	8.2	4.2	9	2.1	1
#35 = e-CH3OH (CO2 DAC) SI ICE	7.6	4.1	4.7	9	7	8	7	4.8	7.2	4.4	7	8.9	4.2
#36 = e-H2 300b ISO LT PEMFC	2.2	1.3	1.9	8.9	7	4	1	1	1	4.8	7	9	9
#37 = CH3OH SI ICE	5.2	4.1	4.7	9	7	4	7	4.8	7.2	4.4	7	3.9	4.2
#38 = H2 300b intg. LT PEMFC	1	1.4	1.8	8.8	7	4	1	1	1	4.8	7	4.5	9
#40 = Diesel (MGO) CI ICE	8.1	8.9	8.7	9	9	5	6.2	4.8	8.2	4.2	9	4.3	1
#41 = LNG DF ICE CI	4.9	4	8.3	9	8	4	1.3	1.5	7.5	5	8	5.2	4.2
#44 = e-H2 300b intg. LT PEMFC	2.5	1.4	2.7	8.9	7	4	1	1	1	4.8	7	9	9
#47 = H2 300b/Dsl 96/4%vol CI ICE	2.2	1.4	1.8	8.8	7	4	4.9	3.3	6.2	4.6	7	4.2	2.6
#48 = Battery-electric (fossil)	8	1	1	1	9	6	9	9	9	9	9	5.8	9
#51 = GTL (natural gas) CI ICE	7.8	8.2	9	9	9	5	6.2	4.8	8.2	4.2	9	3.6	1

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Table A2.2 SPEC operations ranking of Demo 2

Concept	Operations	Cont. energy density on volume, scaled	Cont. energy density on weight, scaled	Operational expenditure, scaled	Generic efficiency, scaled	Harmful emissions, scaled	W2P CO2 emission, scaled
#16 = Diesel (EN590) CI ICE (hi-speed)	8.4	8.7	8.6	8.5	4.2	1	4.3
#4 = Diesel (POME, UCO) CI ICE	9	8.4	9	6	4.2	1	7.8
#5 = Diesel (20% UCO) CI ICE	7.9	9	8.5	6.6	4.2	1	5.1
#6 = Diesel (50% UCO/rapeseed) CI ICE	8.2	8.4	9	6.8	4.2	1	5.8
#8 = e-CH3OH (CO2 PTS)/Dsl 65/35%vol CI ICE	6.6	5.8	6.1	7.3	4.2	2.6	6.3
#9 = e-CH3OH (CO2 PTS)/Dsl 95/5%vol CI ICE	5.5	4.4	4.9	6.1	4.2	2.6	8.3
#10 = e-CH3OH (CO2 PTS) SI ICE	6.3	4.1	4.7	5.8	4.4	4.2	8.6
#12 = CNG SI ICE	4	2.9	2.1	7.8	5	4.2	5.6
#19 = e-LNG (CO2 PTS) SI ICE	6.7	4	8.3	3.6	4.3	4.2	8.1
#21 = Battery-electric (renewable)	6.5	1	1	3	9	9	9
#22 = LNG SI ICE	9	4	8.3	9	5	4.2	5.8
#29 = CH3OH (glycerin) SI ICE	6.4	4.1	4.7	7.4	4.4	4.2	7.1
#30 = Diesel (palm oil) CI ICE	4.5	8.4	9	5	4.2	1	1
#31 = Diesel (soybean oil) CI ICE	5.3	8.4	9	5.2	4.2	1	2.1
#35 = e-CH3OH (CO2 DAC) SI ICE	3.7	4.1	4.7	1	4.4	4.2	8.9
#36 = e-H2 300b ISO LT PEMFC	4.3	1.3	1.9	2.2	4.8	9	9
#37 = CH3OH SI ICE	4.7	4.1	4.7	7.6	4.4	4.2	3.9
#38 = H2 300b intg. LT PEMFC	4.9	1.4	1.8	8	4.8	9	4.5
#40 = Diesel (MGO) CI ICE	8.5	8.9	8.7	8.5	4.2	1	4.3
#41 = LNG DF ICE CI	8.5	4	8.3	8.9	5	4.2	5.2
#44 = e-H2 300b intg. LT PEMFC	4.8	1.4	2.7	2.2	4.8	9	9
#47 = H2 300b/Dsl 96/4%vol CI ICE	1	1.4	1.8	8	4.6	2.6	4.2
#48 = Battery-electric (fossil)	7.2	1	1	7.4	9	9	5.8
#51 = GTL (natural gas) CI ICE	7.6	8.2	9	8	4.2	1	3.6

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Table A2.3 SPEC output of Demo 2

Concept	16 (Diesel (EN590) CI ICE (hi-speed))	4 (Diesel (POME, UCO) CI ICE)	8 (e-CH3OH (CO2 PTS)/Dsl 65/35%vol CI ICE)	9 (e-CH3OH (CO2 PTS)/Dsl 95/5%vol CI ICE)	19 (e-LNG (CO2 PTS) SI ICE)	21 (Battery-electric (re-newable))	36 (e-H2 300b ISO LT PEMFC)
Endurance [d]	4	4	4	4	4	4	4
DownTime [%]	10	10	10	10	10	10	10
LifeSpan [yr]	25	25	25	25	25	25	25
CO_2 price/ton emission [EUR/t]	73	73	73	73	73	73	73
Average power percentage [%]	55	55	55	55	55	55	55
Max. effective power [kW]	1840	1840	1840	1840	1840	1840	1840
Average power [kW]	1012	1012	1012	1012	1012	1012	1012
Fuel weight, contained [t]	36.6	35	54.7	71	37.8	1199.4	236.7
Fuel weight, uncontained [t]	25.4	24.7	39.4	52.1	22.4	454.5	7.7
Volume of fuel, contained [m^3]	32.7	34	52.8	74.2	81.5	1962.7	662.7
Volume of fuel, uncontained [m^3]	29.2	31.6	47.7	65.2	48	144.9	362.4
SPEC systems weight [t]	46.9	46.9	50.1	50.1	54.2	14.9	75.1
SPEC systems volume [m^3]	46.3	46.3	54.2	54.2	59.7	20.6	94.2
SPEC systems+fuel weight [t]	83.5	81.9	104.8	121	92.1	1214.3	311.8
SPEC systems+fuel volume [m^3]	79.1	80.4	107	128.4	141.2	1983.3	756.8
Cost SPEC systems [MEUR]	2.759	2.759	3.705	3.705	2.566	2.392	6.207
Cost SPEC storage of energy carrier [MEUR]	0.033	0.033	0.042	0.051	0.262	92.886	3.396
Cost SPEC systems+storage [MEUR]	2.793	2.793	3.747	3.756	2.828	95.278	9.603
Generic efficiency [-]	0.32	0.32	0.32	0.32	0.33	0.81	0.38
Required consumable energy/trip [kWh]	301714	301714	300780	300780	298012	119941	257698
Total cost of ownership [MEUR]	42.171	80.664	61.476	80.18	115.731	144.536	125.825
Emission based on 100 yrs GWP, W2P/trip [t]	97.62	24.22	55.49	15.41	19.21	0	0
Emission based on 20 yrs GWP, W2P/trip [t]	97.62	24.22	55.55	15.48	39.64	0	0
Lifetime emission based on 100 yrs GWP [t]	200424	49727	113919	31644	39437	0	0
TRL [ID]	9	9	7	7	7	9	7
SRL [ID]	5	5	5	7	4	6	4

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A2.3. Full SPEC output of Demo 3

Table A2.4 SPEC technology & investment ranking of Demo 3

Concept	Technology & Investment	Cont. energy density on vol-	Cont. energy density on	Capex based on energy,	TRL for energy carrier	SRL	Specific volume of power sys-	Specific weight of power sys-	Capex based on power,	Generic effi-ciency, scaled	TRL	Harmful emis-sions, scaled	W2P GHG emission,
#16 = Diesel (EN590) CI ICE (hi-speed)	8.1	8.7	8.6	9	9	5	6.2	4.8	8.2	4.2	9	1	4.3
#4 = Diesel (POME, UCO) CI ICE	9	8.4	9	9	9	5	6.2	4.8	8.2	4.2	9	1	7.8
#5 = Diesel (20% UCO) CI ICE	8.3	9	8.5	9	9	5	6.2	4.8	8.2	4.2	9	1	5.1
#6 = Diesel (50% UCO/rapeseed) CI ICE	8.4	8.4	9	9	9	5	6.2	4.8	8.2	4.2	9	1	5.8
#8 = e-CH3OH (CO2 PTS)/Dsl 65/35%vol CI ICE	5.7	5.8	6.1	9	7	5	5.4	4.3	6.2	4.2	7	2.6	6.3
#9 = e-CH3OH (CO2 PTS)/Dsl 95/5%vol CI ICE	6	4.4	4.9	9	7	7	5.4	4.3	6.2	4.2	7	2.6	8.3
#10 = e-CH3OH (CO2 PTS) SI ICE	7.5	4.1	4.7	9	7	8	7	4.8	7.2	4.4	7	4.2	8.6
#12 = CNG SI ICE	5	2.9	2.1	8.9	8	5	4.8	3	8.6	5	8	4.2	5.6
#19 = e-LNG (CO2 PTS) SI ICE	6.8	4	8.3	9	7	4	4.8	3.8	8.6	4.3	7	4.2	8.1
#21 = Battery-electric (renewable)	8.8	1	1	1	9	6	9	9	9	9	9	9	9
#22 = LNG SI ICE	5.7	4	8.3	9	8	4	2.3	1.9	8.4	5	8	4.2	5.8
#29 = CH3OH (glycerin) SI ICE	6.1	4.1	4.7	9	7	4	7	4.8	7.2	4.4	7	4.2	7.1
#30 = Diesel (palm oil) CI ICE	6.7	8.4	9	9	9	3	6.2	4.8	8.2	4.2	9	1	1
#31 = Diesel (soybean oil) CI ICE	7	8.4	9	9	9	3	6.2	4.8	8.2	4.2	9	1	2.1
#35 = e-CH3OH (CO2 DAC) SI ICE	7.6	4.1	4.7	9	7	8	7	4.8	7.2	4.4	7	4.2	8.9
#36 = e-H2 300b ISO LT PEMFC	2.2	1.3	1.9	8.9	7	4	1	1	1	4.8	7	9	9
#37 = CH3OH SI ICE	5.2	4.1	4.7	9	7	4	7	4.8	7.2	4.4	7	4.2	3.9
#38 = H2 300b intg. LT PEMFC	1	1.4	1.8	8.8	7	4	1	1	1	4.8	7	9	4.5
#40 = Diesel (MGO) CI ICE	8.1	8.9	8.7	9	9	5	6.2	4.8	8.2	4.2	9	1	4.3
#41 = LNG DF ICE CI	4.9	4	8.3	9	8	4	1.3	1.5	7.5	5	8	4.2	5.2
#44 = e-H2 300b intg. LT PEMFC	2.5	1.4	2.7	8.9	7	4	1	1	1	4.8	7	9	9
#47 = H2 300b/Dsl 96/4%vol CI ICE	2.2	1.4	1.8	8.8	7	4	4.9	3.3	6.2	4.6	7	2.6	4.2
#48 = Battery-electric (fossil)	8	1	1	1	9	6	9	9	9	9	9	9	5.8
#51 = GTL (natural gas) CI ICE	7.8	8.2	9	9	9	5	6.2	4.8	8.2	4.2	9	1	3.6

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Table A2.5 SPEC operations ranking of Demo 3

Concept	Operations	Cont. energy density on volume, scaled	Cont. energy density on weight, scaled	OpEx, scaled	Generic efficiency, scaled	Harmful emissions, scaled	W2P CO2 emission, scaled
#16 = Diesel (EN590) CI ICE (hi-speed)	8.4	8.7	8.6	8.5	4.2	1	4.3
#4 = Diesel (POME, UCO) CI ICE	9	8.4	9	6	4.2	1	7.8
#5 = Diesel (20% UCO) CI ICE	7.9	9	8.5	6.6	4.2	1	5.1
#6 = Diesel (50% UCO/rapeseed) CI ICE	8.2	8.4	9	6.8	4.2	1	5.8
#8 = e-CH3OH (CO2 PTS)/Dsl 65/35%vol CI ICE	6.6	5.8	6.1	7.3	4.2	2.6	6.3
#9 = e-CH3OH (CO2 PTS)/Dsl 95/5%vol CI ICE	5.5	4.4	4.9	6.1	4.2	2.6	8.3
#10 = e-CH3OH (CO2 PTS) SI ICE	6.3	4.1	4.7	5.8	4.4	4.2	8.6
#12 = CNG SI ICE	4	2.9	2.1	7.8	5	4.2	5.6
#19 = e-LNG (CO2 PTS) SI ICE	6.7	4	8.3	3.6	4.3	4.2	8.1
#21 = Battery-electric (renewable)	6.5	1	1	3	9	9	9
#22 = LNG SI ICE	9	4	8.3	9	5	4.2	5.8
#29 = CH3OH (glycerin) SI ICE	6.4	4.1	4.7	7.4	4.4	4.2	7.1
#30 = Diesel (palm oil) CI ICE	4.5	8.4	9	5	4.2	1	1
#31 = Diesel (soybean oil) CI ICE	5.3	8.4	9	5.2	4.2	1	2.1
#35 = e-CH3OH (CO2 DAC) SI ICE	3.7	4.1	4.7	1	4.4	4.2	8.9
#36 = e-H2 300b ISO LT PEMFC	4.3	1.3	1.9	2.2	4.8	9	9
#37 = CH3OH SI ICE	4.7	4.1	4.7	7.6	4.4	4.2	3.9
#38 = H2 300b intg. LT PEMFC	4.9	1.4	1.8	8	4.8	9	4.5
#40 = Diesel (MGO) CI ICE	8.5	8.9	8.7	8.5	4.2	1	4.3
#41 = LNG DF ICE CI	8.5	4	8.3	8.9	5	4.2	5.2
#44 = e-H2 300b intg. LT PEMFC	4.8	1.4	2.7	2.2	4.8	9	9
#47 = H2 300b/Dsl 96/4%vol CI ICE	1	1.4	1.8	8	4.6	2.6	4.2
#48 = Battery-electric (fossil)	7.2	1	1	7.4	9	9	5.8
#51 = GTL (natural gas) CI ICE	7.6	8.2	9	8	4.2	1	3.6

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Table A2.6 SPEC output of Demo 3

Concept	16 (Diesel (EN590) CI ICE (hi-speed))	9 (e-CH3OH (CO2 PTS)/Dsl 95/5%vol CI ICE)	19 (e-LNG (CO2 PTS) SI ICE)	21 (Battery-electric (renew-able))	36 (e-H2 300b ISO LT PEMFC)	48 (Battery-electric (fossil))
Endurance [d]	0.67	0.67	0.67	0.67	0.67	0.67
DownTime [%]	10	10	10	10	10	10
LifeSpan [yr]	25	25	25	25	25	25
CO_2 price/ton emission [EUR/t]	73	73	73	73	73	73
Average power percentage [%]	31.13	31.13	31.13	31.13	31.13	31.13
Max. effective power [kW]	811	811	811	811	811	811
Average power [kW]	252	252	252	252	252	252
Fuel weight, contained [t]	1.5	3	1.6	50.1	9.9	50.1
Fuel weight, uncontained [t]	1.1	2.2	0.9	19	0.3	19
Volume of fuel, contained [m^3]	1.4	3.1	3.4	82	27.7	82
Volume of fuel, uncontained [m^3]	1.2	2.7	2	6.1	15.1	6.1
SPEC systems weight [t]	20.7	22.1	23.9	6.5	33.3	6.5
SPEC systems volume [m^3]	20.4	23.9	26.3	9	42	9
SPEC systems+fuel weight [t]	22.2	25	25.5	56.6	43.2	56.6
SPEC systems+fuel volume [m^3]	21.8	27	29.7	91	69.7	91
Cost SPEC systems [MEUR]	1.216	1.633	1.131	1.054	2.736	1.054
Cost SPEC storage of energy carrier [MEUR]	0.001	0.002	0.011	3.882	0.142	3.882
Cost SPEC systems+storage [MEUR]	1.218	1.635	1.142	4.936	2.878	4.936
Generic efficiency [-]	0.32	0.32	0.33	0.81	0.38	0.81
Required consumable energy/trip [kWh]	12608	12569	12453	5012	10768	5012
Total cost of ownership [MEUR]	11.026	20.677	29.267	17.225	31.924	10.502
Emission based on 100 yrs GWP, W2P/trip [t]	4.07	0.64	0.8	0	0	2.79
Emission based on 20 yrs GWP, W2P/trip [t]	4.07	0.65	1.65	0	0	2.79
TRL [ID]	9	7	7	9	7	9
SRL [ID]	5	7	4	6	4	6

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A2.4. Full SPEC output of Demo 4

Table A2.7 SPEC technology & investment ranking of Demo 4

Concept	Technology & Investment	Cont. energy density on volume, scaled	Cont. energy density on weight, scaled	Capex based on energy, scaled	TRL for energy carrier	SRL	Specific volume of power systems, scaled	Specific weight of power systems, scaled	Capex based on power, scaled	Generic efficiency, scaled	TRL	W2P GHG emission, scaled	Harmful emissions, scaled
#16 = Diesel (EN590) CI ICE (hi-speed)	2.5	8.7	8.6	9	9	5	6.2	4.8	8.2	4.2	9	4.3	1
#4 = Diesel (POME, UCO) CI ICE	4.1	8.4	9	9	9	5	6.2	4.8	8.2	4.2	9	7.8	1
#5 = Diesel (20% UCO) CI ICE	2.8	9	8.5	9	9	5	6.2	4.8	8.2	4.2	9	5.1	1
#6 = Diesel (50% UCO/rapeseed) CI ICE	3.1	8.4	9	9	9	5	6.2	4.8	8.2	4.2	9	5.8	1
#8 = e-CH3OH (CO2 PTS)/Dsl 65/35%vol CI ICE	3.2	5.8	6.1	9	7	5	5.4	4.3	6.2	4.2	7	6.3	2.6
#9 = e-CH3OH (CO2 PTS)/Dsl 95/5%vol CI ICE	4	4.4	4.9	9	7	7	5.4	4.3	6.2	4.2	7	8.3	2.6
#10 = e-CH3OH (CO2 PTS) SI ICE	5.8	4.1	4.7	9	7	8	7	4.8	7.2	4.4	7	8.6	4.2
#12 = CNG SI ICE	3.8	2.9	2.1	8.9	8	5	4.8	3	8.6	5	8	5.6	4.2
#19 = e-LNG (CO2 PTS) SI ICE	5.1	4	8.3	9	7	4	4.8	3.8	8.6	4.3	7	8.1	4.2
#21 = Battery-electric (renewable)	9	1	1	1	9	6	9	9	9	9	9	9	9
#22 = LNG SI ICE	2.8	4	8.3	9	8	4	2.3	1.9	8.4	5	8	5.8	4.2
#29 = CH3OH (glycerin) SI ICE	5.1	4.1	4.7	9	7	4	7	4.8	7.2	4.4	7	7.1	4.2
#30 = Diesel (palm oil) CI ICE	1	8.4	9	9	9	3	6.2	4.8	8.2	4.2	9	1	1
#31 = Diesel (soybean oil) CI ICE	1.5	8.4	9	9	9	3	6.2	4.8	8.2	4.2	9	2.1	1
#35 = e-CH3OH (CO2 DAC) SI ICE	5.9	4.1	4.7	9	7	8	7	4.8	7.2	4.4	7	8.9	4.2
#36 = e-H2 300b ISO LT PEMFC	3.5	1.3	1.9	8.9	7	4	1	1	1	4.8	7	9	9
#37 = CH3OH SI ICE	3.7	4.1	4.7	9	7	4	7	4.8	7.2	4.4	7	3.9	4.2
#38 = H2 300b intg. LT PEMFC	1.5	1.4	1.8	8.8	7	4	1	1	1	4.8	7	4.5	9
#40 = Diesel (MGO) CI ICE	2.5	8.9	8.7	9	9	5	6.2	4.8	8.2	4.2	9	4.3	1
#41 = LNG DF ICE CI	1.9	4	8.3	9	8	4	1.3	1.5	7.5	5	8	5.2	4.2
#44 = e-H2 300b intg. LT PEMFC	3.5	1.4	2.7	8.9	7	4	1	1	1	4.8	7	9	9
#47 = H2 300b/Dsl 96/4%vol CI ICE	1.8	1.4	1.8	8.8	7	4	4.9	3.3	6.2	4.6	7	4.2	2.6
#48 = Battery-electric (fossil)	7.6	1	1	1	9	6	9	9	9	9	9	5.8	9
#51 = GTL (natural gas) CI ICE	2.2	8.2	9	9	9	5	6.2	4.8	8.2	4.2	9	3.6	1

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Table A2.8 SPEC operations ranking of Demo 4

Concept	Operations	Cont. energy density on volume, scaled	Cont. energy density on weight, scaled	OpEx, scaled	Generic efficiency, scaled	Harmful emissions, scaled	W2P CO2 emission, scaled
#16 = Diesel (EN590) CI ICE (hi-speed)	5.6	8.7	8.6	8.5	4.2	1	4.3
#4 = Diesel (POME, UCO) CI ICE	6.8	8.4	9	6	4.2	1	7.8
#5 = Diesel (20% UCO) CI ICE	5.1	9	8.5	6.6	4.2	1	5.1
#6 = Diesel (50% UCO/rapeseed) CI ICE	5.7	8.4	9	6.8	4.2	1	5.8
#8 = e-CH3OH (CO2 PTS)/Dsl 65/35%vol CI ICE	6	5.8	6.1	7.3	4.2	2.6	6.3
#9 = e-CH3OH (CO2 PTS)/Dsl 95/5%vol CI ICE	5.9	4.4	4.9	6.1	4.2	2.6	8.3
#10 = e-CH3OH (CO2 PTS) SI ICE	7.1	4.1	4.7	5.8	4.4	4.2	8.6
#12 = CNG SI ICE	5.1	2.9	2.1	7.8	5	4.2	5.6
#19 = e-LNG (CO2 PTS) SI ICE	6.5	4	8.3	3.6	4.3	4.2	8.1
#21 = Battery-electric (renewable)	8.8	1	1	3	9	9	9
#22 = LNG SI ICE	8.2	4	8.3	9	5	4.2	5.8
#29 = CH3OH (glycerin) SI ICE	7	4.1	4.7	7.4	4.4	4.2	7.1
#30 = Diesel (palm oil) CI ICE	1	8.4	9	5	4.2	1	1
#31 = Diesel (soybean oil) CI ICE	2	8.4	9	5.2	4.2	1	2.1
#35 = e-CH3OH (CO2 DAC) SI ICE	4.4	4.1	4.7	1	4.4	4.2	8.9
#36 = e-H2 300b ISO LT PEMFC	7.4	1.3	1.9	2.2	4.8	9	9
#37 = CH3OH SI ICE	4.7	4.1	4.7	7.6	4.4	4.2	3.9
#38 = H2 300b intg. LT PEMFC	7.4	1.4	1.8	8	4.8	9	4.5
#40 = Diesel (MGO) CI ICE	5.7	8.9	8.7	8.5	4.2	1	4.3
#41 = LNG DF ICE CI	7.7	4	8.3	8.9	5	4.2	5.2
#44 = e-H2 300b intg. LT PEMFC	7.6	1.4	2.7	2.2	4.8	9	9
#47 = H2 300b/Dsl 96/4%vol CI ICE	2.2	1.4	1.8	8	4.6	2.6	4.2
#48 = Battery-electric (fossil)	9	1	1	7.4	9	9	5.8
#51 = GTL (natural gas) CI ICE	4.7	8.2	9	8	4.2	1	3.6

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Table A2.9 SPEC output of Demo 4

Concept	16 (Diesel (EN590) CI ICE (hi-speed))	9 (e-CH3OH (CO2 PTS)/Dsl 95/5%vol CI ICE)	19 (e-LNG (CO2 PTS) SI ICE)	21 (Battery-electric (re-newable))	36 (e-H2 300b ISO LT PEMFC)	48 (Battery-electric (fos-sil))
Endurance [d]	1.17	1.17	1.17	1.17	1.17	1.17
DownTime [%]	30	30	30	30	30	30
LifeSpan [yr]	25	25	25	25	25	25
CO_2 price/ton emission [EUR/t]	73	73	73	73	73	73
Average power percentage [%]	25.61	25.61	25.61	25.61	25.61	25.61
Max. effective power [kW]	300	300	300	300	300	300
Average power [kW]	77	77	77	77	77	77
Fuel weight, contained [t]	0.8	1.6	0.8	26.6	5.3	26.6
Fuel weight, uncontained [t]	0.6	1.2	0.5	10.1	0.2	10.1
Volume of fuel, contained [m^3]	0.7	1.6	1.8	43.6	14.7	43.6
Volume of fuel, uncontained [m^3]	0.6	1.4	1.1	3.2	8	3.2
SPEC systems weight [t]	7.7	8.2	8.9	2.4	12.3	2.4
SPEC systems volume [m^3]	7.6	8.8	9.7	3.3	15.5	3.3
SPEC systems+fuel weight [t]	8.5	9.7	9.7	29	17.6	29
SPEC systems+fuel volume [m^3]	8.3	10.5	11.6	46.9	30.2	46.9
Cost SPEC systems [MEUR]	0.45	0.604	0.418	0.39	1.012	0.39
Cost SPEC storage of energy carrier [MEUR]	0.001	0.001	0.006	2.062	0.075	2.062
Cost SPEC systems+storage [MEUR]	0.451	0.605	0.424	2.452	1.087	2.452
Generic efficiency [-]	0.32	0.32	0.33	0.81	0.38	0.81
Required consumable energy/trip [kWh]	6700	6679	6618	2663	5723	2663
Total cost of ownership [MEUR]	2.775	5.116	7.089	5.36	7.952	3.769
Emission based on 100 yrs GWP, W2P/trip [t]	2.17	0.34	0.43	0	0	1.48
Emission based on 20 yrs GWP, W2P/trip [t]	2.17	0.34	0.88	0	0	1.48
Lifetime emission based on 100 yrs GWP [t]	11831	1868	2328	0	0	8084
TRL [ID]	9	7	7	9	7	9
SRL [ID]	5	7	4	6	4	6

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A2.5. Full SPEC output of Demo 5

Table A2.10 SPEC technology & investment ranking of Demo 5

Concept	Technology & Investment	Cont. energy density on volume, scaled	Cont. energy density on weight, scaled	Capex based on energy, scaled	TRL for energy carrier	SRL	Specific volume of power systems, scaled	Specific weight of power systems, scaled	Capex based on power, scaled	Generic efficiency, scaled	TRL	W2P GHG emission, scaled	Harmful emissions, scaled
#52 = Diesel (EN590) CI ICE (hi-speed) Direct	9	8.7	8.6	9	9	5	8.1	9	9	4.7	9	4.9	1
#4 = Diesel (POME, UCO) CI ICE	7.6	8.4	9	9	9	5	6.2	4.5	6.8	4.2	9	7.8	1
#5 = Diesel (20% UCO) CI ICE	7	9	8.5	9	9	5	6.2	4.5	6.8	4.2	9	5.1	1
#6 = Diesel (50% UCO/rapeseed) CI ICE	7.1	8.4	9	9	9	5	6.2	4.5	6.8	4.2	9	5.8	1
#8 = e-CH3OH (CO2 PTS)/Dsl 65/35%vol CI ICE	4.8	5.8	6.1	9	7	5	5.4	4.1	5.2	4.2	7	6.3	2.6
#9 = e-CH3OH (CO2 PTS)/Dsl 95/5%vol CI ICE	5.1	4.4	4.9	9	7	7	5.4	4.1	5.2	4.2	7	8.3	2.6
#10 = e-CH3OH (CO2 PTS) SI ICE	6.4	4.1	4.7	9	7	8	7	4.6	6	4.4	7	8.6	4.2
#12 = CNG SI ICE	4.1	2.9	2.1	8.9	8	5	4.8	2.9	7.1	5	8	5.6	4.2
#16 = Diesel (EN590) CI ICE (hi-speed)	6.8	8.7	8.6	9	9	5	6.2	4.5	6.8	4.2	9	4.3	1
#19 = e-LNG (CO2 PTS) SI ICE	5.7	4	8.3	9	7	4	4.8	3.6	7.2	4.3	7	8.1	4.2
#21 = Battery-electric (renewable)	7.4	1	1	1	9	6	9	8.5	7.4	9	9	9	9
#22 = LNG SI ICE	4.8	4	8.3	9	8	4	2.3	1.8	7	5	8	5.8	4.2
#29 = CH3OH (glycerin) SI ICE	5.1	4.1	4.7	9	7	4	7	4.6	6	4.4	7	7.1	4.2
#30 = Diesel (palm oil) CI ICE	5.6	8.4	9	9	9	3	6.2	4.5	6.8	4.2	9	1	1
#31 = Diesel (soybean oil) CI ICE	5.8	8.4	9	9	9	3	6.2	4.5	6.8	4.2	9	2.1	1
#35 = e-CH3OH (CO2 DAC) SI ICE	6.4	4.1	4.7	9	7	8	7	4.6	6	4.4	7	8.9	4.2
#36 = e-H2 300b ISO LT PEMFC	2.1	1.3	1.9	8.9	7	4	1	1	1	4.8	7	9	9
#37 = CH3OH SI ICE	4.4	4.1	4.7	9	7	4	7	4.6	6	4.4	7	3.9	4.2
#38 = H2 300b intg. LT PEMFC	1	1.4	1.8	8.8	7	4	1	1	1	4.8	7	4.5	9
#40 = Diesel (MGO) CI ICE	6.9	8.9	8.7	9	9	5	6.2	4.5	6.8	4.2	9	4.3	1
#41 = LNG DF ICE CI	4.1	4	8.3	9	8	4	1.3	1.5	6.2	5	8	5.2	4.2
#44 = e-H2 300b intg. LT PEMFC	2.3	1.4	2.7	8.9	7	4	1	1	1	4.8	7	9	9
#47 = H2 300b/Dsl 96/4%vol CI ICE	1.8	1.4	1.8	8.8	7	4	4.9	3.2	5.2	4.6	7	4.2	2.6
#48 = Battery-electric (fossil)	6.7	1	1	1	9	6	9	8.5	7.4	9	9	5.8	9
#51 = GTL (natural gas) CI ICE	6.6	8.2	9	9	9	5	6.2	4.5	6.8	4.2	9	3.6	1

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Table A2.11 SPEC operations ranking of Demo 5

Concept	Operations	Cont. energy density on volume, scaled	Cont. energy density on weight, scaled	OpEx, scaled	Generic efficiency, scaled	Harmful emissions, scaled	W2P CO2 emission, scaled
#52 = Diesel (EN590) CI ICE (hi-speed) Direct	9	8.7	8.6	8.5	4.7	1	4.9
#4 = Diesel (POME, UCO) CI ICE	9	8.4	9	6	4.2	1	7.8
#5 = Diesel (20% UCO) CI ICE	7.9	9	8.5	6.6	4.2	1	5.1
#6 = Diesel (50% UCO/rapeseed) CI ICE	8.2	8.4	9	6.8	4.2	1	5.8
#8 = e-CH3OH (CO2 PTS)/Dsl 65/35%vol CI ICE	6.6	5.8	6.1	7.3	4.2	2.6	6.3
#9 = e-CH3OH (CO2 PTS)/Dsl 95/5%vol CI ICE	5.5	4.4	4.9	6.1	4.2	2.6	8.3
#10 = e-CH3OH (CO2 PTS) SI ICE	6.3	4.1	4.7	5.8	4.4	4.2	8.6
#12 = CNG SI ICE	4	2.9	2.1	7.8	5	4.2	5.6
#16 = Diesel (EN590) CI ICE (hi-speed)	8.4	8.7	8.6	8.5	4.2	1	4.3
#19 = e-LNG (CO2 PTS) SI ICE	6.7	4	8.3	3.6	4.3	4.2	8.1
#21 = Battery-electric (renewable)	6.5	1	1	3	9	9	9
#22 = LNG SI ICE	9	4	8.3	9	5	4.2	5.8
#29 = CH3OH (glycerin) SI ICE	6.4	4.1	4.7	7.4	4.4	4.2	7.1
#30 = Diesel (palm oil) CI ICE	4.5	8.4	9	5	4.2	1	1
#31 = Diesel (soybean oil) CI ICE	5.3	8.4	9	5.2	4.2	1	2.1
#35 = e-CH3OH (CO2 DAC) SI ICE	3.7	4.1	4.7	1	4.4	4.2	8.9
#36 = e-H2 300b ISO LT PEMFC	4.3	1.3	1.9	2.2	4.8	9	9
#37 = CH3OH SI ICE	4.7	4.1	4.7	7.6	4.4	4.2	3.9
#38 = H2 300b intg. LT PEMFC	4.9	1.4	1.8	8	4.8	9	4.5
#40 = Diesel (MGO) CI ICE	8.5	8.9	8.7	8.5	4.2	1	4.3
#41 = LNG DF ICE CI	8.5	4	8.3	8.9	5	4.2	5.2
#44 = e-H2 300b intg. LT PEMFC	4.8	1.4	2.7	2.2	4.8	9	9
#47 = H2 300b/Dsl 96/4%vol CI ICE	1	1.4	1.8	8	4.6	2.6	4.2
#48 = Battery-electric (fossil)	7.2	1	1	7.4	9	9	5.8
#51 = GTL (natural gas) CI ICE	7.6	8.2	9	8	4.2	1	3.6

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Table A2.12 SPEC output of Demo 5

Concept	52 (Diesel (EN590) CI ICE (hi-speed) Direct)	4 (Diesel (POME, UCO) CI ICE)	8 (e-CH3OH (CO2 PTS)/Dsl 65/35%vol CI ICE)	10 (e-CH3OH (CO2 PTS) SI ICE)	21 (Battery-electric (re-newable))	36 (e-H2 300b ISO LT PEMFC)
Endurance [d]	5.01	5.01	5.01	5.01	5.01	5.01
DownTime [%]	10	10	10	10	10	10
LifeSpan [yr]	25	25	25	25	25	25
CO_2 price/ton emission [EUR/t]	73	73	73	73	73	73
Average power percentage [%]	38.47	38.47	38.47	38.47	38.47	38.47
Max. effective power [kW]	692	692	692	692	692	692
Average power [kW]	266	266	266	266	266	266
Fuel weight, contained [t]	10.6	11.5	18	23.6	395.2	78
Fuel weight, uncontained [t]	7.3	8.1	13	17.4	149.8	2.6
Volume of fuel, contained [m^3]	9.4	11.2	17.4	25.2	646.7	218.3
Volume of fuel, uncontained [m^3]	8.4	10.4	15.7	22	47.7	119.4
SPEC systems weight [t]	4.1	17.7	18.9	17.5	6	28.2
SPEC systems volume [m^3]	11	17.4	20.4	14.8	8.4	35.3
SPEC systems+fuel weight [t]	14.6	29.2	36.9	41.1	401.1	106.2
SPEC systems+fuel volume [m^3]	20.4	28.7	37.8	40	655	253.6
Cost SPEC systems [MEUR]	0.553	1.038	1.393	1.23	0.9	2.334
Cost SPEC storage of energy carrier [MEUR]	0.01	0.011	0.014	0.017	30.632	1.118
Cost SPEC systems+storage [MEUR]	0.563	1.049	1.407	1.247	31.532	3.452
Generic efficiency [-]	0.37	0.32	0.32	0.34	0.81	0.38
Required consumable energy/trip [kWh]	86982	99408	99100	95266	39518	84906
Total cost of ownership [MEUR]	9.627	21.555	16.607	21.887	44.501	33.993
Emission based on 100 yrs GWP, W2P/trip [t]	28.14	7.99	18.3	2.64	0	0
Emission based on 20 yrs GWP, W2P/trip [t]	28.14	7.99	18.32	2.66	0	0
Lifetime emission based on 100 yrs GWP [t]	46135	13095	29994	4324	0	0
TRL [ID]	9	9	7	7	9	7
SRL [ID]	5	5	5	8	6	4

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A2.6. Full SPEC output of Demo 6

Table A2.13 SPEC technology & investment ranking of Demo 6

Concept	Technology & Investment	Cont. energy density on volume, scaled	Cont. energy density on weight, scaled	Capex based on energy, scaled	TRL for energy carrier	SRL	Specific volume of power systems, scaled	Specific weight of power systems, scaled	Capex based on power, scaled	Generic efficiency, scaled	TRL	W2P GHG emission, scaled	Harmful emissions, scaled
#16 = Diesel (EN590) CI ICE (hi-speed)	7.8	8.7	8.6	9	9	5	8.1	9	8.7	4.7	9	4.3	1
#4 = Diesel (POME, UCO) CI ICE	9	8.4	9	9	9	5	8.1	9	8.7	4.7	9	7.8	1
#5 = Diesel (20% UCO) CI ICE	8.1	9	8.5	9	9	5	8.1	9	8.7	4.7	9	5.1	1
#6 = Diesel (50% UCO/rapeseed) CI ICE	8.3	8.4	9	9	9	5	8.1	9	8.7	4.7	9	5.8	1
#8 = e-CH3OH (CO2 PTS)/Dsl 65/35%vol CI ICE	6.1	5.8	6.1	9	7	5	7.2	8.6	7.2	4.7	7	6.3	2.6
#9 = e-CH3OH (CO2 PTS)/Dsl 95/5%vol CI ICE	6.6	4.4	4.9	9	7	7	7.2	8.6	7.2	4.7	7	8.3	2.6
#10 = e-CH3OH (CO2 PTS) SI ICE	7.9	4.1	4.7	9	7	8	8.8	9	7.9	4.8	7	8.6	4.2
#12 = CNG SI ICE	5.3	2.9	2.1	8.9	8	5	6.6	7.3	9	5.6	8	5.6	4.2
#19 = e-LNG (CO2 PTS) SI ICE	7	4	8.3	9	7	4	6.6	8	9	4.7	7	8.1	4.2
#21 = Battery-electric (renewable)	8.4	1	1	1	9	6	9	8.5	7.2	9	9	9	9
#22 = LNG SI ICE	6	4	8.3	9	8	4	4.2	6.2	8.8	5.6	8	5.8	4.2
#29 = CH3OH (glycerin) SI ICE	6.5	4.1	4.7	9	7	4	8.8	9	7.9	4.8	7	7.1	4.2
#30 = Diesel (palm oil) CI ICE	6.2	8.4	9	9	9	3	8.1	9	8.7	4.7	9	1	1
#31 = Diesel (soybean oil) CI ICE	6.6	8.4	9	9	9	3	8.1	9	8.7	4.7	9	2.1	1
#35 = e-CH3OH (CO2 DAC) SI ICE	8	4.1	4.7	9	7	8	8.8	9	7.9	4.8	7	8.9	4.2
#36 = e-H2 300b ISO LT PEMFC	2.8	1.3	1.9	8.9	7	4	1	1	1	4.8	7	9	9
#37 = CH3OH SI ICE	5.4	4.1	4.7	9	7	4	8.8	9	7.9	4.8	7	3.9	4.2
#38 = H2 300b intg. LT PEMFC	1	1.4	1.8	8.8	7	4	1	1	1	4.8	7	3.8	9
#40 = Diesel (MGO) CI ICE	7.9	8.9	8.7	9	9	5	8.1	9	8.7	4.7	9	4.3	1
#41 = LNG DF ICE CI	5.4	4	8.3	9	8	4	3.2	5.9	8.1	5.5	8	5.2	4.2
#44 = e-H2 300b intg. LT PEMFC	3	1.4	2.7	8.9	7	4	1	1	1	4.8	7	9	9
#47 = H2 300b/Dsl 96/4%vol CI ICE	2.9	1.4	1.8	8.8	7	4	6.8	7.6	7.1	5	7	4.2	2.6
#48 = Battery-electric (fossil)	7.2	1	1	1	9	6	9	8.5	7.2	9	9	5.4	9
#51 = GTL (natural gas) CI ICE	7.5	8.2	9	9	9	5	8.1	9	8.7	4.7	9	3.6	1

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Table A2.14 SPEC operations ranking of Demo 6

Concept	Operations	Cont. energy density on volume, scaled	Cont. energy density on weight, scaled	OpEx, scaled	Generic efficiency, scaled	Harmful emissions, scaled	W2P CO2 emission, scaled
#16 = Diesel (EN590) CI ICE (hi-speed)	7	8.7	8.6	8.3	4.7	1	4.3
#4 = Diesel (POME, UCO) CI ICE	9	8.4	9	6.3	4.7	1	7.8
#5 = Diesel (20% UCO) CI ICE	7.2	9	8.5	6.4	4.7	1	5.1
#6 = Diesel (50% UCO/rapeseed) CI ICE	7.7	8.4	9	6.7	4.7	1	5.8
#8 = e-CH3OH (CO2 PTS)/Dsl 65/35%vol CI ICE	6.4	5.8	6.1	7.4	4.7	2.6	6.3
#9 = e-CH3OH (CO2 PTS)/Dsl 95/5%vol CI ICE	6.2	4.4	4.9	6.5	4.7	2.6	8.3
#10 = e-CH3OH (CO2 PTS) SI ICE	7.1	4.1	4.7	6.2	4.8	4.2	8.6
#12 = CNG SI ICE	4	2.9	2.1	7.6	5.6	4.2	5.6
#19 = e-LNG (CO2 PTS) SI ICE	7.8	4	8.3	3.7	4.7	4.2	8.1
#21 = Battery-electric (renewable)	7.9	1	1	3.3	9	9	9
#22 = LNG SI ICE	7.9	4	8.3	9	5.6	4.2	5.8
#29 = CH3OH (glycerin) SI ICE	6.4	4.1	4.7	7.7	4.8	4.2	7.1
#30 = Diesel (palm oil) CI ICE	3.8	8.4	9	3.6	4.7	1	1
#31 = Diesel (soybean oil) CI ICE	4.6	8.4	9	4.1	4.7	1	2.1
#35 = e-CH3OH (CO2 DAC) SI ICE	6.1	4.1	4.7	1	4.8	4.2	8.9
#36 = e-H2 300b ISO LT PEMFC	6.2	1.3	1.9	2.4	4.8	9	9
#37 = CH3OH SI ICE	4.1	4.1	4.7	7.1	4.8	4.2	3.9
#38 = H2 300b intg. LT PEMFC	3.8	1.4	1.8	7.5	4.8	9	3.8
#40 = Diesel (MGO) CI ICE	7.2	8.9	8.7	8.3	4.7	1	4.3
#41 = LNG DF ICE CI	7.3	4	8.3	8.7	5.5	4.2	5.2
#44 = e-H2 300b intg. LT PEMFC	6.6	1.4	2.7	2.4	4.8	9	9
#47 = H2 300b/Dsl 96/4%vol CI ICE	1	1.4	1.8	7.5	5	2.6	4.2
#48 = Battery-electric (fossil)	6.1	1	1	6.3	9	9	5.4
#51 = GTL (natural gas) CI ICE	6.3	8.2	9	7.5	4.7	1	3.6

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Table A2.15 SPEC output of Demo 6

Concept	16 (Diesel (EN590) CI ICE (hi-speed))	4 (Diesel (POME, UCO) CI ICE)	9 (e-CH3OH (CO2 PTS)/Dsl 95/5%vol CI ICE)	19 (e-LNG (CO2 PTS) SI ICE)	36 (e-H2 300b ISO LT PEMFC)	21 (Battery-electric (re-newable))
Endurance [d]	0.72	0.72	0.72	0.72	0.72	0.72
DownTime [%]	57	57	57	57	57	57
LifeSpan [yr]	30	30	30	30	30	30
CO_2 price/ton emission [EUR/t]	148	148	148	148	148	148
Average power percentage [%]	39.96	39.96	39.96	39.96	39.96	39.96
Max. effective power [kW]	500	500	500	500	500	500
Average power [kW]	200	200	200	200	200	200
Fuel weight, contained [t]	1.1	1.1	2.2	1.2	8.4	42.6
Fuel weight, uncontained [t]	0.8	0.8	1.6	0.7	0.3	16.2
Volume of fuel, contained [m^3]	1	1.1	2.3	2.5	23.5	69.7
Volume of fuel, uncontained [m^3]	0.9	1	2	1.5	12.9	5.1
SPEC systems weight [t]	3	3	3.8	5	20.5	4
SPEC systems volume [m^3]	7.9	7.9	10	11.5	25.9	5.5
SPEC systems+fuel weight [t]	4.1	4	6	6.1	28.9	46.6
SPEC systems+fuel volume [m^3]	8.9	9	12.3	14.1	49.4	75.3
Cost SPEC systems [MEUR]	0.4	0.4	0.657	0.347	1.687	0.65
Cost SPEC storage of energy carrier [MEUR]	0.001	0.001	0.002	0.008	0.121	3.3
Cost SPEC systems+storage [MEUR]	0.401	0.401	0.658	0.356	1.807	3.95
Generic efficiency [-]	0.37	0.37	0.37	0.37	0.38	0.81
Required consumable energy/trip [kWh]	9382	9382	9356	9281	9158	4262
Total cost of ownership [MEUR]	5.797	8.493	8.476	11.841	14.967	9.524
Emission based on 100 yrs GWP, W2P/trip [t]	3.04	0.75	0.48	0.6	0	0
Emission based on 20 yrs GWP, W2P/trip [t]	3.04	0.75	0.48	1.23	0	0
Lifetime emission based on 100 yrs GWP [t]	19875	4931	3139	3909	0	0
TRL [ID]	9	9	7	7	7	9
SRL [ID]	5	5	7	4	4	6

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