BETTER SHIPS, BLUE OCEANS

# ZERO JIP: WP1 Specification and Exploration

## Operational, System and SPEC Analysis

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# ZERO JIP: WP1 Specification and Exploration

## Operational, System and SPEC Analysis

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| Version | Date | Version description |
|---|---|---|
| 0.1-0.9 | November 2021 | Initial draft versions to summarise WP1 results, checked internally |
| 1.0 | December 2021 | Draft version WP1 sent to ZERO participants and stakeholders |
| 1.1 | January 2022 | Small updates made and typos corrected |
| 1.2 | March 2022 | Resulting PPE system overview specifications give per Use Case |
| 1.6 | August 2022 | Reviewed and final version |
| 1.61 | November 2022 | Small updates in Mission Requirements Use Cases 3, 4, 5, 6. No effect on results. |

## CONTENTS PAGE

# REVIEW OF REPORTS

## Deliverables of the current project phase[1]

| Item | Title | Date |
|---|---|---|
| MARIN report No. 32697-1-SHIPS | ZERO JIP: WP1 Specification and Exploration | August 2022 |

1 At the moment of writing.

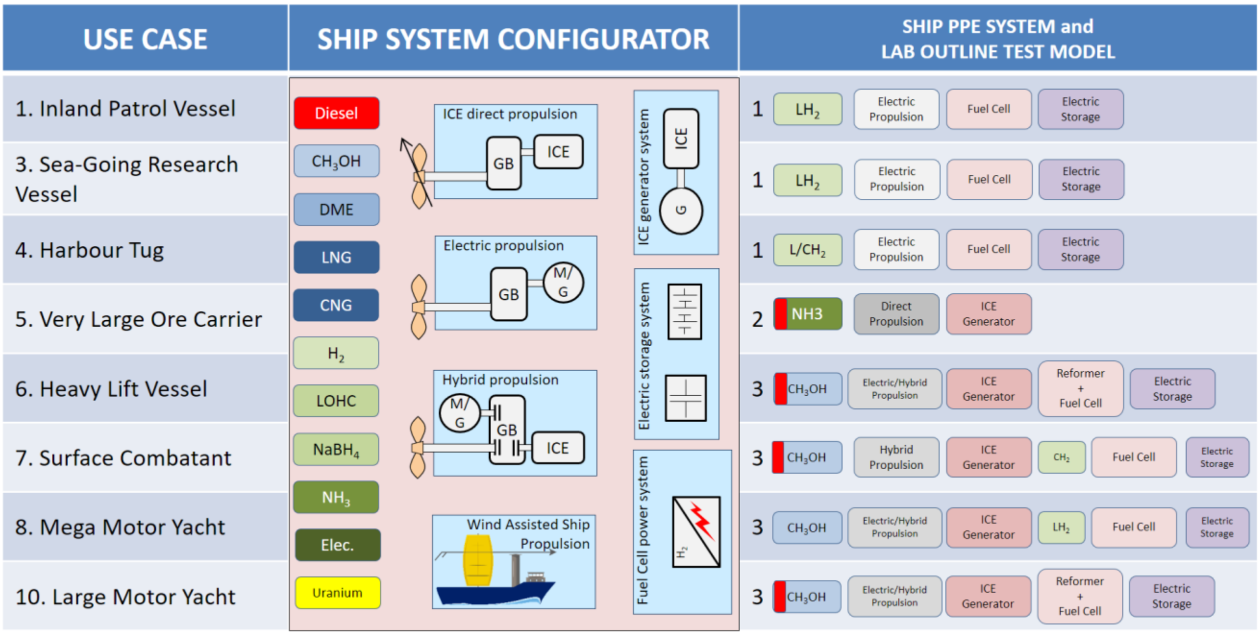
## MANAGEMENT SUMMARY

This report provides the overview of the analysis approach and results for the 8 Use Case (specific ships) studies in work package (WP) 1 of the ZERO Joint Industry Project (JIP).
The ZERO JIP is a MARIN research initiative to come to the new propulsion, power and energy (PPE) system for maritime use, using clean(er) fuels, combinations of internal combustion engines, fuels cells and electrical storage where needed. Five work packages are defined:

- WP1: Specification and exploration of new PPE for 8 Use Cases.
- WP2: Concept Design PPE for 8 Use Cases.
- WP3: Basic Engineering PPE for three selected PPEs.
- WP4: Development and Verification of Lab Test Models following from the PPE designs.
- WP5: Testing and validation of the Lab Test Models.

Here Lab Test Models are the representatives of the actual PPE designs, either for physical testing in the lab, or digital testing in simulations). More on the 8 Use Cases and the project partners can be found on https://www.marin.nl/en/jips/zero.

The studies for the eight different ships (the Use Cases) comprised of the operational and system analysis in which the Operational Needs are determined. The needs are used as input for a conceptual exploration of possible PPE configurations. For this MARIN's tool SPEC (Ship, Power and Energy Concept, see also https://www.marin.nl/en/news/recording-ship-power-and-energy-concepts-webinar) is used. In the SPEC analysis different energy and power concepts are compared w.r.t. weight, size and costs. This finally resulted in a PPE choice per Use Case. In the figure below the resulting PPE systems per Use Case are listed in the right column.




Note Use Cases 2 and 9 (Offshore supply vessel and General cargo vessel, respectively) are not listed, because, although suggested to the ZERO participants at the start of the project, they were not chosen for ZERO. However, they are still defined outside ZERO and therefore the numbering remained the same.

The numbers in front of the test models in the right column are to cluster w.r.t. the system configuration:

1. Full electric FC solution.
2. Direct ICE solution.
3. Combined ICE and FC hybrid solution.

Note, for some Use Cases the definite choice of the propulsion type (direct, electric or hybrid) is obvious, for other Use Cases less. WP2 (Concept Design) will take these results as input and the propulsion type choice will be considered and checked in more detail.

The results in this report are a summary of the results provided in separate Use Case reports named *Report User Needs and Concept Design PPE system - ZERO Use Case x …….*
Those reports can be consulted on the secure part of https://www.marin.nl/en/jips/zero in case more details are needed.

# 1 INTRODUCTION

## 1.1 Problem definition

In the maritime energy transition there are many unknowns. Which fuels to choose? Which power & energy system are suitable for my operation? How reliable are these new systems and what emission reductions can we achieve?

To answer these and many more questions MARIN initiated the ZERO JIP which started Q4 2020. It is a Joint Industry Project lead by MARIN with 20 participants (see picture below), research partners (TNO, TUD, HAN) and stakeholders (NMT, KVNR, Ministry of I&W).


*Figure 1-1: ZERO JIP participants*

## 1.2 Objectives

The aim of the ZERO JIP is: *to design, build and test the prototype Engine Rooms of the Future to assure reliable future operations in realistic conditions while meeting functional and emission requirements.*

This is done for 8 Use Cases (ships with their specific missions), see Figure 1-2. Those 8 Use Cases were defined with all participants at the start of the project.
A systematic MBSE (Model Based System Engineering) based approach is used to come from operational requirements to Design of the propulsion, power & energy (PPE) systems (see Figure 1-3). We start with the NEEDS analysis: What are the operational requirements? Which operations should be performed and what are the related power requirements? Which emission requirements are set? Which system maturity level (TRL) do I allow?
Once these requirements are clear an exploration of possible PPE-system configurations can start. Which system components could fit and meet the requirements? What is the expected total size and weight of such a system and could it, in theory, fit in the ship?
For this the Ship Power & Energy Concept (SPEC) tool is used. SPEC makes use of a large database (see also https://sustainablepower.application.marin.nl/ ) in which PPE system component properties (such as size, weight, power or energy density, efficiency, emissions, costs) are listed based on available information in literature, internet and companies product information sheets. From the SPEC analysis for every Use Case a preferred PPE-system will follow. This feeds into the Logical Architecture which is the start of work package 2.

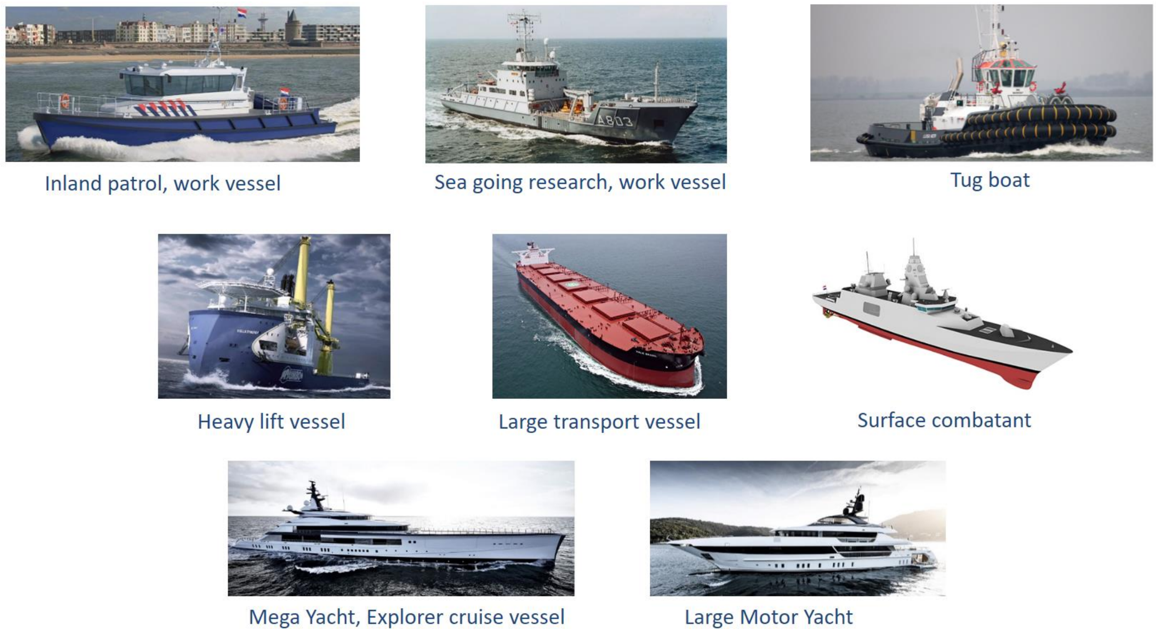



*Figure 1-2: ZERO JIP Use Cases*

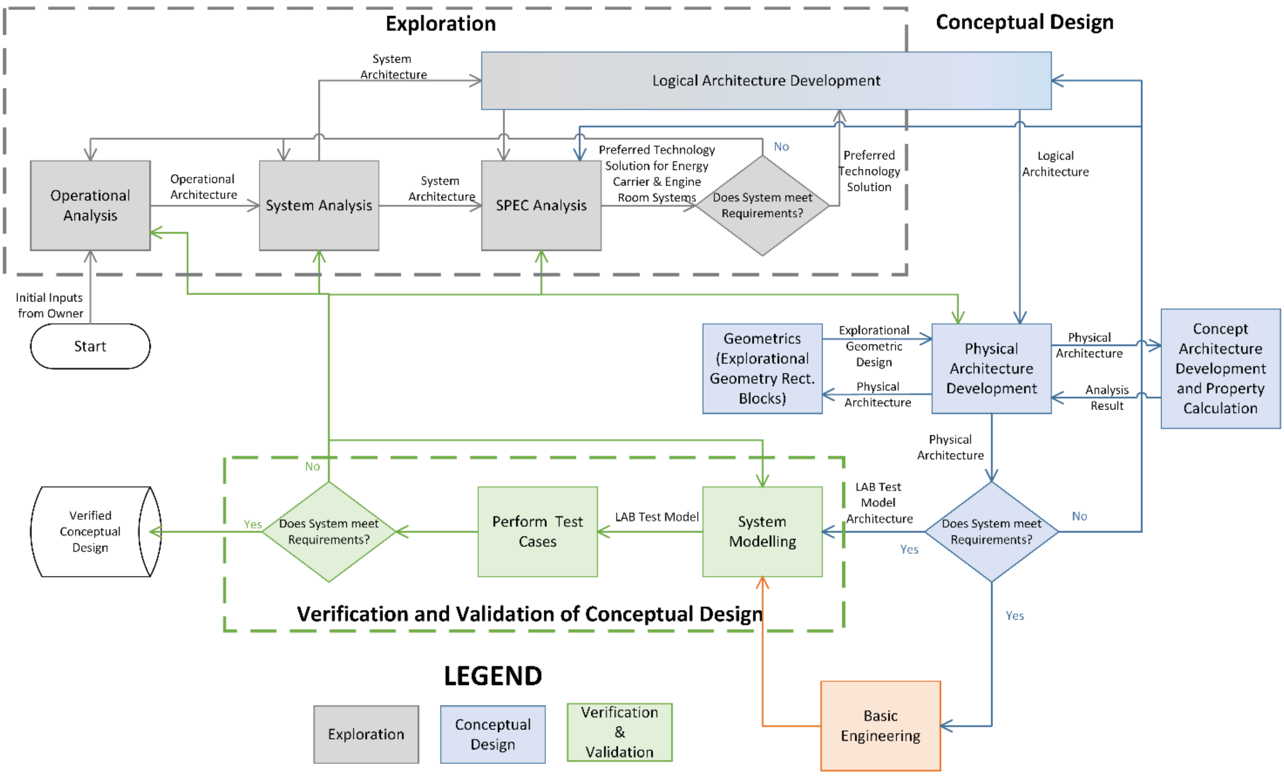



*Figure 1-3: MBSE design and V&V workflow*

## 1.3 Report outline

This summary report provides the WP1 results per Use Case in one overview. Chapter 2 provides the steps taken in the Operational, System and SPEC analysis. Chapters 3 to 10 cover the 8 Use Cases, respectively. The layout per section is as much as possible a "dashboard" providing information in tables and figures with limited text to keep uniformity. The detailed starting points and results per Use Case can be found on the secure part of https://www.marin.nl/en/jips/zero. Chapter 11 provides the Conclusions & Recommendations.

## 2 MBSE ANALYSIS STEPS

In this section the subsequent Model Based Systems Engineering (MBSE) steps covered by work package 1 are described. It starts with the so-called NEEDS analysis consisting of the Operational Analysis (What operations should the ship do?), System Analysis (What must the PPE system do?) and the related Power Time Characteristics (What are the power characteristics in those operations?). The power needs will be summarised and structured in so-called Mission Types.

Some specific Use Case 1 (Inland patrol vessel) outputs are used to clarify the MBSE steps. More details are provided in the Use Case reports on the secure part of https://www.marin.nl/en/jips/zero. For ease of understanding a short terminology list is added in Table 2-1.

*Table 2-1: MBSE Terminology list*

| | |
|---|---|
| **Operational Analysis** | This is the first step in the workflow. The goal here is to focus on the identification of the needs and objectives of future users of the system in order to guarantee the adequacy of the system faced with these operational needs.<br>At this level, the system is not (yet) recognised as a modelling element. It will only be recognised as such from the System Analysis level onward. |
| Operational Capability | These are high-level objectives. These are detailed out using a network of Operational Activities that exchange interactions. |
| Operational Requirement | These are high-level requirements that set “vessel level” requirements.<br>(for example ship speed, operational range, specific operations such as dredging, hoisting, dynamic positioning, …) |
| Operational Entity | An entity belonging to the real world (organisation, existing system, etc.) whose role is to interact with the system being studied or with its users (for example Crew, Ship, etc.) |
| Operational Activity | A process step carried out in order to reach a precise objective by an operational entity, which might need to use the future system in order to do so. |
| Operational Architecture | In this diagram the activities are allocated to the actors resulting in an overview of the operations. At this stage a first definition of the “system” can be defined by identifying the activities we intend to perform with the system. This boundary will be formalised in the System Analysis step. |
| **System Analysis** | The System Analysis step answers the following questions:<br>• What must the system do?<br>• What are the external interactions (interfaces) of the system? |
| PPE system capabilities | These are the capabilities of the “System.” They are derived from the Operational Capabilities by identifying what the system must do to fulfil these Operational Capabilities. |
| System Requirements | These are requirements that deal with the system. They are derived from Operational Requirements or refine a System Capability. |
| System Functions | These are the functions that the system must do. They are derived from the Operational Activities that were identified to be a part of the system. |
| System Actors | These are the Operational Actors/Entities identified in the Operational Analysis that are external to the “System” under study. |
| System Architecture | This gives the architecture of the system under study. It defines the boundary of the system by identifying all the functions that the system must fulfil and the interaction between the system and the System Actors. |

### 2.1 Operational, System analysis and Power Time characteristics (NEEDS analysis)

In the operational and system analysis the user needs are explored and structured in a focussed systems overview with their associations. The Operational Architecture and System Architecture of the Power, Propulsion and Energy (PPE) system is setup in the MBSE tool Capella. Finally the Capella diagrams will be extended with the consumer Power-Time Charts in the System Analysis to cover the consumer power demands. These power needs will be summarised and structured in so-called Mission Types.

#### 2.1.1 Operational analysis

The first step is setting up the Operational Capability Diagram (see Figure 2-1 for an example of Use Case 1), which shows the Operational Capabilities (OC), the associated entities (in grey blocks, these can be ship systems, persons) and the Operational Requirements (R in purple blocks).
Note Operational Requirements 2 to 5 (OR-2 to OR-5) define mission types and link to mission profiles which will be set up in Section. 2.1.3. There the specific system requirements per Mission Types are determined. At this moment this is not done at this stage, because the system boundaries still need to be defined.

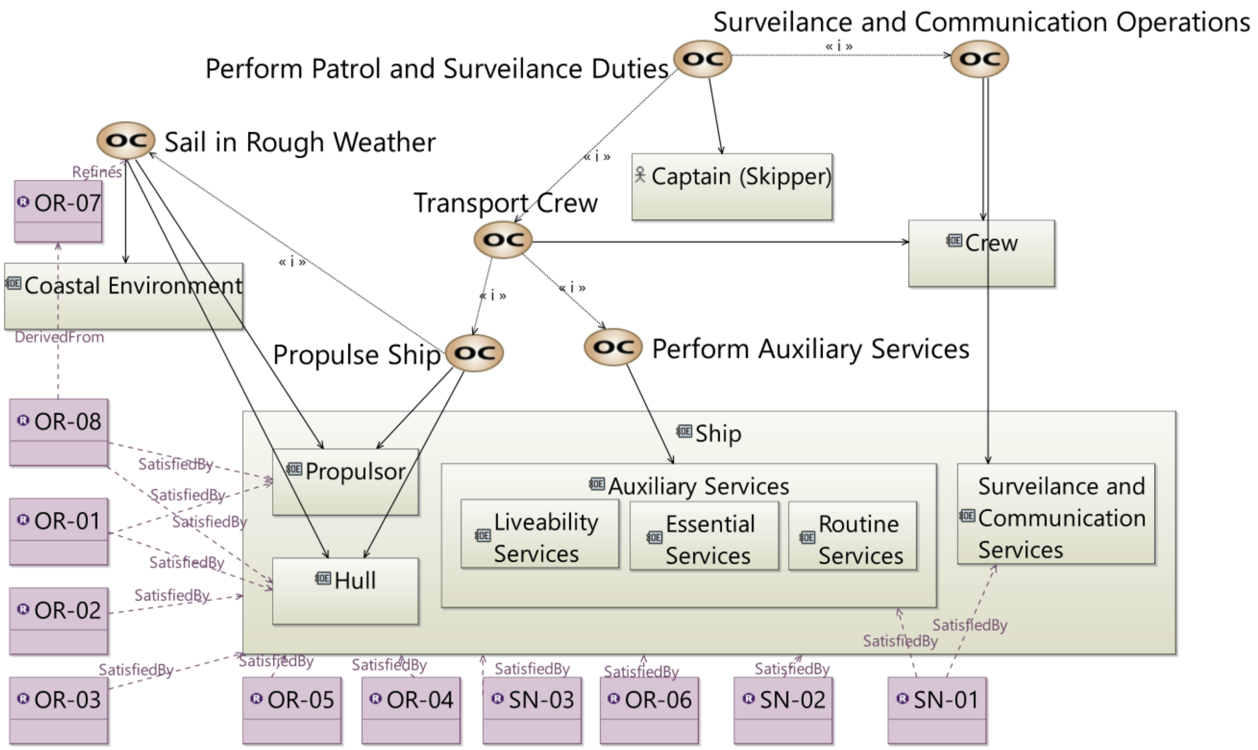



*Figure 2-1: Operational Capability Diagram Inland Patrol Vessel*

The next step is working out the activities and interactions involved in the Operational Capabilities at a lower level. This is done by defining each Operational Capability as a set of Operational Activities required to meet it. Finally the activities are combined with the formerly assigned entities and the Operational Architecture appears. This is shown in Figure 2-2. The YES and NO labels are a first pass at defining the boundary of the 'system' that is modelled and indicate whether the activity will be included in the PPE system or not.

*Table 2-2: Operational Requirements (OR) and Stakeholder Needs (SN) for an Inland Patrol Vessel*

| Operational Requirements and Stakeholder Needs | Short description |
|---|---|
| OR-01 | The maximum speed of the vessel shall be 25 knots |
| OR-02 | Mission Profile I - Surveillance (Region Rotterdam) |
| OR-03 | Mission Profile II - Traffic Management (Region Dordrecht) |
| OR-04 | Mission Profile III - Surveillance (Region Vlissingen) |
| OR-05 | Mission Profile IV - Surveillance (Region Amsterdam) |
| OR-06 | The structural design as the Damen StanPatrol 2506 |
| OR-07 | The vessel shall be capable of operating in Sea State 6 |
| OR-08 | The vessel shall achieve a speed of 17 knots in Sea State 6 |
| SN-01 | SOLAS, Class Rules and Flag State Rules apply |
| SN-02 | The vessel shall be a zero emission vessel |
| SN-03 | The total costs should be (to be defined) |

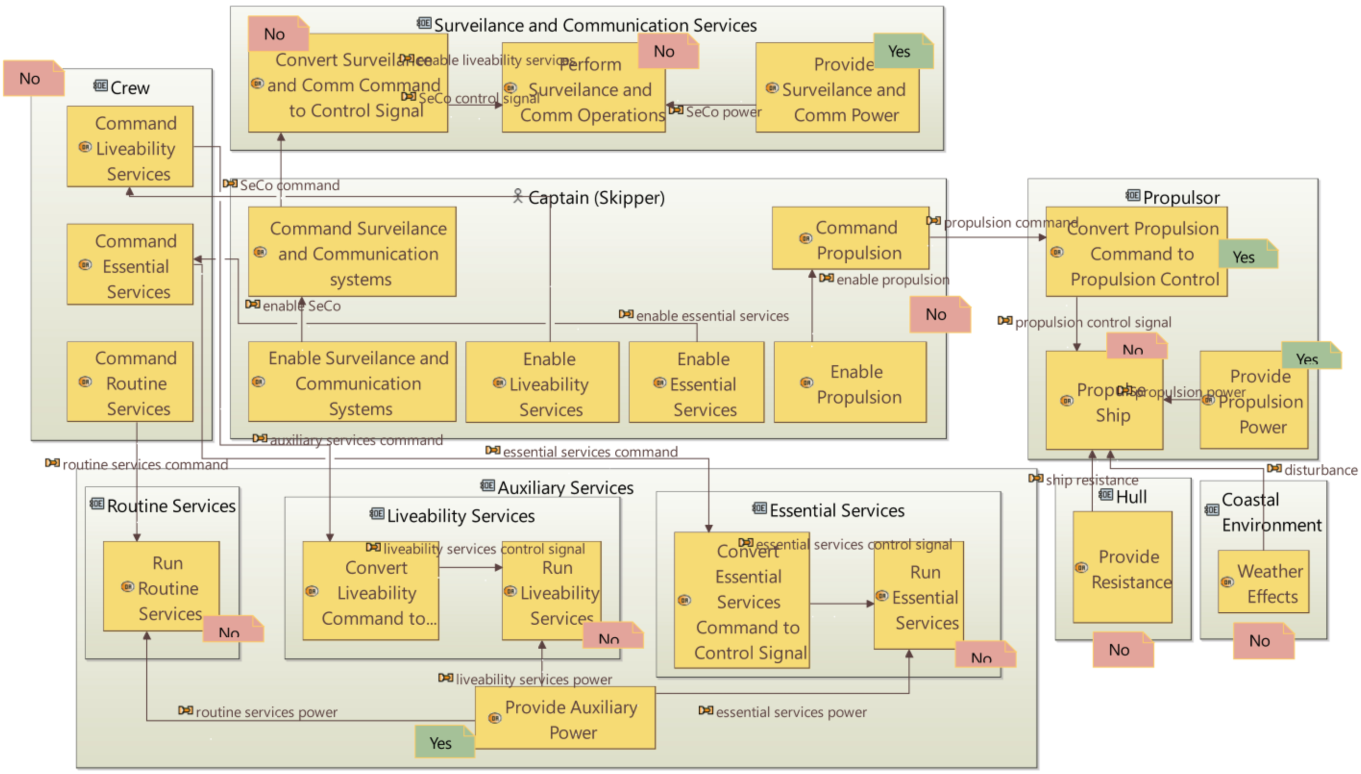



*Figure 2-2: Operational Architecture Inland Patrol Vessel*

### 2.1.2 System Analysis

In the system analysis we define the systems that have to perform the activities, set the boundary around our system and define the external interfaces.

The first step is translating the Operational Capabilities into PPE system capabilities. What must the PPE system do in order to fulfil the Operational Capabilities?
Further, the ‘System Requirements’ are defined and in some cases derived from the ‘Operational Requirements.’ Some requirements can be related to different Mission Types and their power and energy requirements. The details of these Mission Types and requirements will be dealt with in Section 2.1.3.

Finally the Operational Activities are converted into System Functions and the Operational Entities into System Actors. Capella provides means to perform these conversions automatically. These System Functions can now be allocated either to the PPE System or the System Actors external to it. Then the System Architecture appears, as shown in Figure 2-3 and Figure 2-4.

The PPE is within the medium blue block in the middle. The surrounding systems are located in the light blue blocks. The interactions between Operational Activities are converted into functional exchanges that have Input and Output ports in the function blocks. This relational structure remains throughout the system design.

An important objective of the System Architecture is to define the boundary of the system and its interfaces. Figure 2-3 shows that there are a number of interfaces that deal with power for the different System Actors. Therefore, defining the characteristics of these interfaces requires an analysis of the Power Time Characteristics which is performed in the following section.

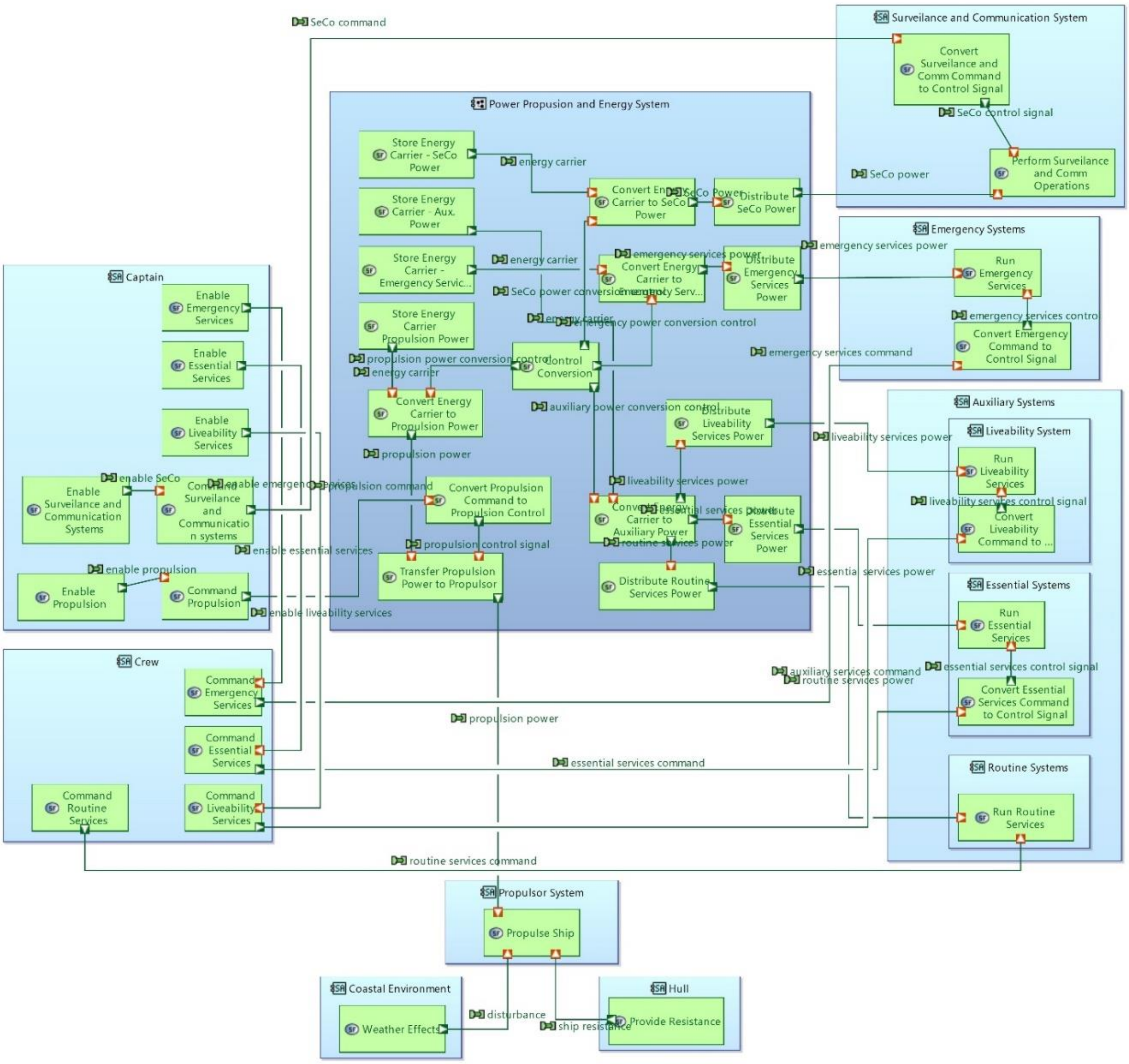



*Figure 2-3: System Architecture Inland patrol vessel*

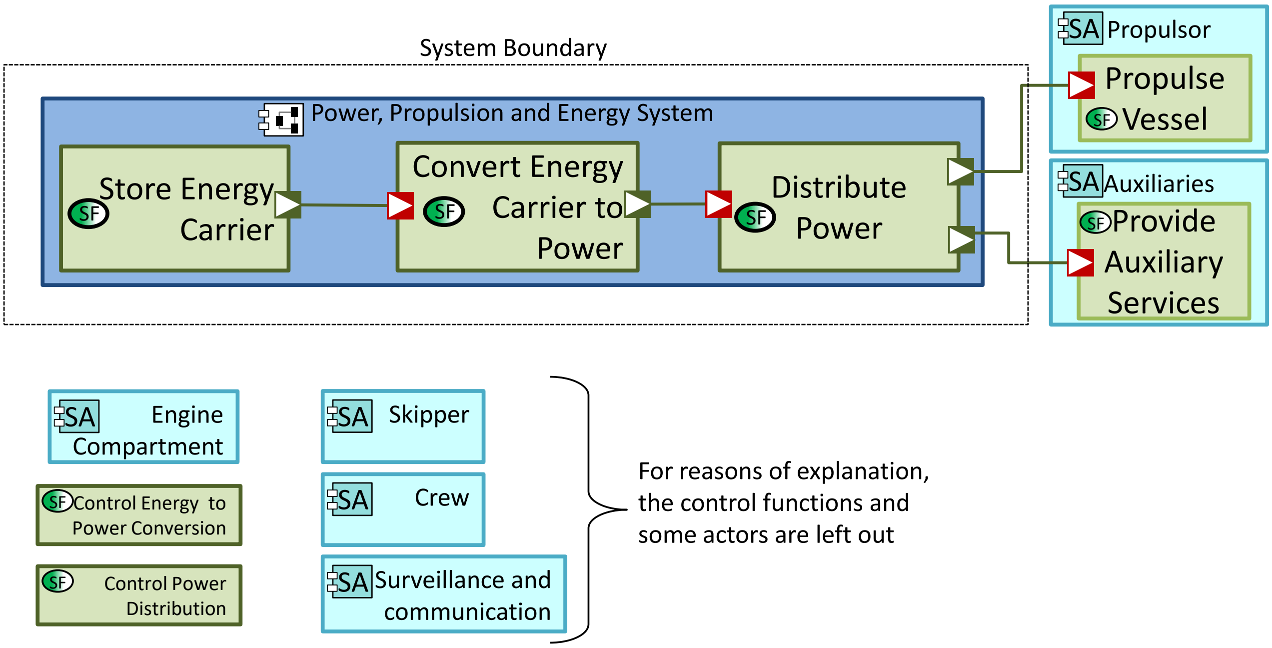



*Figure 2-4: Simplified System Architecture ZERO Inland Patrol Vessel*

### 2.1.3 Power Time Characteristics

Power Time Characteristics (PTC) represent the consumed power profile in time. They are important for understanding what the System Actors outside the boundary require from the PPE system. Here the power exchanges from the PPE system to the consumer systems outside the boundary are characterised by the PTCs.
What are the characteristics of their power consumptions? For how long do they require, how much power? What are the dynamic disturbances in amplitudes and time steps?
The Power Time Characteristics are connected to the Capella model as System Requirements to the power exchanges.

There are three types of PTCs:

1. The '*Mission Power-Time Chart*' (MPTC) is meant for:
   a. Calculating consumer power statistics (like averages, minima, and maxima @ large time steps). From the average power consumption $P_{av}$ the amount of effective energy and energy carrier can be calculated.
   b. Understanding power need during ship events by connecting the power recordings to ship events.
   c. Identifying the events that will probably have dynamics and should be looked at in more detail.

   The time step of a MPTC is 'minutes'. It can be constructed from measured or synthesised data. Figure 2-5 shows a typical example.

   A 'Mission' is a demarcated autonomous journey of a ship, from bunkering to bunkering.
   A 'Mission Type' is a typical standard mission that is regularly performed by the vessel. A vessel has a few Mission Types. An operational year of a vessel mainly consists of a certain number of those Mission Types.

2. The '*Event Power-Time Charts*' (EPTC) that are meant for detailed transient analysis in Test Cases. The time step of an EPTC is approx. 1 sec. This is typically input for testing in WP4 (Development and Verification of Lab Test Models) and WP5 (Testing and validation of the Lab Test Models).

3. If Mission Types have dominant events, like 'Economic Cruising' or 'Operations' that should have a specific autonomy or endurance, then the required total average power and energy can directly be calculated by a distribution of those events in time. In that case use is made of and Event Power Distribution Table (EPDT) of that specific ship, see Table 2-3 for an example. In that case a more detailed MPTC is not necessary, but the causal relationship (time sequence) between events is not present.

For the work in WP1 of ZERO PTC types 1 and 3 are used to come to the maximum total effective power and effective energy in that specific mission for every Use Case. That is the input for the SPEC analysis.

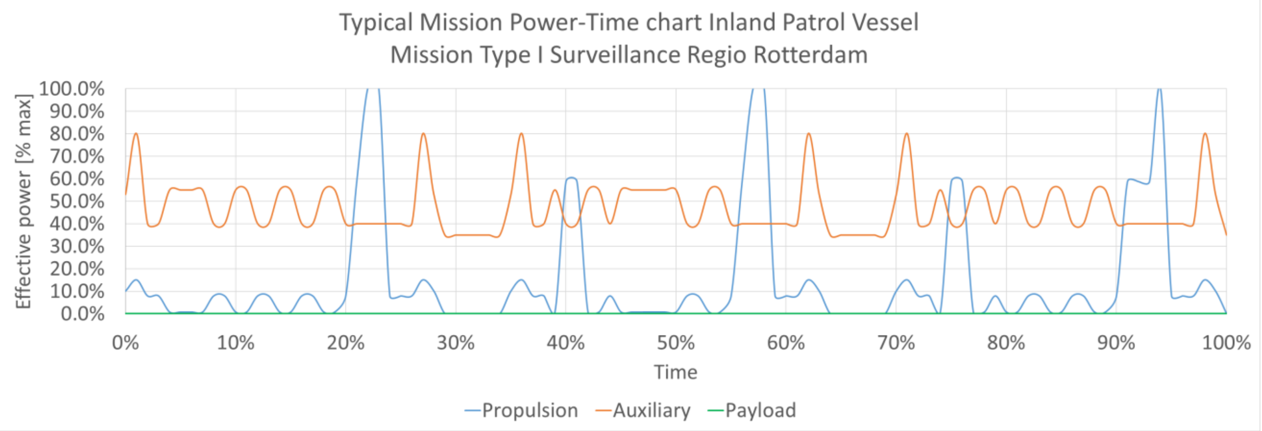



*Figure 2-5: Typical Mission Power Time Chart for Mission Type I (Surveillance for an Inland Patrol Vessel)*

*Table 2-3: Typical Event Power Table Inland Patrol Vessel*

| Events | Speed [Kts] | Pprop [kW] | Pprop [%max] | Ppayload [kW] | Ppayload [% max] | PAux [%max] | PAux [kW] | PTot [kW] |
|---|---|---|---|---|---|---|---|---|
| Anchoring | 2 | 1 | 0% | 0 | 0% | 47% | 37.6 | 39 |
| At anchor | 0 | 0 | 0% | 0 | 0% | 33% | 26.4 | 26 |
| Berthed | 0 | 0 | 0% | 0 | 0% | 35% | 28 | 28 |
| Berthing | | 120 | 10% | 0 | 0% | 53% | 42.4 | 162 |
| De-anchoring | 2 | 1 | 0% | 0 | 0% | 60% | 48 | 49 |
| Economic cruising | 15 | 399.1 | 33% | 0 | 0% | 40% | 32 | 431 |
| Economic cruising Sea State 3 | 15 | 458.9 | 38% | 0 | 0% | 47% | 37.6 | 497 |
| Economic cruising Sea State 6 | 15 | 538.7 | 45% | 0 | 0% | 47% | 37.6 | 576 |
| Fast cruising | 19 | 704.9 | 59% | 0 | 0% | 40% | 32 | 737 |
| Fast cruising Sea State 3 | 18 | 715.9 | 60% | 0 | 0% | 47% | 37.6 | 754 |
| Fast cruising Sea State 6 | 17 | 733.8 | 61% | 0 | 0% | 47% | 37.6 | 771 |
| Fast surveillance | 12 | 223.3 | 19% | 0 | 0% | 55% | 44 | 267 |
| Fast surveillance Sea State 3 | 12 | 256.8 | 21% | 0 | 0% | 59% | 47.2 | 304 |
| Fast surveillance Sea State 6 | 12 | 301.4 | 25% | 0 | 0% | 59% | 47.2 | 349 |
| Manoeuvring | | 180 | 15% | 0 | 0% | 80% | 64 | 244 |
| Max speed | 25 | 1203.5 | 100% | 0 | 0% | 40% | 32 | 1236 |
| Reduced max speed | 21.6 | 850 | 71% | 0 | 0% | 40% | 32 | 882 |
| Slow sailing | 9 | 94.2 | 8% | 0 | 0% | 40% | 32 | 126 |
| Slow surveillance | 4 | 8.3 | 1% | 0 | 0% | 55% | 44 | 52 |
| Unberthing | | 120 | 10% | 0 | 0% | 53% | 42.4 | 162 |
| Very slow sailing | 5 | 16.2 | 1% | 0 | 0% | 40% | 32 | 48 |

## 2.2 SPEC Analysis

SPEC groups the ship into a number of building blocks (see Figure 2-6). For each of these a volume, weight and cost is attributed based on parametric information (see website link above). In the output of the SPEC calculations the information is grouped together into Energy Storage and Power Systems. Energy Storage is one of the building blocks noted below. Power Systems includes the following building blocks: Pre-Treatment, Energy Conversion, After-Treatment and Power distribution & drives. The Power Systems group contains all these elements as they are all considered to scale with power (kW), whilst Energy Storage scales with energy (kWh). More detailed information can be found in the SPEC method description (see secure part of https://www.marin.nl/en/jips/zero).

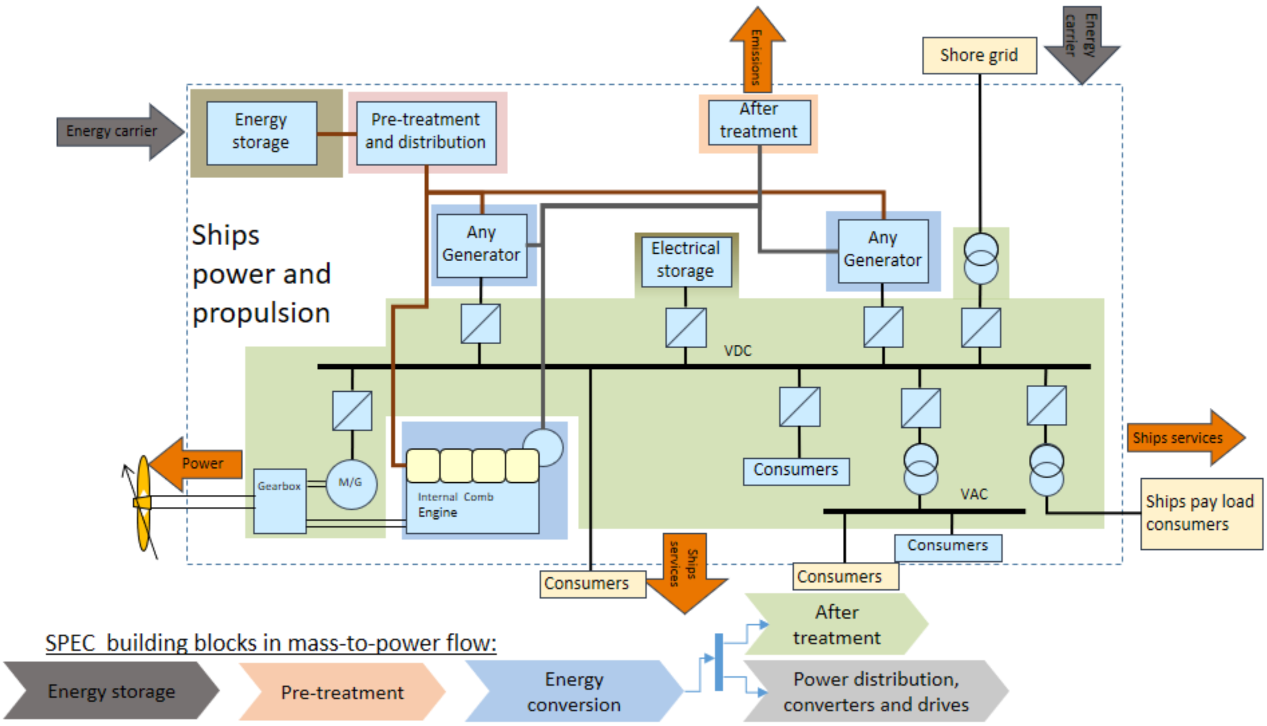



*Figure 2-6: SPEC system boundary and building blocks*

In the SPEC analysis only solutions are considered that have a maritime TRL of 5 (the scope of solutions for JIP ZERO is set to TRL 5). See Table 2-4 for a full list of solutions and the corresponding TRL levels. Note that there is no distinction between fossil fuels, bio-fuels or synthetic fuels: for the ship's systems these are considered identical, and therefore these are omitted.

*Table 2-4: TRL levels dated 23-09-2021*

| Solution name | TRL of ship's system |
|---|---|
| Diesel (MGO) CI ICE | 9 |
| $CH_3OH$/Dsl 95/5%vol CI ICE | 7 |
| $CH_3OH$ SI ICE | 7 |
| $CH_3OH$ LT PEMFC | 5 |
| CNG SI ICE | 8 |
| CNG LT PEMFC | 5 |
| $H_2$ 700b LT PEMFC | 6 |
| $H_2$ 700b/Diesel 98/2%vol CI ICE | 6 |
| Diesel (EN590) CI ICE | 9 |
| DME CI ICE | 5 |
| FePowder Steam turbine ECE | 4 |
| $LH_2$ LT PEMFC | 6 |
| Battery-electric | 9 |
| LNG SI ICE | 8 |
| LOHC LT PEMFC | 5 |
| NaBH4 LT PEMFC | 5 |
| $NH_3$ LT PEMFC | 4 |
| $NH_3$ SOFC | 4 |
| $NH_3$/Dsl 95/5%vol CI ICE | 5 |
| Uranium Steam turbine Nuclear Reactor | 5 |
| $CH_2O_2$ Reformer + LT PEMFC | 4 |
| $H_2$ 300b (ISO container) LT PEMFC | 6 |
| LNG DF ICE | 8 |
| $H_2$ 300b (integrated tanks) LT PEMFC | 6 |

SPEC contains many properties, however, in this analysis the focus is on volume, weight, emissions (where applicable) and capital cost. This is because the operational analysis does not provide year-round operational data, so operational costs cannot be covered. Moreover, the uncertainty associated with operational energy expenses is also very high as many new energy carriers are limitedly available.

In the next sections for every Use Case the PPE systems that are taken into account differ because of differences in emission requirements. However, for all Use Cases the reference PPE (diesel) systems is also shown.
In these sections per Use Case the reference vessel specifications are provided together with specifications of the ZERO design case. For some Use Cases the reference and the design case specifications are identical. For some, already early in the ZERO JIP changes are made to facilitate the step to cleaner PPE systems.

# 3 RESULTS USE CASE 1: INLAND PATROL VESSEL

## Ship

As reference a DAMEN Stan Patrol 2506 is taken. At this moment the ZERO design case is similar in size, but as mentioned below the ship might need an extension in order to fit the preferred PPE system.

| | **Autonomy**<br>NautMiles | **Max Speed**<br>kts | **Full displ.**<br>metric tons | **Dead weight tonnage**<br>metric tons | **Gross Tonnage**<br>GT | **Installed power**<br>kW | **Engine room Architecture**<br>- |
|---|---|---|---|---|---|---|---|
| **Reference** | 250 | 25 | 50 | 4 | 67 | 1360 | ICE-Direct |
| **Design case** | 250 | 25 | 50 | 4 | 67 | t.b.d. | t.b.d. |

## Operational analysis

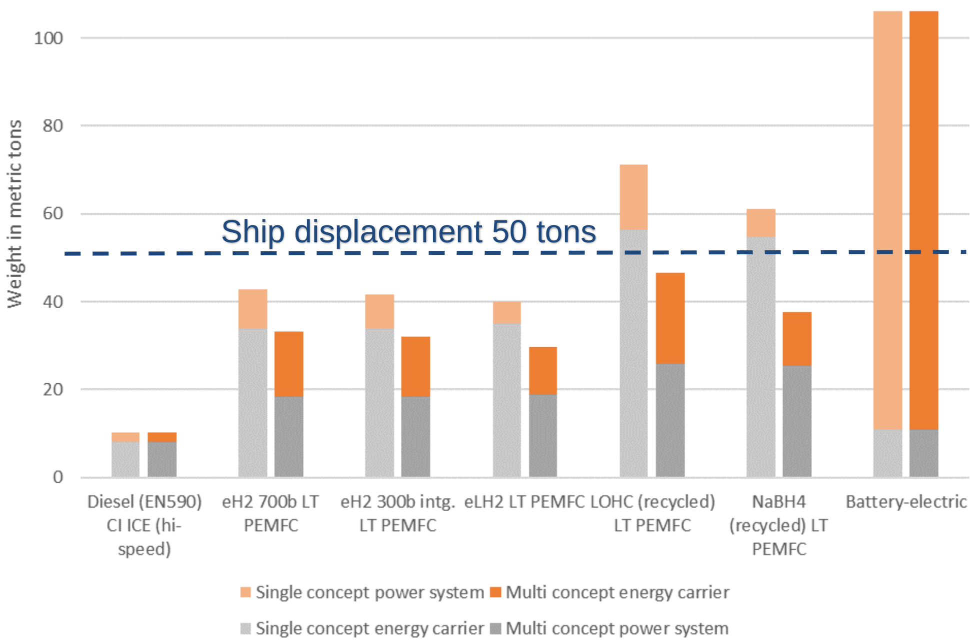
Based on input from the Rijksrederij the following missions are determined.

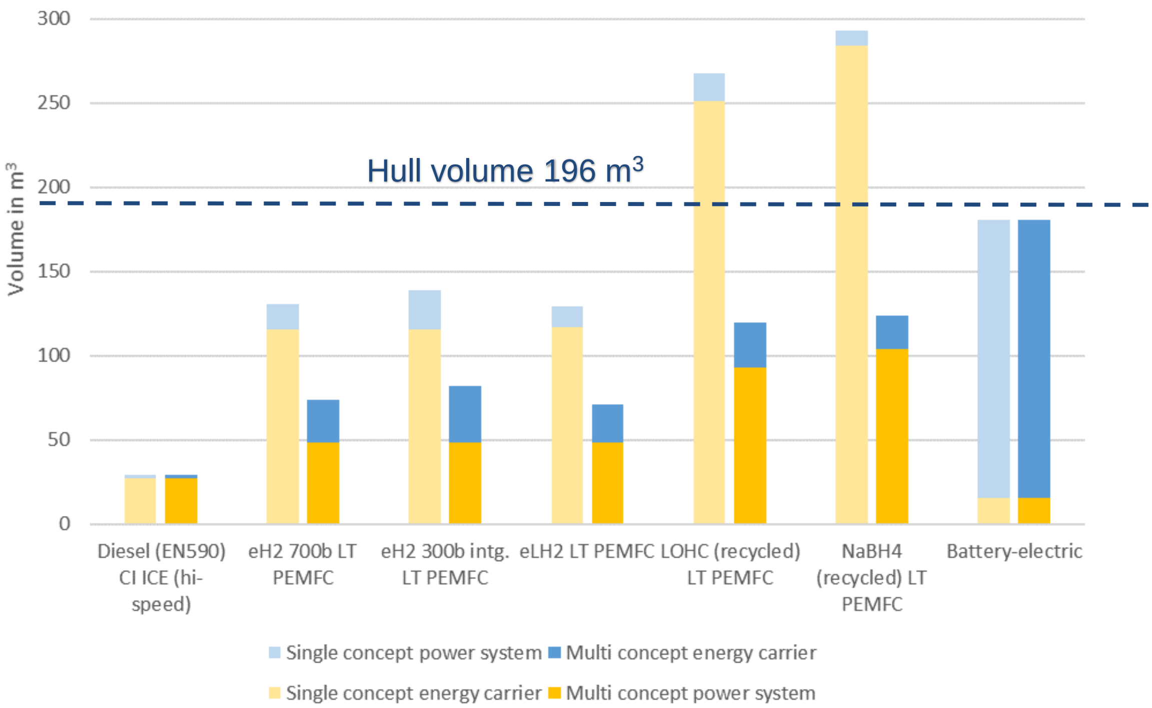
| Mission Type | Maximum total effective power & Effective Energy | | | Requirements | |
|---|---|---|---|---|---|
| | Criterion | [kW] | [MWh] | GHG | Pollutants |
| I - Surveillance (Regio Rotterdam) | Endurance: 24 hrs | 1236 | 5,1 | Zero Emission | |
| II - Verkeersbegeleiding (Regio Dordrecht) | Endurance: 16 hrs | 1236 | 6,5 | Zero Emission | |
| III - Surveillance (Regio Vlissingen) | Endurance: 8 hrs | 1236 | 8,3 | Zero Emission | |
| IV - Surveillance (Regio Amsterdam) | Endurance: 16 hrs | 1236 | 2,3 | Zero Emission | |

Mission Type III has the highest effective energy, but its operational profile deviates significantly from the typical inland patrol vessel. The amount of effective energy is too high compared to the roughly estimated energy storage capability of the design case vessel. Therefore, in consultation with the Rijksrederij, Mission Type II is chosen to be determinative for the total amount of energy carrier.

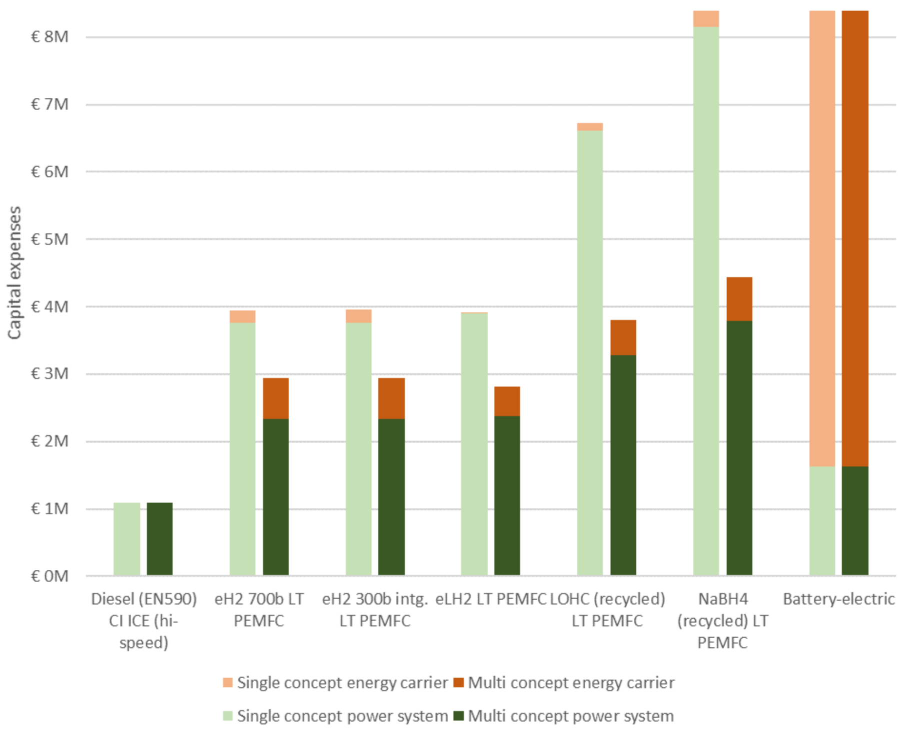
## SPEC analysis

Because of the wide operational range multi-concepts are investigated. In these cases a supporting battery system is added to the fuel cell systems, which can reduce the fuel cell system size and weight significantly as can be seen below.



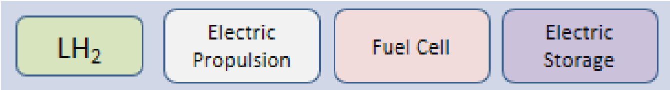



The indicative costs are shown below and cover system costs (CAPEX) only. As seen, also costs are reduced by introducing a supporting battery. Costs for further ship changes and operational costs are not accounted for.



**SPEC conclusion & outline test model**

The preferred PPE-system is a liquid hydrogen low temperature PEM fuel cell – battery with an electric power and propulsion system. This gives the following outline test model:




with the following specifications:

| | |
|---|---|
| **Energy carrier** | |
| $LH_2$ weight (uncontained) | 0.5 metric tons |
| $LH_2$ weight (contained) | 4.9 metric tons |
| $LH_2$ volume (contained) | 12.4 $m^3$ |
| Energy carrier weight (incl. batteries) | 11 metric tons |
| Energy carrier volume (incl. batteries) | 22 $m^3$ |
| **Power system** | |
| Power system weight | 19 metric tons |
| Power system volume | 49 $m^3$ |
| **Total concept** | |
| Total system weight | 30 metric tons |
| Total system volume | 71 $m^3$ |
| Effective power by fuel cell concept | 404 kW |
| Effective energy by battery concept | 421 kWh |
| Max. effective power[2] | 1236 kW |

A quick design case analysis shows that in case the rest of the ships equipment is to be untouched the ship's length should increase from 25 to 28 m and the displacement to 82 tons. The exact consequences of this PPE choice will become clear in the conceptual design in WP2.

More detailed information can be found in the separate report *Report User Needs and Concept Design PPE system - ZERO Use Case 1 Inland Patrol Vessel vx.x* on www.marin.nl/jips/zero (login account required).

[2] Sustained for max. 14 minutes because of battery capacity limitations.

# 4 RESULTS USE CASE 3: SEA GOING, RESEARCH, WORK VESSEL

### Ship

As reference the HOV (Hydrografisch OpnemingsVaartuig) of the Dutch Navy is taken. At the moment the ZERO design case is similar in size, but as mentioned below the ship might need an extension in order to fit the preferred PPE system.

| | **Autonomy** | **Max Speed** | **Full displ.** | **Dead weight tonnage** | **Gross Tonnage** | **Installed power** | **Engine room Architecture** |
|---|---|---|---|---|---|---|---|
| | NautMiles | kts | metric tons | metric tons | GT | kW | - |
| **Reference** | 8500 | 13.5 | 2400 | 800 | 1805 | 3000 | ICE-Electric |
| **Design case** | 4300 | 13.5 | 2400 | 800 | 1990 | t.b.d. | t.b.d. |

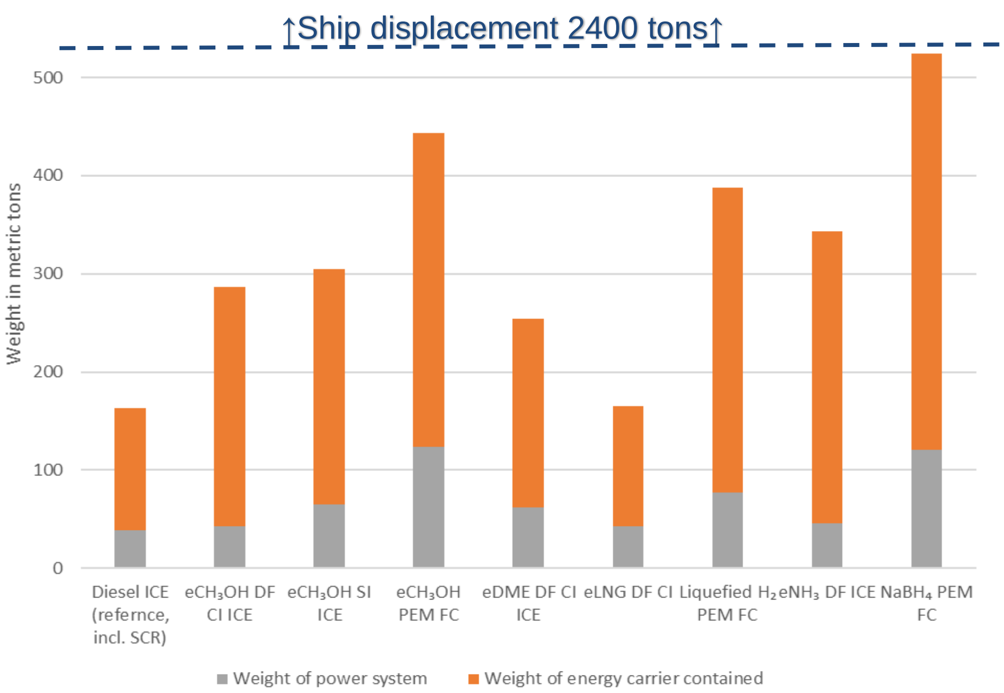
### Operational analysis

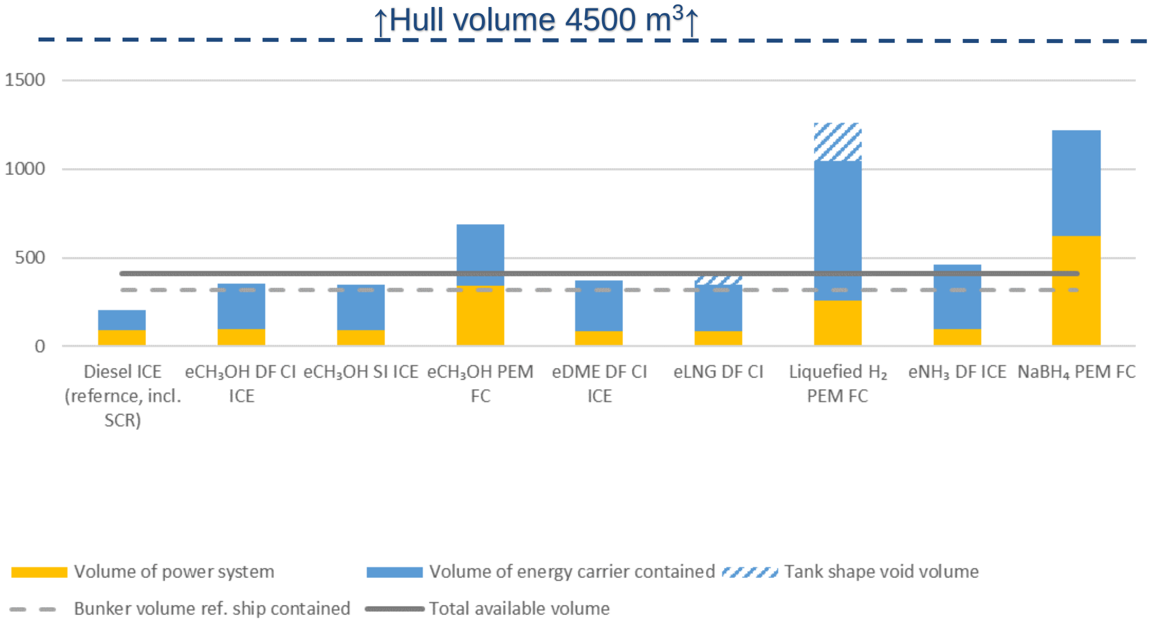
Based on input from DMO the following missions are determined.

| Mission Type | Maximum total effective power & Effective Energy | | | Requirements | |
|---|---|---|---|---|---|
| | Criterion | [kW] | [MWh] | GHG | Pollutants |
| I – Hydrographic Voyage | Required Autonomy: 4300nmi Endurance: 23.6 days | 1770 | 462 | 70% Climate neutral | IMO Tier III |
| II – Atlantic Crossing | Required Autonomy: 4300nmi Endurance: 16.9 days | 1770 | 451 | 70% Climate neutral | IMO Tier III |

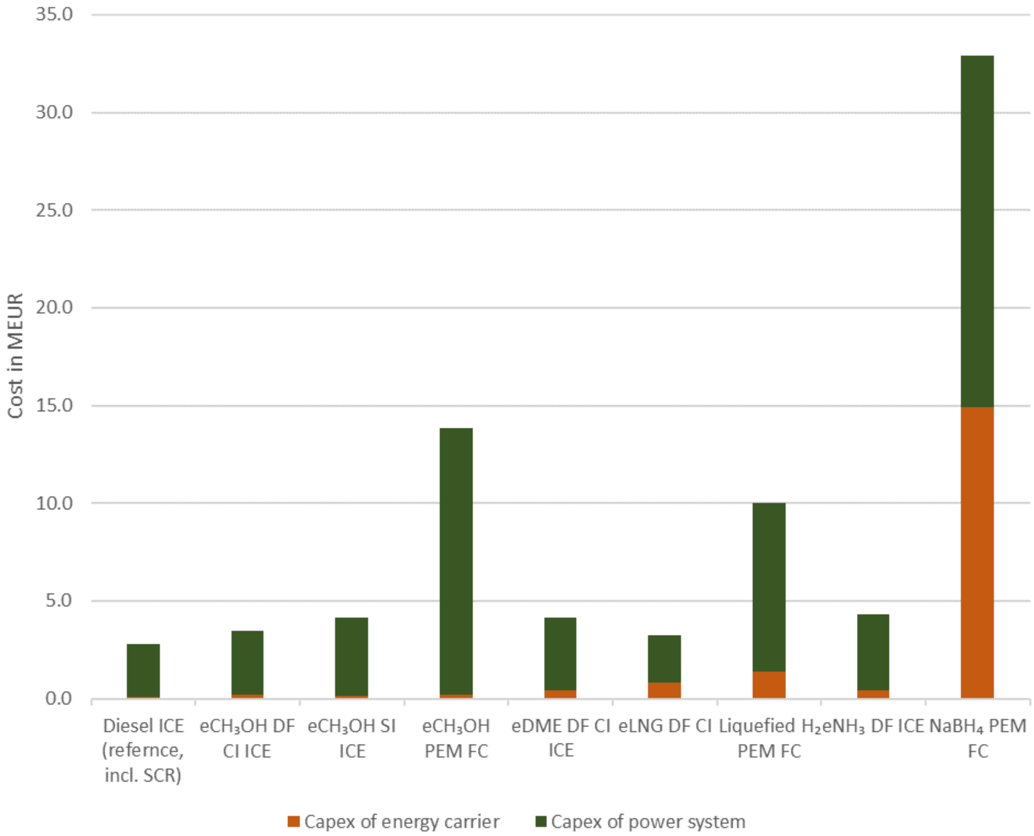
### SPEC analysis

Only single-concepts (one power converter and energy carrier, no ‘clever’ combinations) are looked at. As can be seen below volume wise the ICE solutions perform well and ammonia or methanol solutions are likely candidates. However, an attractive option is the liquefied hydrogen solution with a relatively low weight and zero emission operation. The volume of liquid hydrogen solution will be challenging. Moreover, zero emission operation was however not a strict requirement, but there is agreement in the group to raise the ambitions and to consider this solution for WP2, because the methanol solution is also investigated in other research projects and ammonia is considered less suitable for naval use.



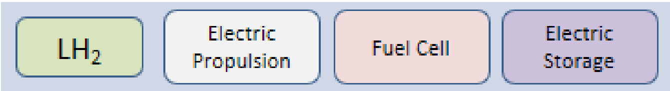



The indicative costs are shown below and cover system costs (CAPEX) only. Costs for further ship changes and operational costs are not accounted for.



**SPEC conclusion & outline test model**

The preferred PPE-system is a liquid hydrogen low temperature PEM fuel cell – battery with an electric power and propulsion system. This gives the following outline test model:




with the following specifications:

| | |
|---|---|
| **Energy carrier** | |
| $LH_2$ weight (uncontained) | 30 metric tons |
| $LH_2$ weight (contained) | 310 metric tons |
| $LH_2$ volume (contained) | 788 $m^3$ |
| **Power system** | |
| Power system weight | 78 metric tons |
| Power system volume | 257 $m^3$ |
| **Total concept** | |
| Total system weight | 108 metric tons |
| Total system volume | 1045 $m^3$ |
| Max. effective power of concept | 3000 kW |

A quick design case analysis shows that in case the rest of the ships equipment is to be untouched the ship's length should increase about 10%. The exact consequences of this PPE choice will become clear in the conceptual design in WP2.

More detailed information can be found in the separate report *Report User Needs and Concept Design PPE system - ZERO Use Case 3 Seagoing Research Vessel.vx.x*. on www.marin.nl/jips/zero (login account required).

# 5 RESULTS USE CASE 4: TUG BOAT

## Ship

As reference a DAMEN Azimuth Stern Drive Tug 3212 is taken.

| | **Autonomy**<br>NautMiles | **Max Speed**<br>kts | **Full displ.**<br>metric tons | **Dead weight tonnage**<br>metric tons | **Gross Tonnage**<br>GT | **Installed power**<br>kW | **Engine room Architecture**<br>- |
|---|---|---|---|---|---|---|---|
| **Reference** | 3500 | 13.5 | 800 | 215 | 450 | 5300 | ICE-Direct |
| **Design case** | 150 | 13.5 | 800 | 215 | 450 | t.b.d. | t.b.d. |

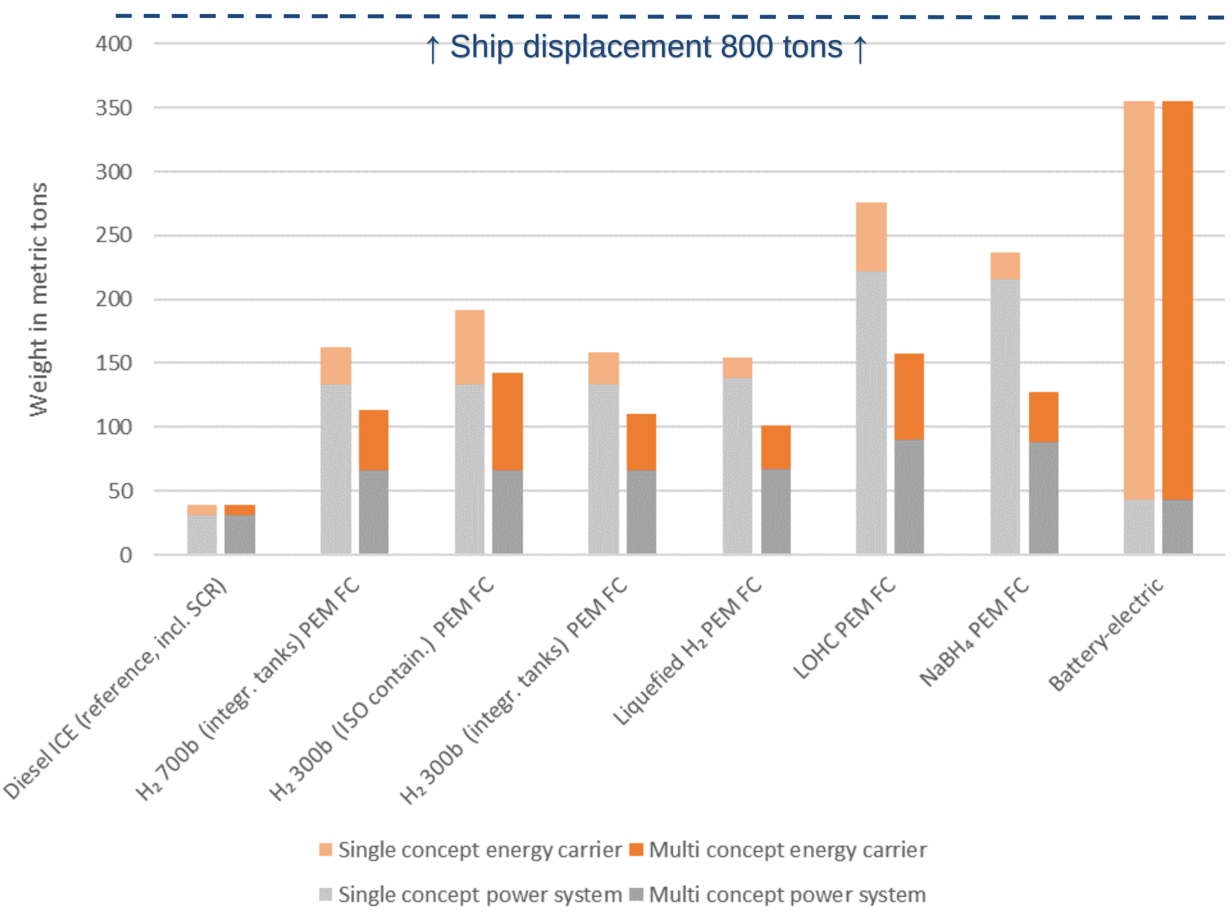
## Operational analysis

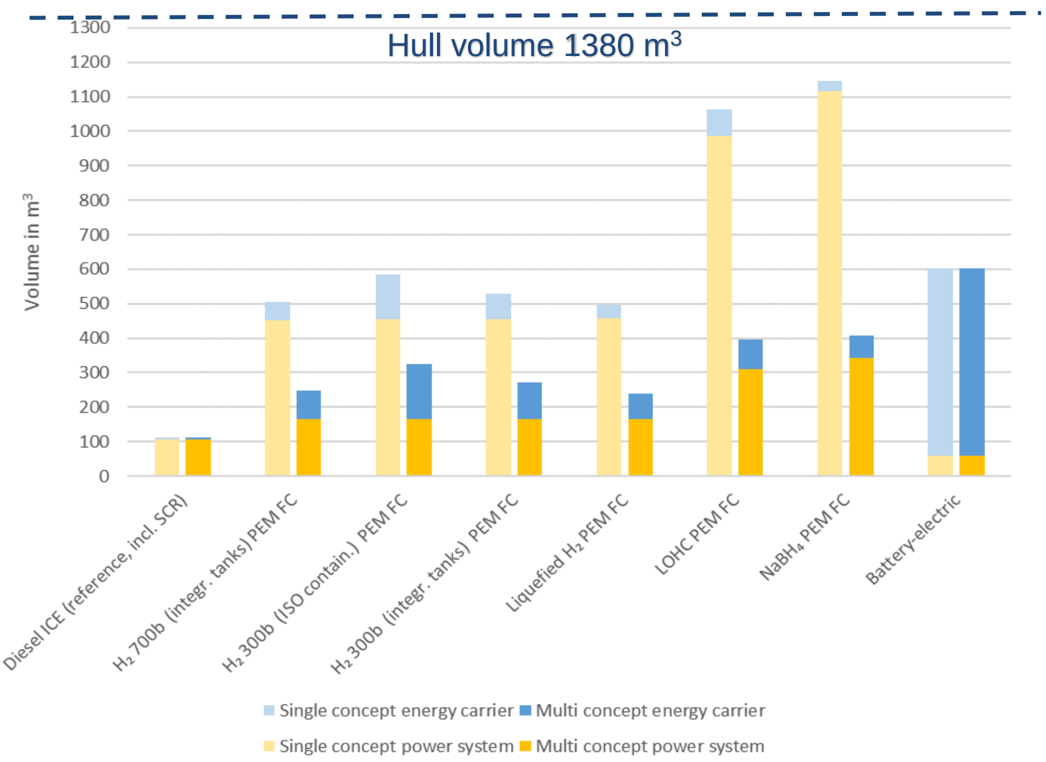
Based on input from several participants the following missions are determined.

| Mission Type | Maximum total effective power & Effective Energy | | | Requirements | |
|---|---|---|---|---|---|
| | Criterion | [kW] | [MWh] | GHG | Pollutants |
| I – Tug Jobs | Endurance: 12 Hrs | 5023 | 12.9 | ZE | ZE |
| II – Free Sailing | Autonomy: 150 NautMi | 5023 | 21 | ZE | ZE |
| III – Fire Fighting | Endurance: 12 Hrs | 5023 | 18.2 | None | EU Stage V |

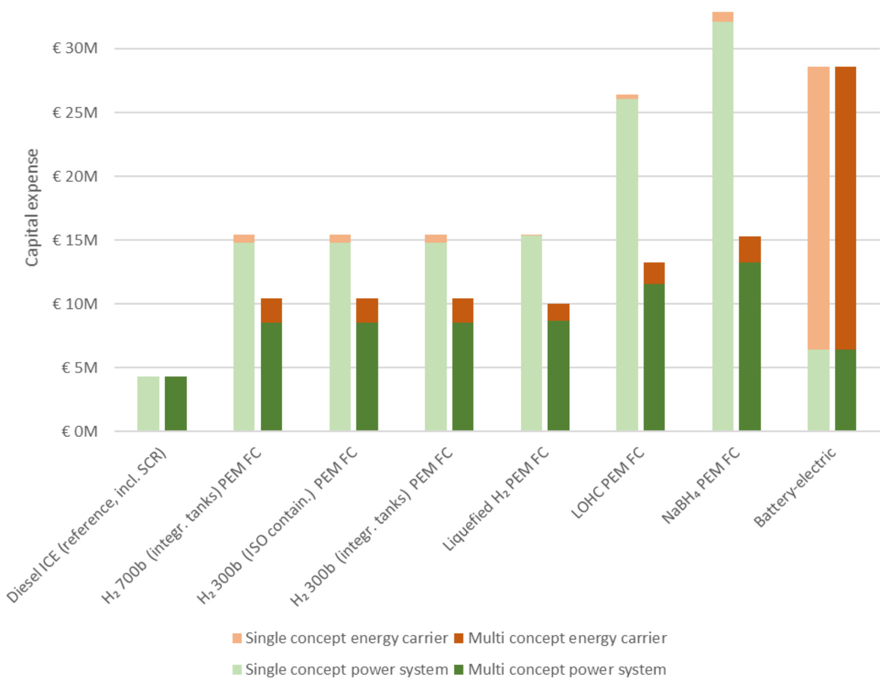
## SPEC analysis

Because of the wide operational range multi-concepts are investigated: the fuel cell systems are supported by a battery system for power peaks. These concepts show a considerable improvement in weight and volume compared to single-concepts that were firstly assessed.



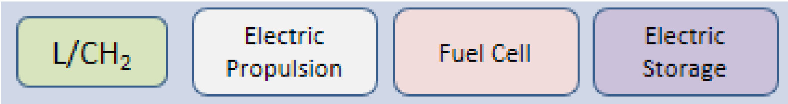



The indicative costs are shown below and cover system costs (CAPEX) only. The multi-concept shows a lower overall cost due to the addition of the battery system. Costs for further ship changes and operational costs are not accounted for.



### SPEC conclusion & outline test model

The preferred PPE-system is a hydrogen low temperature PEM fuel cell – battery with an electric propulsion system. Whether compressed or liquid hydrogen should be used is under discussion. The following outline test model is used as starting point for WP2:




with the following specifications:

| | |
|---|---|
| **Energy carrier** | |
| $LH_2$ weight (uncontained) | 1.6 metric tons |
| $LH_2$ weight (contained) | 16.5 metric tons |
| $LH_2$ volume (contained) | 38.3 $m^3$ |
| Energy carrier weight (incl. batteries) | 34 metric tons |
| Energy carrier volume (incl. batteries) | 72 $m^3$ |
| **Power system** | |
| Power system weight | 68 metric tons |
| Power system volume | 166 $m^3$ |
| **Total concept** | |
| Total system weight | 102 metric tons |
| Total system volume | 238 $m^3$ |
| Effective power by fuel cell concept | 1450 kW |
| Effective energy by battery concept | 1358 kWh |
| Max. effective power[3] | 5213 kW |

More detailed information can be found in the separate report *Report User Needs and Concept Design PPE system - ZERO Use Case 4 Harbour Tug.vx.x* on www.marin.nl/jips/zero (login account required).

[3] Sustained for max. 14 minutes because of battery capacity limitations.

# 6 RESULTS USE CASE 5: LARGE TRANSPORT VESSEL

### Ship

As reference a Vale Very Large Ore carrier is taken.

| | Autonomy | Max Speed | Full displ. | Dead weight tonnage | Gross Tonnage | Installed power | Engine room Architecture |
|---|---|---|---|---|---|---|---|
| | NautMiles | kts | metric tons | metric tons | GT | kW | - |
| **Reference** | 25000 | 15 | 370000 | 325000 | 175521 | 21000 | ICE-Direct |
| **Design case** | 25500 | 15 | 370000 | 325000 | 175521 | t.b.d. | ICE-Direct |

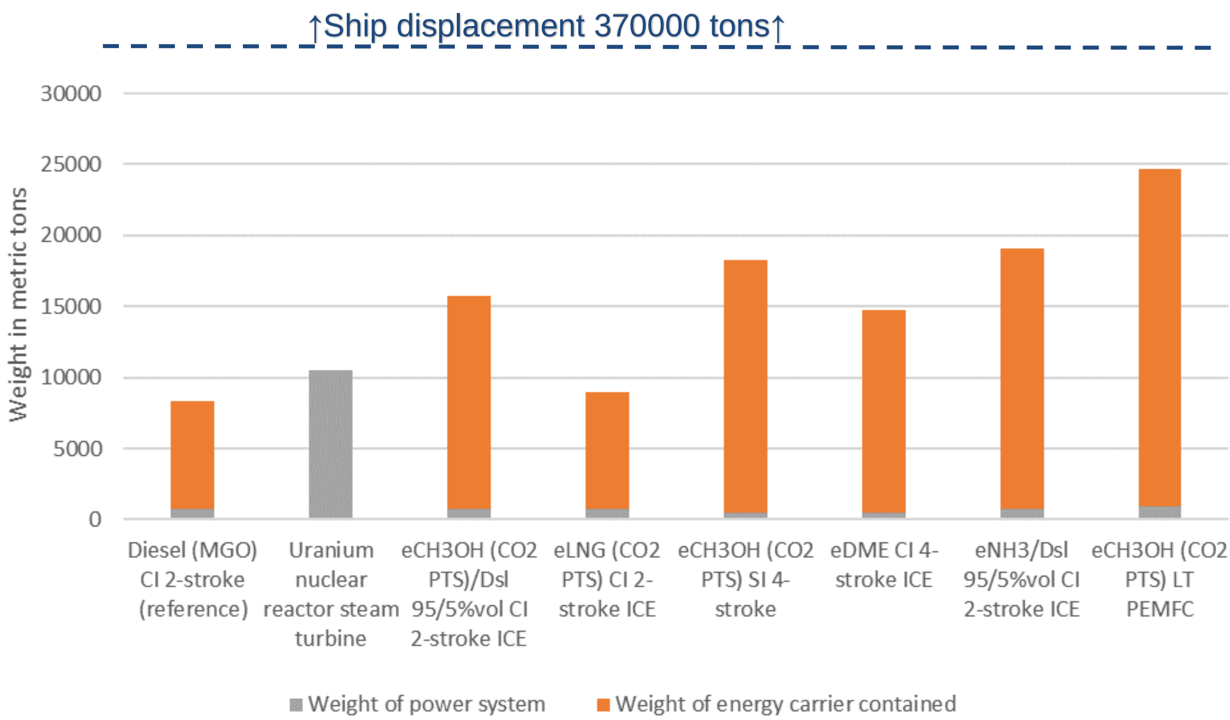
### Operational analysis

Based on input from Vale the following missions are determined.

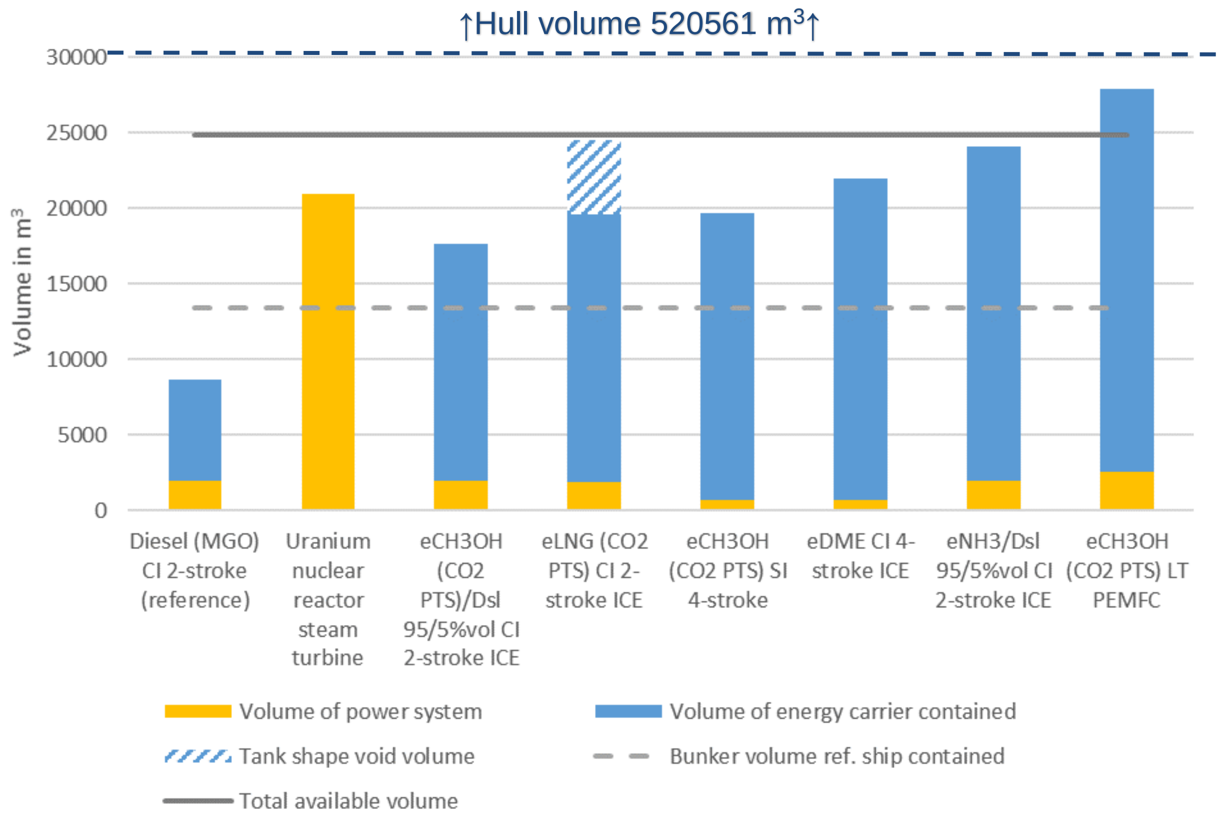
| Mission Type | Maximum total effective power & Effective Energy | | | Requirements | |
|---|---|---|---|---|---|
| | Criterion | [kW] | [MWh] | GHG | Pollutants |
| I – Round-trip Voyage Brazil – Singapore - Qingdao – Brazil | Autonomy: 25500 NautMi | 21197 | 30307 | 70% Carbon-Neutral | IMO Tier II |
| II – Round-trip Voyage Brazil – Singapore – Brazil | Autonomy: 20500 NautMi | 21197 | 24188 | 70% Carbon-Neutral | IMO Tier II |
| III – Round-trip Voyage Singapore – Qingdao – Singapore | Autonomy: 5400 NautMi | 21197 | 6384 | 70% Carbon-Neutral | IMO Tier II |

### SPEC analysis

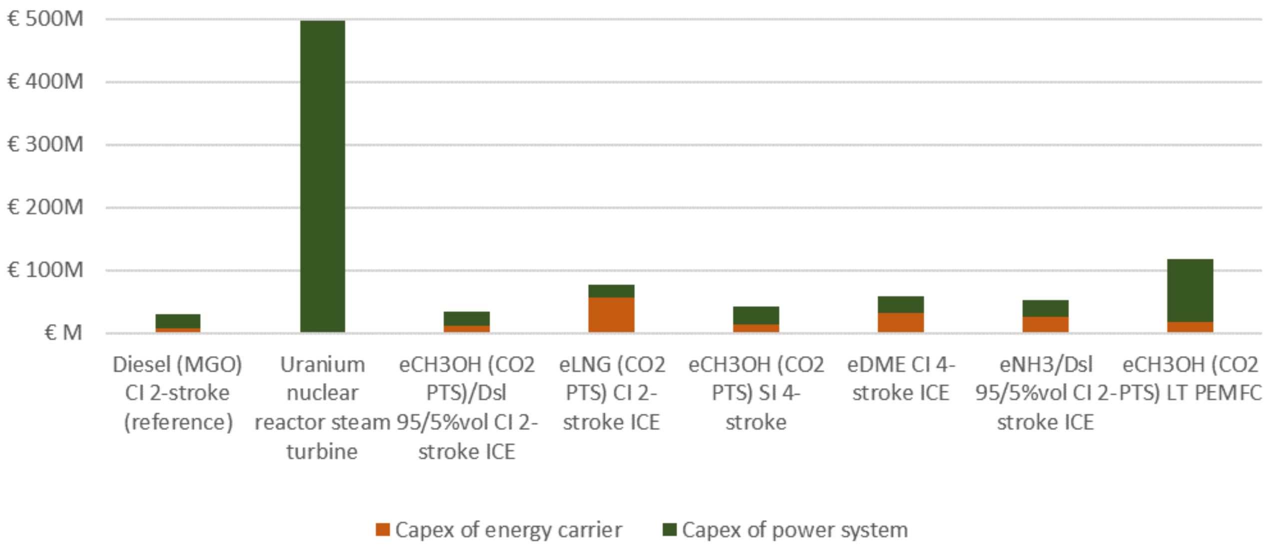
The high autonomy limits the energy carrier choice. Typically 2-stroke ICE solutions are considered for these high power solutions. For some solutions only 4-stroke ICE information is available because 2-stroke solutions are not or still under development.



Vale indicated there is an additional space available for the PPE system bringing the total available volume to about 25000 m$^3$ (see figure below). Note the bunker volume of the reference vessel is much larger than the energy carrier volume of the reference diesel system. This shows the reference vessel's bunker is much larger than the ship's missions require.

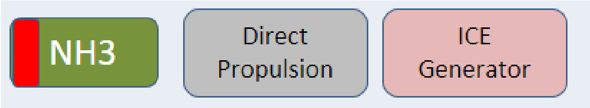



The indicative costs are shown below and cover system costs (CAPEX) only. Costs for further ship changes and operational costs are not accounted for.



**SPEC conclusion & outline test model**

The methanol 2-stroke systems is the smallest. However the ammonia 2-stroke solution results in the lowest operational costs, due to lower fuel costs, and lower emissions than the methanol solutions. Therefore the preferred PPE-system is an ammonia direct propulsion ICE solution, resulting in this outline test model:




with the following specifications:

| | |
|---|---|
| **Energy carrier** | |
| Ammonia + pilot weight (uncontained) | 11660 metric tons |
| Ammonia + pilot weight (contained) | 18285 metric tons |
| Ammonia + pilot volume (contained) | 22065 $m^3$ |
| **Power system** | |
| Power system weight | 762 metric tons |
| Power system volume | 1968 $m^3$ |
| **Total concept** | |
| Total system weight | 19047 metric tons |
| Total system volume | 24033 $m^3$ |
| Max. effective power of concept | 22000 kW |

More detailed information can be found in the separate report *Report User Needs and Concept Design PPE system - ZERO Use Case 5 VLOC.vx.x* on www.marin.nl/jips/zero (login account required).

# 7 RESULTS USE CASE 6: HEAVY LIFT VESSEL

### Ship

As reference the Jumbo Stella Synergy is taken.

| | Autonomy | Max Speed | Full displ. | Dead weight tonnage | Gross Tonnage | Installed power | Engine room Architecture |
|---|---|---|---|---|---|---|---|
| | NautMiles | kts | metric tons | metric tons | GT | kW | - |
| **Reference** | 12000 | 13.5 | 42600 | 14000 | 36900 | 22000 | ICE-Electric |
| **Design case** | 9200 | 13.5 | 42600 | 14000 | 36900 | t.b.d. | t.b.d. |

### Operational analysis

Based on input from several participants the following missions are determined.

| Mission Type | Maximum total effective power & Effective Energy | | | Requirements | |
|---|---|---|---|---|---|
| | Criterion | [kW] | [MWh] | GHG | Pollutants |
| I – Long Lifting and Transport Voyage | Autonomous range: 9200 nmi | 8442 | 6363 | None | IMO Tier II/III |
| II – Zero Emission Transit and Demobilisation | Endurance: 140 Hrs | 3600 | 362 | 90% Climate neutral | ZE |
| III - Jacket Installation Trip | Endurance: 400 Hrs | 6819 | 1299 | 80% Climate Neutral | IMO Tier III |

Note, for reason of redundancy in DP mode a total effective power of 20000kW is used for Mission Type I in the SPEC analysis.

### SPEC analysis

For this Use Case a slightly different approach was used because all missions have different emission and power requirements. After analysing the solutions per mission type three multi-concept PPE-configurations were constructed with the following restrictions:

1. In all configurations a diesel fallback option should be possible.
2. No more than two fuels are allowed.

The resulting PPE configurations are:

| | Active components per mission type | | |
|---|---|---|---|
| **Multi-concept PPE configuration** | **Mission Type I** | **Mission Type II** | **Mission Type III** |
| Diesel ICE + $H_2$ DF ICE + $LH_2$ PEMFC | Diesel ICE | $LH_2$ PEMFC | $LH_2$ PEMFC + $LH_2$ DF ICE |
| $CH_3OH$ DF ICE + $LH_2$ PEMFC | $CH_3OH$ DF ICE | $LH_2$ PEMFC | $CH_3OH$ DF ICE |
| $CH_3OH$ DF ICE + $CH_3OH$ PEMFC | $CH_3OH$ DF ICE | $CH_3OH$ PEMFC | $CH_3OH$ DF ICE |

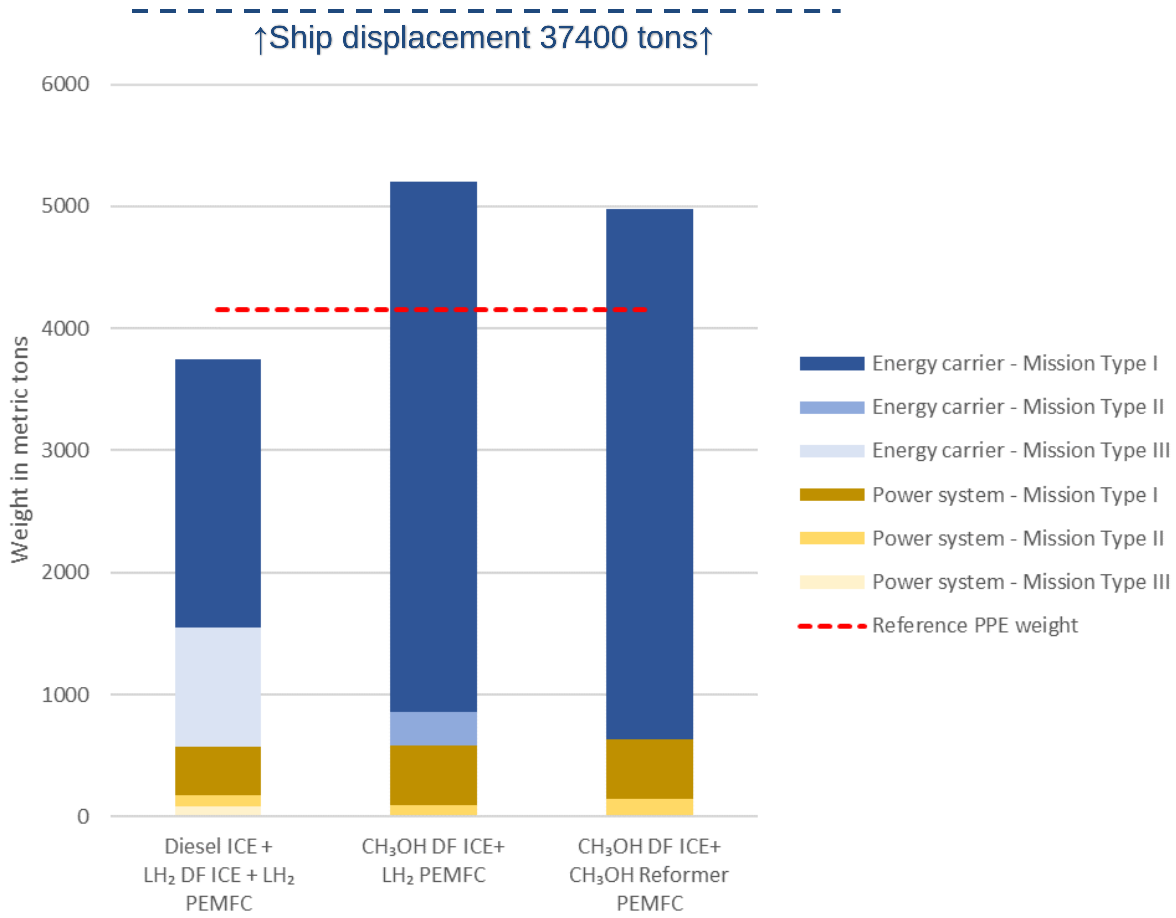
The Diesel ICE solution in the first configuration is represented by single fuel engine(s), used to cover the majority of the power in Mission Type I. It is complemented by a smaller set of dual-fuel hydrogen engine(s) which are already present due to the need for climate neutral power in Mission Type III. The diesel single fuel engine is still within the emission requirements of Mission Type I.

In general, the Mission Types have an overlap. For instance, PPE configuration 1 uses both a hydrogen fuel cell system for Mission Types II and III, in the calculations it is only counted once. The same goes for the methanol storage used in configurations 2 and 3: it is only included in Mission Type III as this one is determinative.

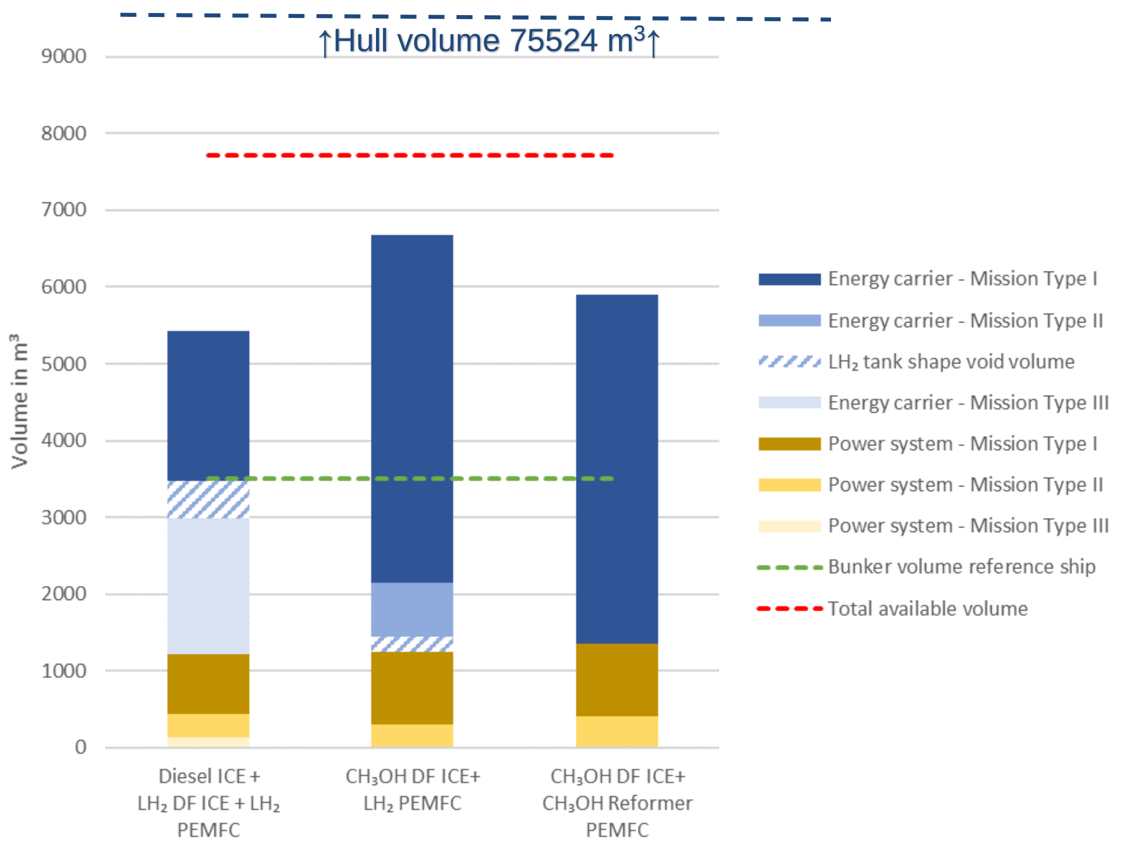
This results in an installed power per PPE configuration of:

| | Mission Type I / III | | Mission Type II |
|---|---|---|---|
| **Multi-concept PPE configuration** | Single fuel engine | Dual fuel engine | Fuel cell system |
| Diesel ICE + $LH_2$ DF ICE + $LH_2$ PEMFC | 17000 kW | 3000 kW | 3600 kW |
| $CH_3OH$ DF ICE + $LH_2$ PEMFC | | 20000 kW | 3600 kW |
| $CH_3OH$ DF ICE + $CH_3OH$ PEMFC | | 20000 kW | 3600 kW |

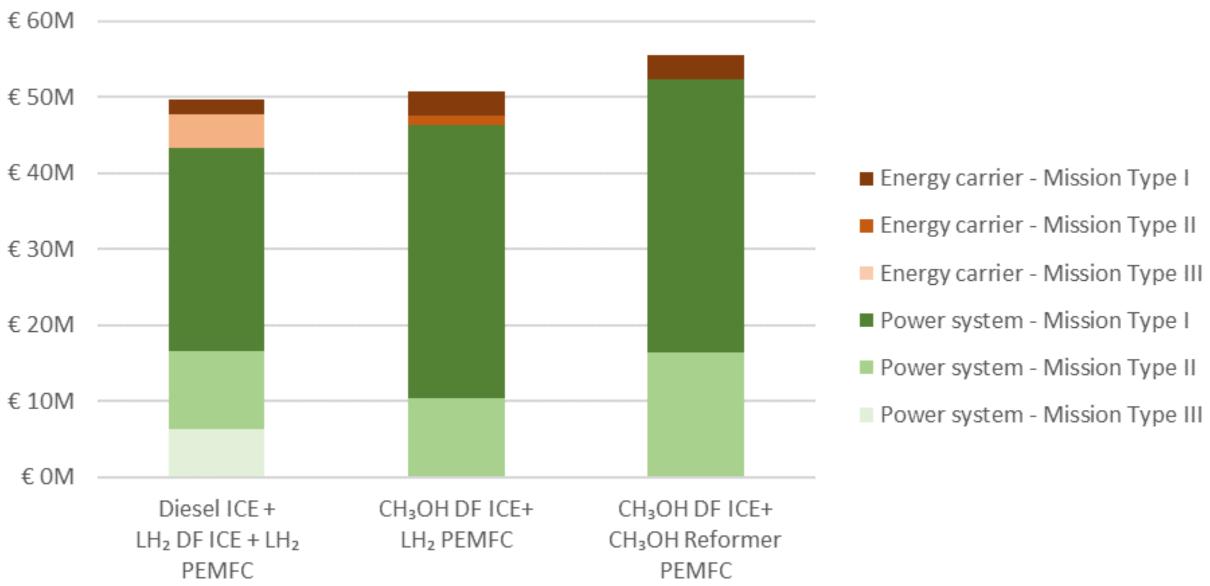
The weight and volume of the systems are shown below. Note, the 100% diesel reference is indicated with the red and green dashed lines.




Jumbo indicated extra space is available for a new PPE system as indicated in the figure below.

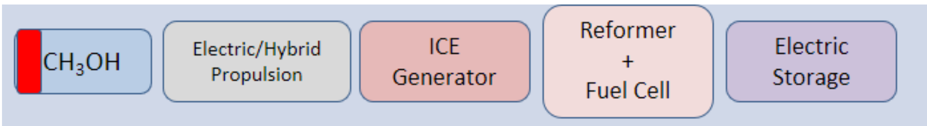



The indicative costs are shown below and cover system costs (CAPEX) only. Costs for further ship changes and operational costs are not accounted for.



**SPEC conclusion & outline test model**

The third configuration is chosen, because of the fuel reformer only one fuel needs to be carried on-board (except for the pilot diesel). Volume wise it is more compact than hydrogen storage, and yet more ambitious than choosing diesel for the longer voyages.
Hence, the preferred PPE-system is a dual fuel methanol ICE solution with a methanol-to-hydrogen reformer low temperature PEM fuel cell – battery. The following outline test model is now chosen:




with the following specifications:

| | |
|---|---|
| **Energy carrier** | |
| Methanol + pilot fuel (diesel) weight (uncontained) | 3188 metric tons |
| Methanol + pilot fuel (diesel) weight (contained) | 4345 metric tons |
| Methanol + pilot fuel (diesel) volume (contained) | 4542 $m^3$ |
| **Power system** | |
| Power system weight Methanol DF ICE | 489 metric tons |
| Power system weight Methanol Reformer PEM FC | 148 metric tons |
| Power system volume Methanol DF ICE | 943 $m^3$ |
| Power system volume Methanol Reformer PEM FC | 414 $m^3$ |
| **Total concept** | |
| Total system weight | 4982 metric tons |
| Total system volume | 24033 $m^3$ |
| Max. effective power of Methanol DF ICE concept | 20000 kW |
| Max. effective power of Methanol Reformer PEM FC concept | 3600 kW |

Due to the fuel reformer, only one additional fuel needs to be carried on-board. Volume wise it is more compact than hydrogen storage, and yet more ambitious than choosing diesel for the longer voyages.
Looking at greenhouse gas performance, this solution still performs very well. Batteries are also preferred for spinning reserve, for both ICEs and fuel cells. In WP2, it should be attempted to reduce the overall energy storage by improving the system efficiency and consider reducing redundancy, to reduce the overall installed power (and thereby volume and weight). This will also include considerations for electric or hybrid propulsion.

More detailed information can be found in the separate report *Report User Needs and Concept Design PPE system - ZERO Use Case 6 Heavy Lift Vessel.vx.x* on www.marin.nl/jips/zero (login account required).

# 8 RESULTS USE CASE 7: SURFACE COMBATANT

### Ship

As reference a possible successor of the Dutch Air Defence Frigate is taken. Obviously the reference for this Use Case is less clear due to confidentiality restrictions.

| | **Autonomy** | **Max Speed** | **Full displ.** | **Dead weight tonnage** | **Gross Tonnage** | **Installed power** | **Engine room Architecture** |
|---|---|---|---|---|---|---|---|
| | NautMiles | kts | metric tons | metric tons | GT | kW | - |
| **Reference** | 5500 | 30 | 5163 | 1600 | 4722 | 47000 | ICE-Direct |
| **Design case** | 6000 | 27 | 5163 | 1600 | 4722 | t.b.d. | t.b.d. |

### Operational analysis

Based on input from the participants the following missions are determined.

| Mission Type | Maximum total effective power & Effective Energy | | | Requirements | |
|---|---|---|---|---|---|
| | Criterion | [kW] | [MWh] | GHG | Pollutants |
| I – Intercontinental Transit | Required Autonomy: 6000nmi | 12547 | 2613 | None | IMO Tier III |
| II – Short Military Voyage | Required Endurance: 4.5 days | 24078 | 638 | None | IMO Tier III |
| III – Long Military Voyage | Required Endurance: 14.5 days | 12547 | 1097 | None | IMO Tier III |
| IV – Zero Emission Transit | Required Autonomy: 120nmi | 2202 | 27 | Zero Emission | |

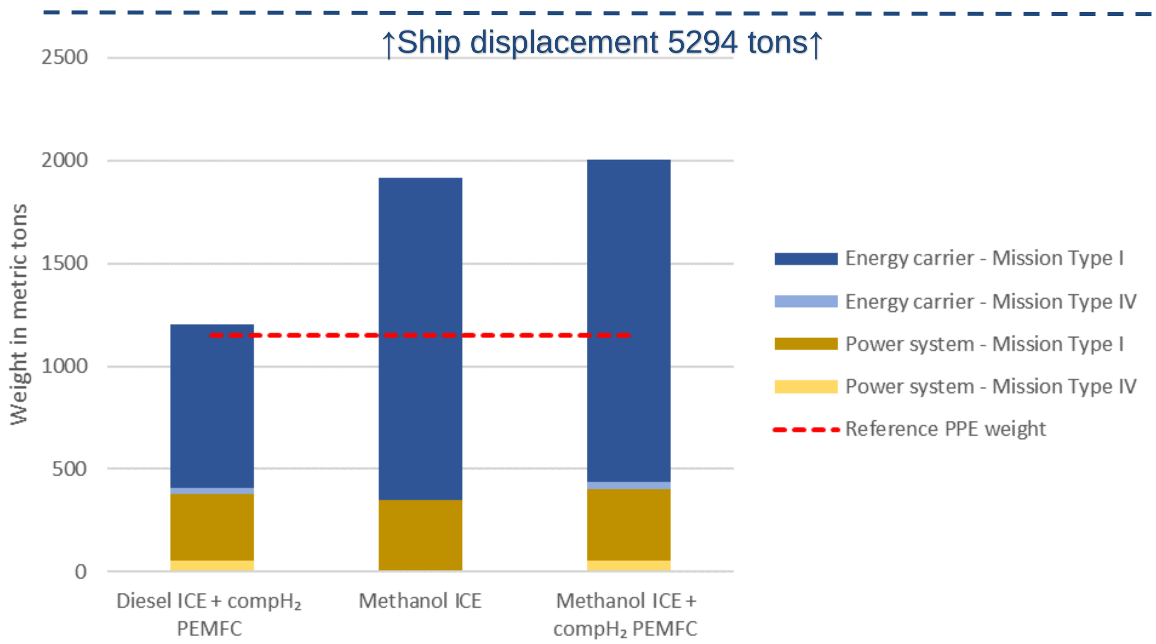
### SPEC analysis

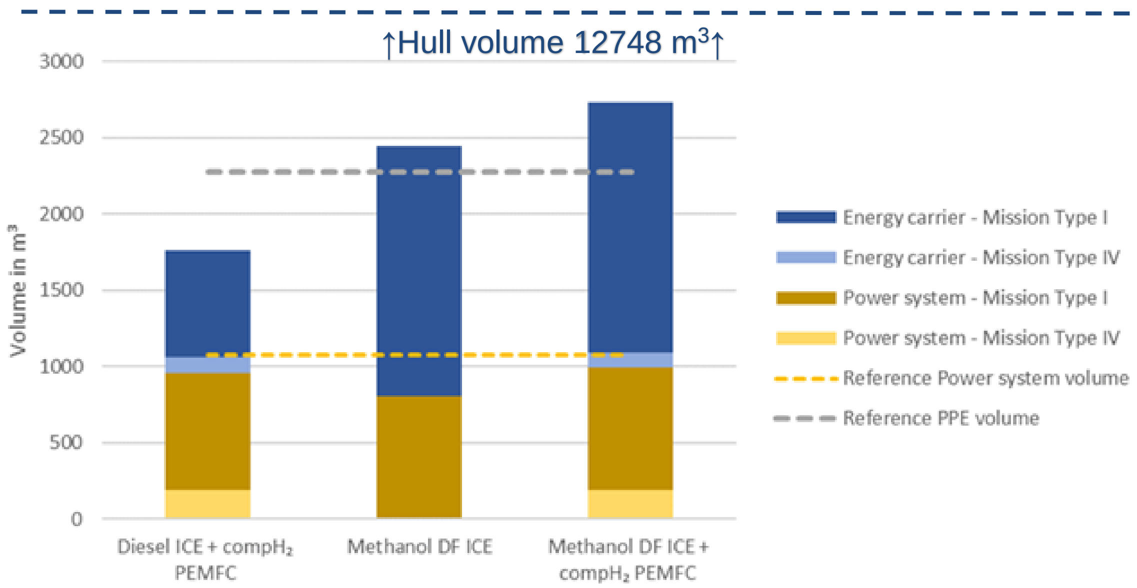
Mission Types I, II and II can be performed by one power system. Mission Type I is determinative for energy, and Mission Type II for power. Therefore the exploration was done for Mission Type I using the power requirement of Mission Type II. Mission Type IV was considered separately because of the different emission requirements.

The initial evaluation showed diesel is the only viable option within the current specifications. However the Use Case 7 group aims higher and the following options are selected for further investigation:

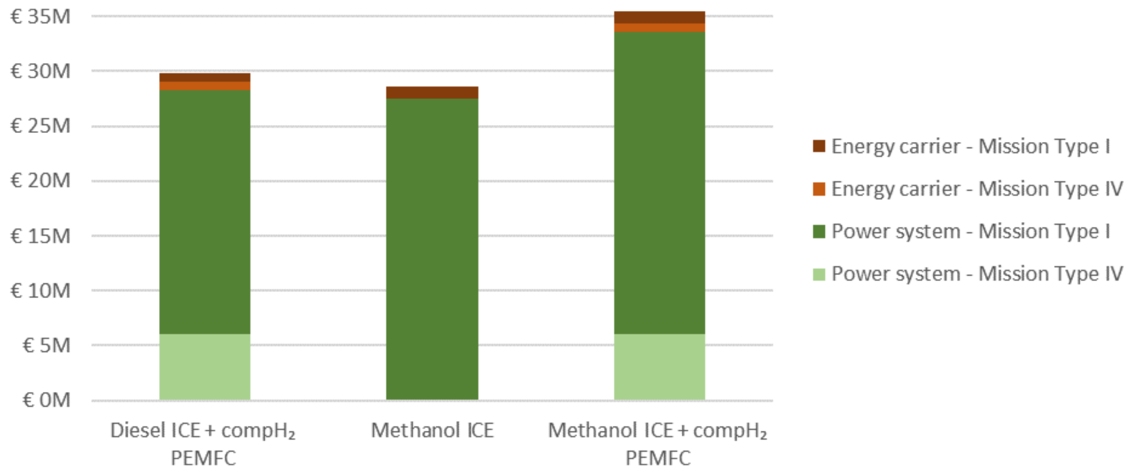
1. Diesel ICE + comp$H_2$ fuel cell system for Mission Type IV.
2. Methanol ICE DF.
3. Methanol ICE DF + comp$H_2$ fuel cell system for Mission Type IV.

Below the resulting weight and volume are shown for the energy and power systems for mission types I (note, with the power from Mission Type II) and IV. The diesel reference is indicated by dashed lines.



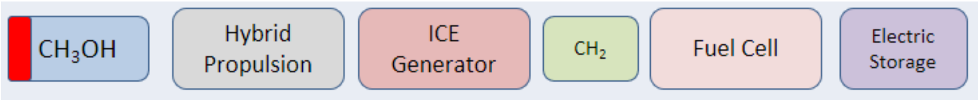




The indicative costs are shown below and cover system costs (CAPEX) only. Costs for further ship changes and operational costs are not accounted for.



**SPEC conclusion & outline test model**

The preferred PPE-system is a methanol ICE DF solution with compressed hydrogen PEMFC for Mission Type IV:




with the following specifications:

| | |
|---|---|
| **Energy carrier** | |
| Methanol + pilot fuel (diesel) weight (uncontained) | 1589 metric tons |
| Methanol + pilot fuel (diesel) weight (contained) | 2166 metric tons |
| Methanol + pilot fuel (diesel) volume (contained) | 2264 $m^3$ |
| **Power system** | |
| Power system weight Methanol DF ICE | 555 metric tons |
| Power system weight Comp $H_2$ PEM FC | 88 metric tons |
| Power system volume Methanol DF ICE | 1286 $m^3$ |
| Power system volume Comp $H_2$ PEM FC | 187 $m^3$ |
| **Total concept** | |
| Total system weight | 2809 metric tons |
| Total system volume | 3737 $m^3$ |
| Max. effective power of Methanol DF ICE concept | 40000 kW |
| Max. effective power of Comp $H_2$ PEM FC concept | 2200 kW |

The diesel based solution is too conservative, and the other methanol option does not comply with the emission requirements. Some variations are explored (ship elongation, reducing autonomy, max speed and a combination of the latter two). Any of the options show quite significant changes. Before the start of WP2 it has to be decided which of the options will be chosen to realise the preferred system.

More detailed information can be found in the separate report *Report User Needs and Concept Design PPE system - ZERO Use Case 7 Surface Combatant.vx.x* on www.marin.nl/jips/zero (login account required).

# 9 RESULTS USE CASE 8: MEGA YACHT, EXPLORER CRUISE VESSEL

### Ship

As reference the OCEANCO MY Dar is taken.

| | Autonomy<br>NautMiles | Max Speed<br>kts | Full displ.<br>metric tons | Dead weight tonnage<br>metric tons | Gross Tonnage<br>GT | Installed power<br>kW | Engine room Architecture<br>- |
|---|---|---|---|---|---|---|---|
| **Reference** | 5000 | 18 | 2350 | 400 | 2926 | 5700 | ICE-Direct |
| **Design case** | 3800 | 18 | 2350 | 400 | 2926 | t.b.d. | t.b.d. |

### Operational analysis

Based on input from mainly OCEANCO the following missions are determined.

| Mission Type | Maximum total effective power & Effective Energy | | | Requirements | |
|---|---|---|---|---|---|
| | Criterion | [kW] | [MWh] | GHG | Pollutants |
| I – Transatlantic Crossing | Autonomy 3800 NautMi | 1290 | 413 | Climate Neutral | IMO Tier III |
| II – Expedition Voyage | Endurance 14 days | 4560 | 378 | Climate Neutral | IMO Tier III |
| III – Leisure Voyage | Endurance 7 days | 4560 | 124 | Zero Emission*) | |

*) except from the events 'fast cruising' and 'maximum speed'

### SPEC analysis

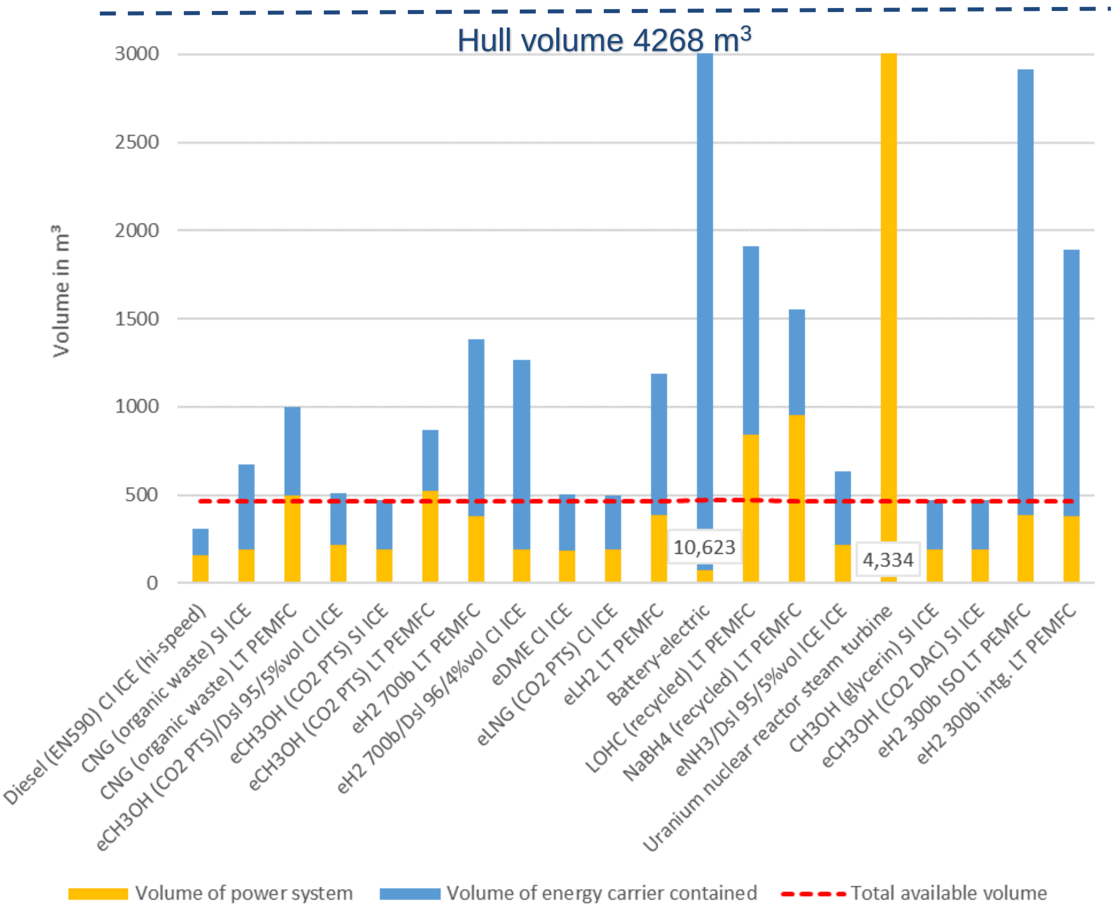
Only single-concepts per mission type are studied. A preferred combined solution is chosen for which details should be worked out in WP2, because in the current status it does not fit the available size and weight.
Mission Type I is determinative for energy. Mission Type II features the same emission requirements and could be executed by the same powering concept. However, the peak powers needed for events like max. speed, are higher than specified for Mission Type I. Therefore the maximum continuous power of Mission Type II is used here, together with the energy needs for Mission Type I. Mission type III is considered separately.

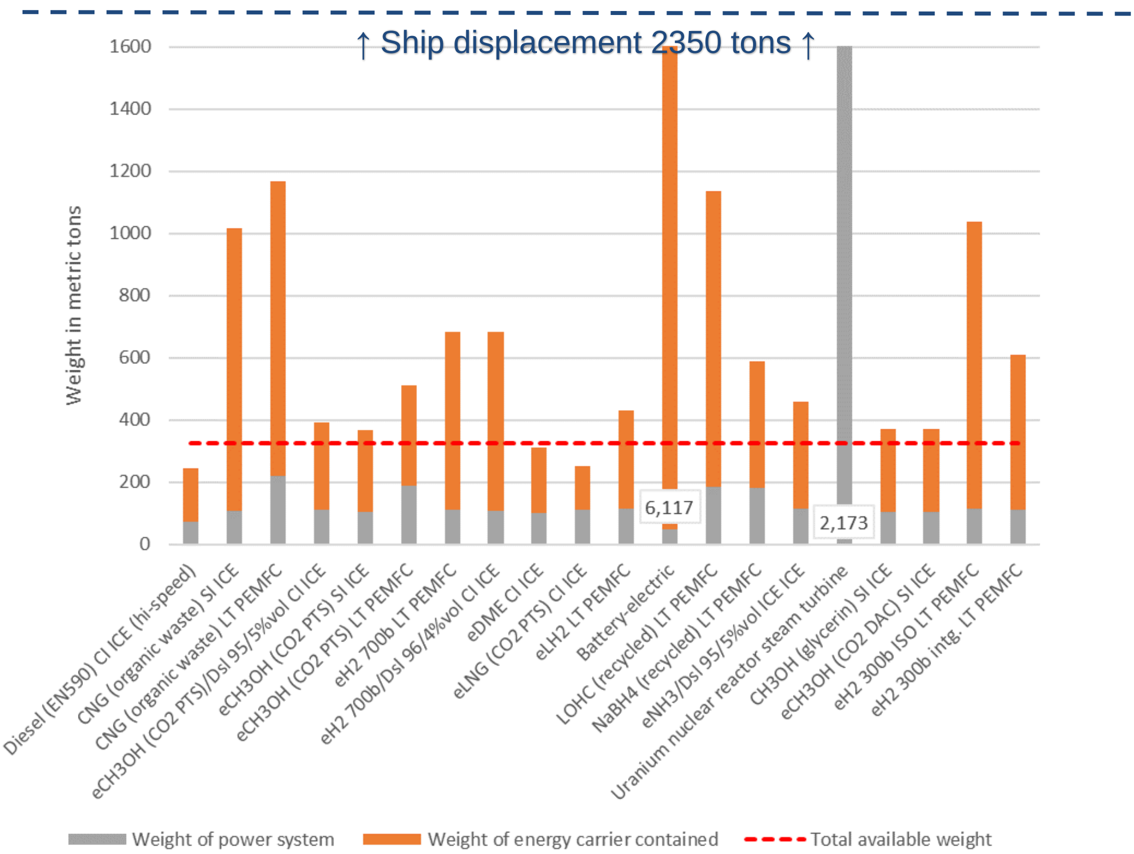
Mission Type I and II (figures on next page) show that ICE solutions with high density energy carriers are to be selected. The figures show that in fact only methanol, DME and eLNG can be integrated within the available bunker space. Because of the ease of integration, methanol is considered as preferred solution. The $CH_3OH$ SI ICE solution is specifically chosen: a (single fuel) spark ignited engine. This solution 'just' fits within the allowed volume. Note that in this assessment, a medium speed spark ignited engine is used because that information was available. However the actual power system will use a high speed engine of the volume should be less, giving some margin.

For Mission Type III (figures thereafter) liquid hydrogen can be considered, as it has the lowest overall volume need. Nevertheless, the volume needed (incl. full fuel cell power system) is almost as much as the system for Mission Type I-II.

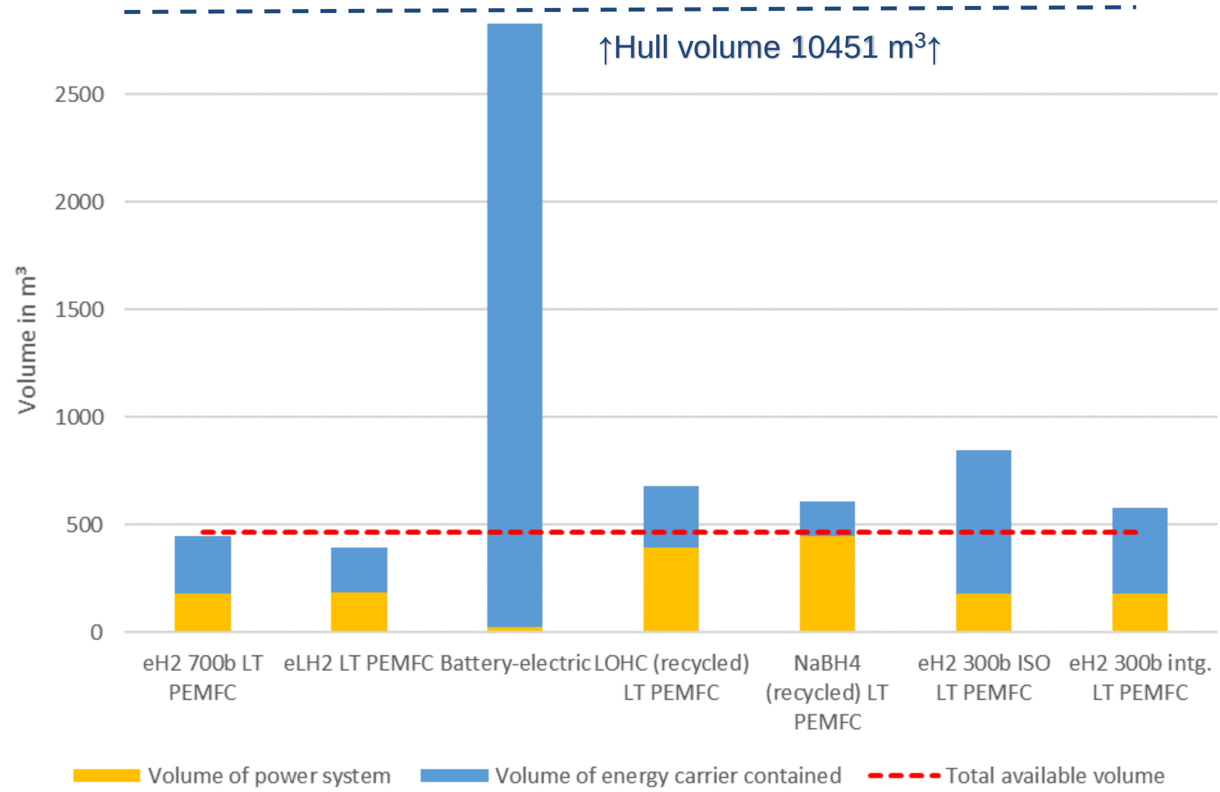
The total power would add up to 6710 kW, when combining both options. This is (well) beyond what is needed. A combination of fuel cell and ICE power, together with batteries for short peaks should be investigated in WP2. Together with a reduction of system volume by using high-speed methanol SI ICE instead of the medium speed dual fuel engines which are contained in SPEC. This all could lead to a significant reduction in volume (and weight) for the solution, making it (more) feasible.

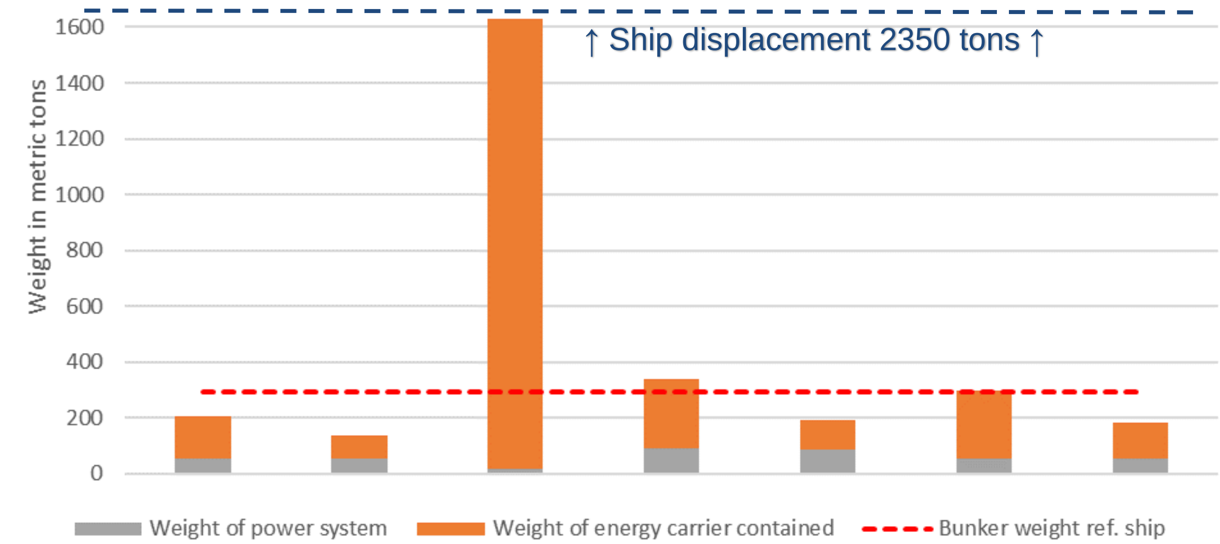
The weight and volume of the PPE system for mission type I and II are shown below.



The weight and volume of the PPE system for mission type III are shown below.

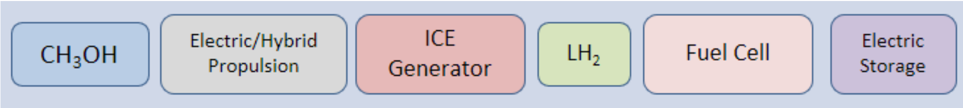



The indicative costs are not considered (yet) for this Use Case because the combined solution in WP2 will result in a significant change or system size, weight and costs.

**SPEC conclusion & outline test model**

The preferred PPE-system is a methanol ICE SI (single fuel) solution with liquid hydrogen PEMFC:




with the following specifications:

| | |
|---|---|
| **Energy carrier** | |
| Methanol weight (uncontained) | 196 metric tons |
| Methanol weight (contained) | 265 metric tons |
| Methanol volume (contained) | 282 $m^3$ |
| $LH_2$ weight (uncontained) | 8 metric tons |
| $LH_2$ weight (contained) | 83 metric tons |
| $LH_2$ volume (contained) | 210 $m^3$ |
| **Power system** | |
| Power system weight Methanol SI ICE | 105 metric tons |
| Power system weight $LH_2$ PEM FC | 56 metric tons |
| Power system volume Methanol SI ICE | 191 $m^3$ |
| Power system volume $LH_2$ PEM FC | 184 $m^3$ |
| **Total concept** | |
| Total system weight | 509 metric tons |
| Total system volume | 867 $m^3$ |
| Max. effective power of Methanol SI ICE concept | 4560 kW |
| Max. effective power of $LH_2$ PEM FC concept | 2150 kW |

More detailed information can be found in the separate report *Report User Needs and Concept Design PPE system - ZERO Use Case 8 Mega Motor Yacht.vx.x* on www.marin.nl/jips/zero (login account required).

# 10 RESULTS USE CASE 10: LARGE MOTOR YACHT

### Ship

As reference a SanLorenzo motor yacht is taken.

| | **Autonomy**<br>NautMiles | **Max Speed**<br>kts | **Full displ.**<br>metric tons | **Dead weight tonnage**<br>metric tons | **Gross Tonnage**<br>GT | **Installed power**<br>kW | **Engine room Architecture**<br>- |
|---|---|---|---|---|---|---|---|
| **Reference** | 3200 | 16.5 | 920 | 180 | 970 | 2550 | ICE-Direct |
| **Design case** | 2700 | 16.5 | 920 | 180 | 970 | t.b.d. | t.d.b. |

### Operational analysis

Based on input from SanLorenzo the following missions are determined.

| Mission Type | Maximum total effective power & Effective Energy | | | Requirements | |
|---|---|---|---|---|---|
| | Criterion | [kW] | [MWh] | GHG | Pollutants |
| I – Busy Leisure Voyage | Endurance: 14 Days | 2404 | 139 | 50% CN | Tier III |
| II – Zero Emission Leisure | Endurance: 34 Hrs | 383 | 5 | 50% CN | ZE |
| III – Atlantic Crossing | Autonomy: 2700 Nmi | 1554 | 255 | None | IMO Tier II |

Mission type III is determinative for energy and power.

### SPEC analysis

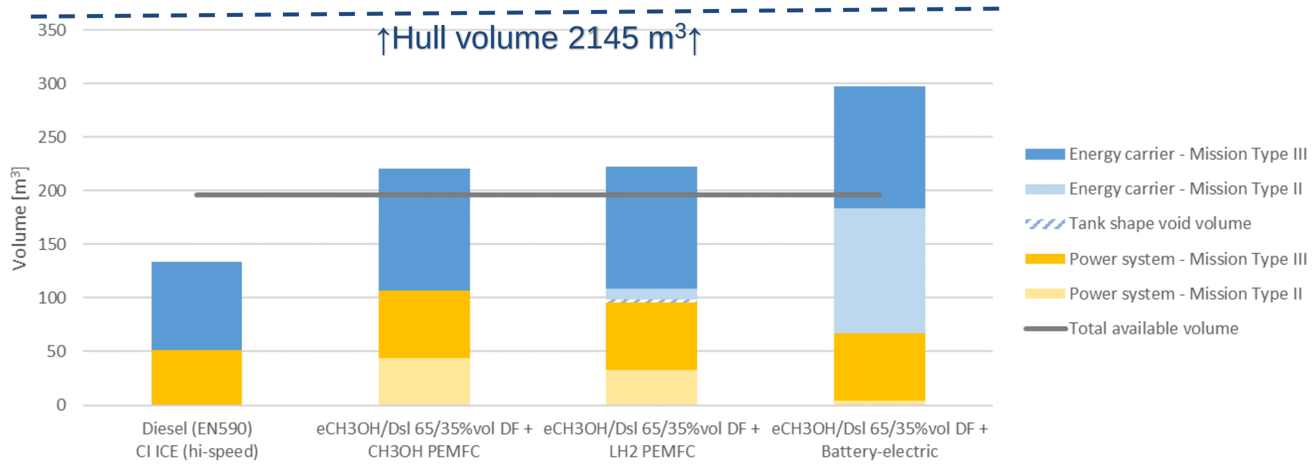
Based on initial single-concept evaluations the following multi-concepts are considered:

| Mission Type III | Mission Type II | Total (multi-concept) |
|---|---|---|
| $eCH_3OH$/Dsl 65/35%vol DF | CH3OH PEMFC | $eCH_3OH$/Dsl 65/35%vol DF + $CH_3OH$ PEMFC |
| $eCH_3OH$/Dsl 65/35%vol DF | LH2 PEMFC | $eCH_3OH$/Dsl 65/35%vol DF + $LH_2$ PEMFC |
| $eCH_3OH$/Dsl 65/35%vol DF | Battery-electric | $eCH_3OH$/Dsl 65/35%vol DF + Battery-electric |

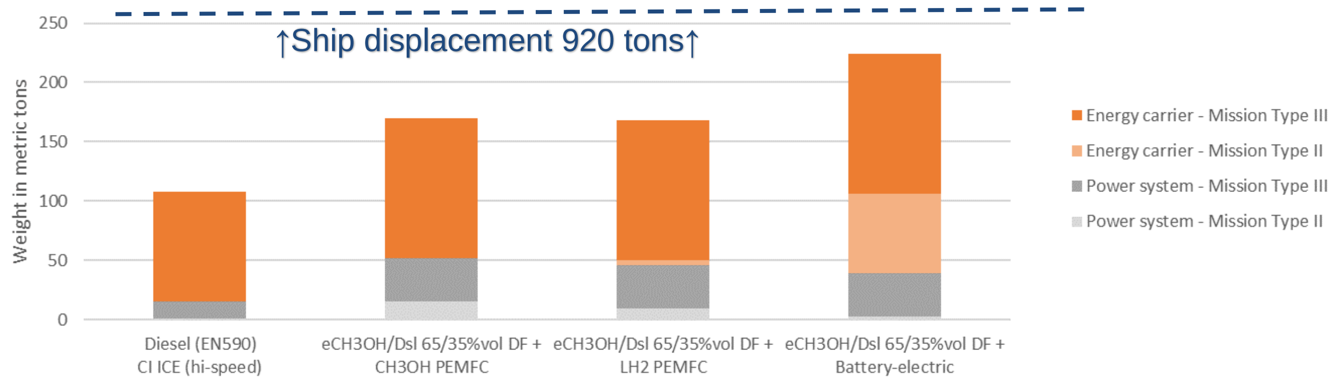
For mission type III, approximately the same bunker volume is required for the eCH3OH 95/5% DF solution, as compared with the bunker volume of the reference vessel. The power system volume of $eCH_3OH$/Dsl from Mission Type III can be reduced, due to the power of the second system from Mission Type II.

As can be seen in the figure below, this reduction has not resulted in a combined solution which fits within the available volume limit. This is mainly due to the system volume of the dual fuel engines, which are now included in SPEC as medium-speed engines (no data was available for dual fuel high speed engines). The medium-speed engines require more volume than a high-speed engine like the diesel reference concept.

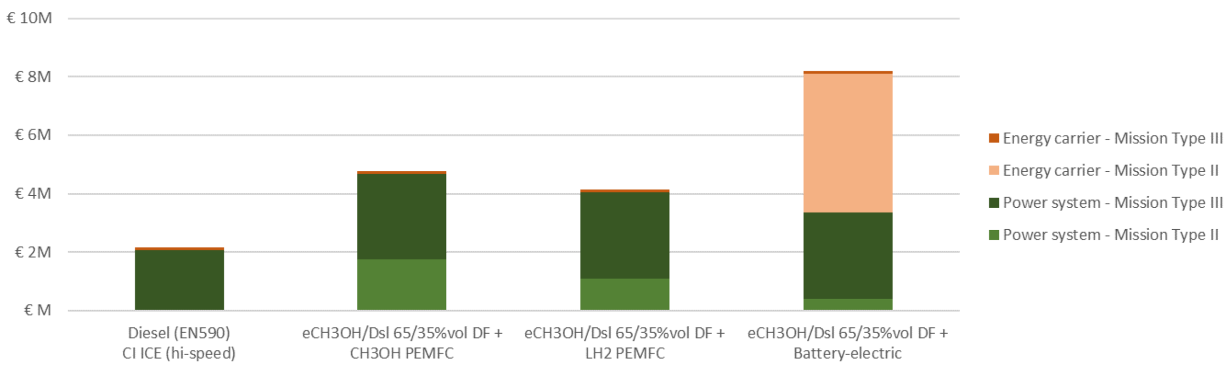
The PEMFC $eCH_3OH$ is still preferred due to the presence of only two fuels, instead of three when PEMFC $LH_2$ is chosen for Mission Type II.




The options with an $eCH_3OH$ and $LH_2$ PEMFC show about the same weight of ~160 metric tons which is approximately 17% of the vessel displacement. The option with a battery weighs 221 metric tons which is about 24% of the vessel displacement.



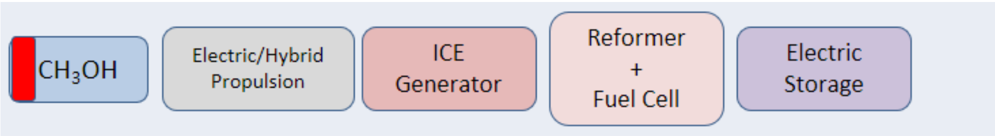

The indicative costs are shown below and cover system costs (CAPEX) only. Costs for further ship changes and operational costs are not accounted for.




Summarising the above findings, the concepts, $eCH_3OH$ and $LH_2$ PEMFC for Mission Type II combined with eCH3OH 65/35% DF for mission Types I and III, are the closest to the available volume. $eCH_3OH$ PEMFC seems to be favourable for Mission Type II, as it would only require bunkering of two different fuels (diesel and methanol).

**SPEC conclusion & outline test model**

The preferred PPE-system is an eCH3OH 65/35% DF ICE - $eCH_3OH$ PEMFC solution:




with the following specifications:

| | |
|---|---|
| **Energy carrier** | |
| Methanol + diesel weight (uncontained) | 118 metric tons |
| Methanol + diesel weight (contained) | 85 metric tons |
| Methanol + diesel volume (contained) | 114 $m^3$ |
| **Power system** | |
| Power system weight Methanol DF ICE | 36 metric tons |
| Power system weight Methanol Reformer PEM FC | 16 metric tons |
| Power system volume Methanol DF ICE | 63 $m^3$ |
| Power system volume Methanol Reformer PEM FC | 44 $m^3$ |
| **Total concept** | |
| Total system weight | 170 metric tons |
| Total system volume | 221 $m^3$ |
| Max. effective power of Methanol DF ICE concept | 2600 kW |
| Max. effective power of Methanol Reformer PEM FC concept | 383 kW |

More detailed information can be found in the separate report *Report User Needs and Concept Design PPE system - ZERO Use Case 10 Large Motor Yacht.vx.x* on www.marin.nl/jips/zero (login account required).

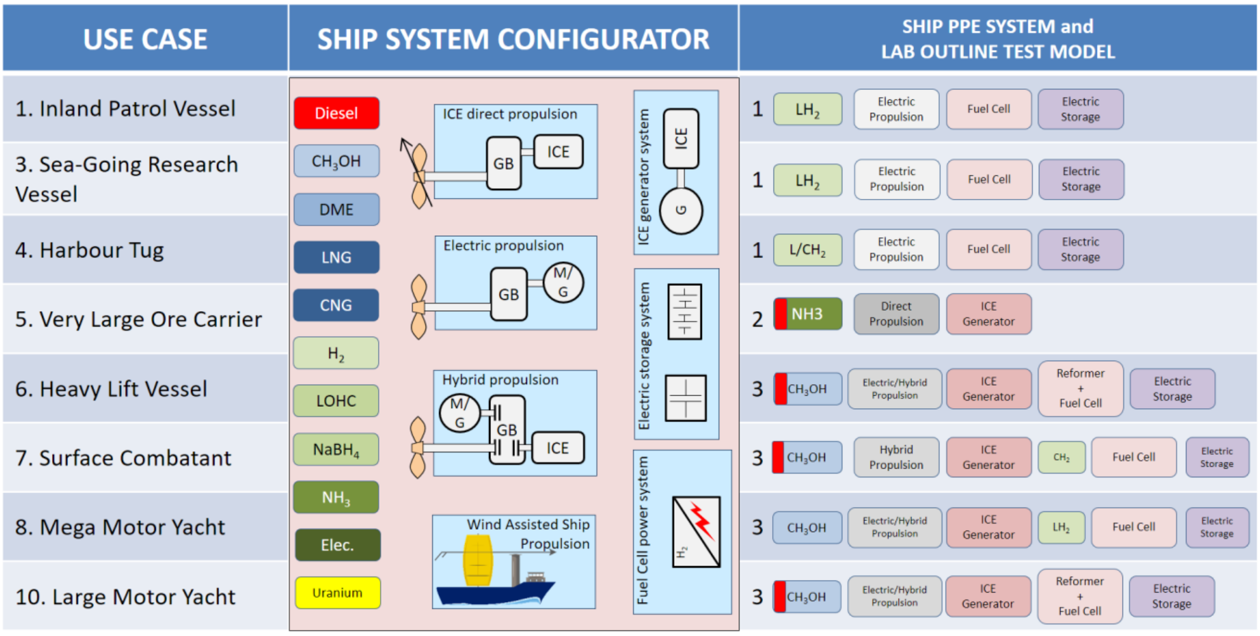
# 11 CONCLUSIONS AND RECOMMENDATIONS

## 11.1 Conclusions

This report provided the overview of the main results from the 8 ZERO JIP WP1 Use Case studies. Those studies comprised of the operational and system analysis is which the operational needs are determined which are used as input for the SPEC analysis. In the SPEC analysis different energy and power concepts are compared w.r.t. weight, size and costs.

Depending on the Use Case and the Mission Types defined, different system configurations were investigated. For some Use Cases a single-power concept approach (using one power converter and energy carrier) was sufficient to provide a good overview to choose from. For other Use Case specific multi-power concepts (e.g. combinations of power converters, energy carriers, use of batteries) were determined based on an initial single-power assessment to come to more realistic PPE solutions. Especially Use Case with a wide variety of mission types need multi-power concepts to be able to keep PPE size and weight low.

This study resulted in the following PPE system choices per Use Case (right column):




These resulting PPE systems are also called the Lab outline test models; the first step towards the definition of the actual models that will be configured and tested in WP4 (Development and Verification of Lab Test Models) and WP5 (Testing and validation of the Lab Test Models).
The numbers in front of the test models in the right column are to cluster w.r.t. the system configuration:

1. Full electric FC solution.
2. Direct ICE solution.
3. Combined ICE and FC hybrid solution.

Note, for some Use Cases the definite choice of the propulsion type (direct, electric or hybrid) is obvious, for other Use Cases less. WP2 (Concept Design) will take these results as input and the propulsion type choice will be considered and checked in more detail.

## 11.2 Recommendations

For all solutions considered in this work package holds, that they are defined based on average characteristic of the PPE system components, like energy and power density, costs and emissions.

WP2 (Concept Design) and WP3 (Basic Engineering) should take this a step further, using more specific PPE-system component properties, optimising on efficiency, size and weight versus power density, optimising battery size for peak shaving, deciding on propulsion type and finally determine the overall PPE system specifications.

The emission estimates should be verified by means of in depth simulations and tests in which the PPE system is dynamically tested with time dependant power loadings. This will be done in WP4 (Development and Verification of Lab Test Models) and WP5 (Testing and validation of the Lab Test Models).

The above conclusions and recommendations do not supersede the statements made in the previous chapters and in the tables and figures with results.

Wageningen, November 2022
MARITIME RESEARCH INSTITUTE NETHERLANDS

Ir. G. Gaillarde
Head of Ships Department

## APPENDIX A: LIST OF ACRONYMS

| | |
|---|---|
| 300b | Storage system designed for 300 bar pressure |
| 700b | Storage system designed for 700 bar pressure |
| CAPEX | Capital expense |
| $CH_2O_2$ | Molecular formula of formic acid (energy carrier) |
| $CH_3OH$ | Molecular formula of methanol (energy carrier) |
| CI | Compressed ignited cycle |
| CN | Carbon-neutral |
| CNG | Compressed Natural Gas (energy carrier) |
| Comp | Compressed |
| DF | Dual-fuel (usually features a diesel pilot fuel) |
| DME | DiMethyl Ether (energy carrier) |
| DP | Dynamic positioning |
| Dsl | Diesel (energy carrier) |
| EPDT | Event Power Distribution Table |
| EPTC | Event Power Time Chart |
| FC | Fuel cell |
| FePowder | Iron powder (energy carrier) |
| GHG | Greenhouse gasses, specifically $CO_2$, $CH_4$ and $N_2O$ |
| $H_2$ | Molecular formula of hydrogen |
| hrs | hours |
| ICE | Internal Combustion Engine |
| ICE-direct | Engine room architecture in which the main engines directly drive the propulsion shafts and the electric distribution is provided via a separated electric distribution |
| ICE-electric | Engine room architecture in which the propulsion power is delivered by electric motors powered by ICE generator sets |
| IMO | International Maritime Organisation |
| JIP | Joint Industry Project |
| kW | kilowatt |
| kWh | kilowatt-hour |
| $LH_2$ | Liquefied Hydrogen (energy carrier) |
| LNG | Liquefied Natural Gas (energy carrier) |
| LOHC | Liquid Organic Hydrogen Carrier (energy carrier) |
| LT PEMFC | Low Temperature Prototon-Exchange Membrane Fuel Cell |
| MBSE | Model Based Systems Engineering |
| MPTC | Mission Power Time Chart |
| MWh | Megawatt-hour |

| | |
|---|---|
| MY | Motor yacht |
| $NaBH_4$ | Molecular formula of sodium borohydride (energy carrier) |
| NautMiles | Nautical miles |
| $NH_3$ | Molecular formula of ammonia (energy carrier) |
| OC | Operational Capability |
| OR | Operational Requirement |
| PPE | Power, propulsion & energy |
| PTC | Power Time Characteristics |
| PTO | Power take-off |
| Reformer | Fuel pre-treatment system that can extract hydrogen from other energy carriers |
| SeCo | Surveillance and communication |
| SI | Spark ignited cycle |
| SOFC | Solid Oxide Fuel Cell |
| SPEC | Ship Power and Energy Concepts (tool) |
| Tier II | Emission standards for NOx emissions (7.7 - 14.4 g/kWh) |
| Tier III | Emission standards for NOx emissions (2 - 3.4 g/kWh) |
| TRL | Technical readiness level |
| V&V | Verification & validation |
| WP | Work package |
| ZE | Zero Emission |

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