

Green Deal Electrification

Electrification of sea-going vessels





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Summary

This report, produced by TNO and MARIN, investigates the feasibility, benefits, and challenges of electrifying propulsion systems for oceangoing vessels. The study is part of the Dutch Green Deal program, aiming to validate emission reduction technologies for the maritime sector, with a focus on electrification as a pathway to meet ambitious greenhouse gas (GHG) reduction targets set by the IMO and the Dutch government.

The report provides a nuanced, data-driven assessment of maritime electrification, highlighting both the potential and the limitations. While electrification can deliver environmental and operational benefits for certain vessel types, widespread adoption will require careful consideration of technical, economic, and operational factors, as well as further research into emerging technologies and infrastructure support.

Our key research questions addressed include:

- For which ship types and operations is electrification advantageous ?
Can electrification of the propulsion line benefit from lower fuel consumption over a typical operational profile by load distribution compared to a diesel-direct solution ?
- Can an electrified propulsion line benefit from applying battery assistance by operational load distribution ? What is the impact on the ship and operational use of applying batteries in operation in and near harbour areas ?
- Can the electrification of the propulsion line benefit from total average system efficiency in dynamic operation conditions by improved control strategies ?
- How significant is the electrification of the propulsion line on the total cost of ownership for the whole vessel in its operation ?

Methodology

The study combines literature review, market analysis, operational profiling, technical feasibility studies, dynamic simulations, and economic modelling.

- Literature & Market Survey: Assesses current adoption and readiness of electrification in shipping.
- Operational Profiles: Defines typical journeys and power demands for six vessel archetypes.
- Technical Feasibility: Evaluates weight, volume, and integration challenges for electrified systems. For 'electrified systems' we mean that electricity is used to power the ship propulsion systems. This electricity can come from generator sets or from a battery. We studied three types of propulsion (Internal Combustion Engine as a reference, ICE-electric and Hybrid).
- Dynamic Simulations: Analyses system efficiency under real-world conditions.
- Economic Analysis: Uses the NavigaTE TCO model to compare costs across propulsion types.

Vessel Archetypes Studied

The six reference ship types as defined in the Green Deal were analysed:

- Short Sea Transport Vessel
- Harbour Tugboat
- Offshore Supply Vessel

- Crew Tender Catamaran
- Trailing Suction Hopper Dredger
- Mega Motor Yacht

Each archetype was assessed for technical feasibility, operational efficiency, and economic impact of electrification.

Key Findings

The key findings are tabulated in the table below for each vessel archetype.

Vessel Type	Technical Feasibility	Fuel Savings	TCO Impact	Environmental Benefit	Notes
Harbour Tugboat	High	~5%	Moderate	High	Good candidate for hybrid / electric
Offshore Supply Vessel	High	~7%	Moderate	High	Layout flexibility, Dynamic Positioning benefits
Dredger Vessel	High	~9%	Moderate	High	High payload power, electrification common
Short Sea Transport Vessel	Moderate	0–2%	Small	Limited	Weak business case for electrification
Crew Tender Catamaran	Low (full electric)	0–2%	Small	Limited	Weight / space constraints, hybrid possible
Mega Motor Yacht	Moderate	0–1%	Small	Comfort / noise focus	Layout and comfort benefits

a. Technical and Safety Challenges

- Complexity in Ship Design: Electrification increases the complexity of ship design, especially regarding space, weight, and integration of new systems. Not all vessel types are equally suited for electrification; feasibility depends heavily on operational profile and vessel design.
- Battery Safety: Batteries introduce specific safety risks, such as fire hazards, and require robust management and safety systems.
- Space and Weight Constraints: For certain vessels (e.g., crew tenders, mega yachts), space and weight limitations make full electrification impractical. Hybrid or battery-assisted systems may be more suitable for these cases.

b. Environmental Impact

- Electrification of the propulsion line and application of battery systems can affect the operating conditions of main machinery significantly in specific conditions, hence reducing GHG emissions, air pollutants (NO_x, SO_x, PM), and noise, which is especially beneficial in near-shore operations.
- The actual environmental benefit depends on whether the energy used is from renewable or fossil-based sources, as well as the vessel’s operational pattern. Vessels with frequent low-speed or dynamic operations (like tugs, dredgers, offshore supply vessels) see the greatest environmental benefits from electrification.

- c. Operational and Economic Analysis
 - Significant fuel savings were observed for harbour tugboats (5%), offshore supply vessels (7%), and dredger vessels (9%). For other types, savings are marginal (0–2%).
 - For general cargo vessels, the TCO differences between internal combustion engine (ICE), hybrid, and ICE-electric systems are small. Electrified systems have higher capital expenditures (CAPEX), but operational expenditures (OPEX) such as fuel and maintenance are similar across architectures.
 - Batteries enable zero-emission and silent operation near ports, but their economic and technical feasibility is highly case-dependent. Shore-based charging could improve the viability of battery solutions.
- d. Design and Integration
 - Electrification offers greater flexibility in ship layout and can reduce noise and vibration.
 - For some vessel types (e.g., crew tenders, mega yachts), space and weight constraints limit the practicality of full electrification.
 - Hybrid and battery-assisted systems may be more suitable for vessels with highly variable load profiles or frequent low-speed operations as they can optimise engine loading and reduce emissions during idling or manoeuvring.

Main conclusions

- Electrification is not a one-size-fits-all solution; its feasibility and benefits are highly dependent on vessel type, operational profile, and integration challenges.
- The most promising candidates for electrification are vessels with frequent low-speed or dynamic operations (tugs, dredgers, offshore supply).
- For general cargo vessels and similar types, the business case for electrification is weak under current assumptions.
- Further research is recommended on advanced control strategies, battery integration for other vessel types, and the impact of shore-based charging infrastructure.

Recommendations for Further Research

- Extend dynamic simulation studies to more vessel types and hybrid architectures.
- Investigate TCO for tugs and dredgers, where fuel savings are more substantial.
- Explore the scalability of battery systems and the role of port infrastructure in supporting electrification.

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1 Introduction

The current study is a part of the NL Green Deal program, which aims to validate options for emission reduction technologies in the maritime industry. In this case there is no specific solution of a technology provider validated, but the investigation of the potential effects by changing the ship's drive train design to full or partial electric propulsion.

The change to electric propulsion has impact on many aspects of the ship design and can have different effects on various type of vessels. In other words it is very much depending on the specific application how favourable electrification is for emission reduction, technical applicability and economic feasibility. Hence, earlier defined application cases are utilized to explore the impact of electrification of the propulsion system of ships.

1.1 The 'Green Deal'

The increase in global exhaust and greenhouse gas (GHG) emissions combined with a rapid depletion of fossil fuels over the past decades, have swayed the transportation industry towards more sustainable energy sources. The revised strategy of the European Union (EU) and the IMO (International Maritime Organization) to reach a goal of net zero emissions from ships "by or around 2050", is a major increase in the level of ambition compared to the previous strategy of reducing emissions from ships by just 50% in the same time horizon. A trajectory has also been agreed with indicative checkpoints set at reducing GHG emissions from ships by at least 20% - striving for 30% - in 2030 and at least 70% - striving for 80% - in 2040, both in comparison to 2008 levels [1]. They aim to eliminate GHG emissions entirely within this century, by using various technologies and innovative solutions that would make the ships operate more efficiently.

These ambitious goals call for solutions that can be applied today, because ships that are put into service today will most likely still be operational in 2050. The diversity of available sustainable maritime solutions makes it difficult to determine which solution is most suitable for application on a ship as this depends on many factors. For example, each solution differs in the required space on board, the layout of the ship and integration with other systems, as well as for the costs and earning capacity of the ship itself.

There is a large array of available sustainable solutions for various ship types, for various operational conditions and lengths of shipping routes. It is therefore important that the effects of these solutions are made transparent in an independent manner and that through validation reliable information is collected so that these solutions can be weighed against each other (ref. NL Green Deal art.12 paragraph 3: "Knowledge institutions will work with the industry to provide independent insight into and validate the effects of the sustainable maritime solutions so that comparison of these solutions is possible and it is easier for shipowners and financiers to compare."). The results of the performed validations aim to provide reliable information for all parties in the maritime chain, making it easier to choose sustainable solutions.

Green Deal validation program

The Green Deal validation program of the Ministry of Infrastructure and Water management (I&W) offers the opportunity to independently review reduction measures. The marine sector, represented by KVNR and NMT, plays an important role in putting forward the key solutions for GHG reductions which can be implemented or scaled up in the near future. KVNR and NMT consult the sector (technology providers and ship owners) to identify the most important techniques to validate.

Validation is performed by the knowledge institutes TNO and MARIN.

This validation includes the following aspects:

- **Environmental impact** - impact on reduction of GHG and pollutant emissions
 - This is the core of the validation: the provider claims an emission reduction technique, which is validated by an independent study.
- **Applicability** to the maritime fleet (categories)
 - Related to the 6 reference ships identified in the Green Deal [3].
 - Identifying possible opportunities and obstacles.
- **Technical impacts**
 - Impact on technical implementation to the ship design is given for each use case
- **Economic aspects**
 - Total cost of ownership is calculated including CO₂ price evaluations for 1 use case

1.2 Research questions on electrification

Consultation of KNVR and NMT to shipowners figured that many find it unclear what options there are for electrifying their ships and the potential impact it could have. The absence of clear and transparent information regarding these options might deter shipowners from embracing electrification. Consequently, shipowners may miss out on more suitable technological solutions, leading to ships emitting more greenhouse gases than their electrified counterparts.

This study is motivated by typical research questions from the sector:

- When (for which type of ship and operation) can electrification of an ICE-mechanical powered ship be advantageous?
- What impact does electrification have on the propulsion, power, and energy systems, including propellers ?
- What efficiency gains can be achieved by altering the entire propulsion train?
- What are the impacts of applying batteries to operations in and close to the harbour?

Electrification of the ship's propulsion train can be achieved in various ways. And the potential impact on fuel consumption reduction and therefore economic (OPEX) and environmental impact (CO₂) can also be made in various manners. High over, the above sector questions combine into the main research question:

- *How feasible is electrification of the ship propulsion drive system?*

To answer this, the following sub-questions are addressed:

- *For which ship types and operations is electrification advantageous? Can electrification of the propulsion line benefit from lower fuel consumption over a typical operational profile by load distribution compared to a ICE-mechanical solution?*

This question explores which vessel types and operational scenarios are most likely to benefit from electrification, and whether improved load distribution in electric or hybrid systems can lead to measurable fuel savings compared to conventional ICE-mechanical propulsion.

- ***Can an electrified propulsion line benefit from applying battery assistance by operational load distribution? What is the impact on the ship and operational use of applying batteries in operation in and near harbour areas?***

Here, the focus is on the potential of batteries to further optimize energy use—either by supporting propulsion during specific operational phases (such as manoeuvring or port operations) or by enabling zero-emission and silent operation in sensitive areas. The question also considers the technical and operational implications of integrating batteries into ship systems.

- **Can the electrification of the propulsion line benefit from total average system efficiency in dynamic operation conditions by improved control strategies?**

This question investigates whether advanced control strategies in electrified systems can enhance overall efficiency, especially under dynamic or variable operating conditions, such as those encountered in rough seas or during frequent changes in speed and load.

- **How significant is the electrification of the propulsion line on the total cost of ownership for the whole vessel in its operation?**

Finally, this question addresses the economic dimension: does electrification (including hybrid and battery-assisted configurations) offer a compelling business case when considering both capital expenditures (CAPEX) and operational expenditures (OPEX) over the vessel's lifecycle?

Scope and boundaries

The study focusses on three main electrification architectures

- **ICE-electric:** full electric propulsion powered by Internal Combustion Engine (ICE)-driven generator sets.
- **ICE-mechanical & ICE-electric hybrid:** combined mechanical and electric propulsion, with flexibility for different operational modes.
- **Battery assisted:** integration of battery packs to support or replace generator sets, particularly for zero-emission or low-emission operations near ports.

All electrified configurations are benchmarked against the conventional **ICE-mechanical** reference architecture, with an ICE directly coupled to the propeller, typically via a reduction gear for the vessels in scope. The electric energy on board is supplied with Genset, and potentially a shaft generator.

1.3 Reference ships

As indicated, to investigate the environmental effects of electrification of the propulsion plant of ships, the reference ship types as indicated in the former Green Deal project 'Vervolgstappen validatie methodieken t.b.v. transitie naar emissieloze scheepvaart' [3] are being explored. For each vessel type, a reference ship was chosen to which the electrification is being investigated.

These include:

Table 1-1: Ship types and case study reference vessels from [3]

Ship archetype	Use case specific reference vessel in this study
Small to medium size General Cargo Vessel	Short Sea Transport Vessel
Small tugging ships	Harbour Tugboat
Small offshore vessel	Offshore Supply Vessel
Small working vessel	Crew Tender Catamaran
Dredging vessel	Trailing Suction Hopper Dredger
Superyachts	Mega Motor Yacht

The use case specific reference ships are given in the following sub paragraphs.

1.3.1 Short sea transport vessel

The short sea transport vessel is a general cargo vessel that typically operates in near coastal areas and visiting European ports along the Baltic, North Atlantic, North Sea and Mediterranean Sea. Capable of ocean crossings. In the specific use case, the use of electric cooled containers (reefers) is assumed as payload.



Figure 1-1: Example General Cargo Vessel

Table 1-2: Particulars of the Short sea transport reference vessel

Length	Beam	Displacement	Installed power	DWT	Autonomy
[m]	[m]	[m ³]	[kW]	[tonnes]	[days]
112	18.2	12800	4540	9216	30

Table 1-3: Propulsion power and energy (PPE) system layout of the Short sea transport reference vessel

Number of propulsion lines	Propeller type	Propulsion prime movers	Electric power supply	Payload equipment
1	CPP	1x 4000bkw ICE	2x 270 kWe genset 1x 500 kWe shaft generator	450 kWe reefer connection

1.3.2 Harbour tug boat

The harbour tug boat is based on a typical harbour constraint tug that allows vessel escort from open sea towards a unloading quay and vice versa.

In the specific use case, the hydraulic winch is assumed as payload.



Figure 1-2: Example Harbour Tug Boat

Table 1-4: Particulars of the harbour tug

Length	Beam	Displacement	Installed power	DWT	Autonomy
[m]	[m]	[m3]	[kW]	[tonnes]	[days]
32	12	1140	5350	285	15

Table 1-5: Propulsion power and energy (PPE) system layout of the Harbour tug

Number of propulsion lines	Propeller type	Propulsion prime movers	Electric power supply	Payload equipment
2	Azimuthing FPP in nozzle	2x 2525bKW ICE	2x 150 kWe genset	Main engine driven hydraulic pumps

1.3.3 Offshore supply vessel

The Offshore supply vessel is a small offshore transport vessel that typically operates between European ports and near shore offshore structures in the North Atlantic and North Sea. To offload near offshore structures, Dynamic Positioning is available. In the specific use case, offloading equipment is assumed as payload equipment.



Figure 1-3: Example Offshore Supply Vessel

Table 1-6: Particulars of the Offshore supply vessel

Length	Beam	Displacement	Installed power	DWT	Autonomy
[m]	[m]	[m3]	[kW]	[tonnes]	[days]
82	17.5	5800	7200	2900	5

Table 1-7: Propulsion power and energy (PPE) system layout of the Offshore supply vessel

Number of propulsion lines	Propeller type	Propulsion prime movers	Electric power supply	Payload equipment
2	CPP in nozzle	2x 3000b kW ICE	3x 400 kWe genset	600 kWe offloading equipment

1.3.4 Fast crew transfer vessel

The fast crew transfer vessel is a small offshore workboat that typically operates in near coastal areas and transiting between European ports and offshore installations such as offshore windfarms along the Baltic, North Sea and Mediterranean Sea. In the specific use case, the hotel services are assumed as payload.



Figure 1-4: Example Crew Tender Catamaran

Table 1-8: Particulars of the Crew transfer vessel

Length	Beam	Displacement	Installed power	DWT	Autonomy
[m]	[m]	[m ³]	[kW]	[tonnes]	[days]
25	9	90	2360	20	3

Table 1-9: Propulsion power and energy (PPE) system layout of the Crew transfer vessel

Number of propulsion lines	Propeller type	Propulsion prime movers	Electric power supply	Payload equipment
2	FPP	2x 1100bkW ICE	2x 80 kWe genset	120 kWe HVAC

1.3.5 Trailing suction hopper dredger

The trailing suction hopper dredger is a dredging vessel that typically operates in near coastal areas and offloading in near shore locations. In the specific use case, the dredging and offloading pumps are assumed as payload equipment.



Figure 1-5: Example Trailing Suction Hopper Dredger

Table 1-10: Particulars of the Trailing suction hopper dredger

Length	Beam	Displacement	Installed power	DWT	Autonomy
[m]	[m]	[m3]	[kW]	[tonnes]	[days]
125	28	29750	13870	21000	14

Table 1-11: Propulsion power and energy (PPE) system layout of the Trailing suction hopper dredger

Number of propulsion lines	Propeller type	Propulsion prime movers	Electric power supply	Payload equipment
2	CPP in nozzle	2x 6000b kW ICE	1x 1870 kWe genset 2x 4000 kWe shaft generator	7500 kWe dredge pump 2x 1500 kWe jet pump

1.3.6 Mega motor yacht

The mega motor yacht is the largest type of super yachts that typically operates in Mediterranean sea and Caribe. Capable of ocean crossings. In the specific use case, the hotel services of the passengers are assumed as payload equipment.



Figure 1-6: Example Mega Motor Yacht

Table 1-12: Particulars of the Mega motor yacht

Length	Beam	Displacement	Installed power	DWT	Autonomy
[m]	[m]	[m3]	[kW]	[tonnes]	[days]
100	17.2	4600	17700	460	14

Table 1-13: Propulsion power and energy (PPE) system layout of the Mega motor yacht

Number of propulsion lines	Propeller type	Propulsion prime movers	Electric power supply	Payload equipment
2	FPP	2x 7500kW ICE	3x 900 kWe genset	600 kWe hotel services

1.4 Reading guide

This report is structured to guide the reader through the investigation of ship electrification, starting from the context and research questions, moving through methodology, and then presenting results and conclusions. The chapters are organised as follows:

Summary

Provides a concise overview of the study’s objectives, key findings, and main conclusions. Start here for a high-level understanding of the report’s scope and outcomes.

1. Introduction

Sets the context for the Green Deal program and the motivation for the study. It explains the background, the sector’s questions, and the reference ship types used for analysis.

2. Methodology

Describes the approach taken in the study, including literature review, market analysis, operational profiling, technical feasibility studies, dynamic simulations, and economic modelling. This chapter clarifies how the research questions are addressed and introduces the analytical tools and models used.

3. Generic Feasibility Study

Presents the literature and market survey on the current state of ship electrification, identifies driving factors, and assesses ship design parameters. This chapter answers the initial feasibility question and provides context for the detailed studies that follow.

4. Detailed Feasibility Studies

Examines each reference vessel type in detail, analysing operational profiles, propulsion architectures, and the technical and economic feasibility of electrification. Results are presented for general cargo vessels, harbour tugs, offshore supply vessels, crew tender catamarans, dredger vessels, and mega motor yachts. Each section includes operational analysis, architecture comparison, and fuel efficiency assessment.

5. Dynamic Simulation Studies

Explores the impact of batteries and advanced control strategies on system efficiency and emissions, using time-domain simulations for selected vessel types. This chapter provides deeper insights into operational scenarios such as zero-emission sailing and generator downsizing.

6. Total Cost of Ownership Analysis

Compares the total cost of ownership (TCO) for different propulsion system architectures, focusing on the general cargo vessel. It details capital and operational expenditures and discusses the economic implications of electrification.

7. Conclusions

Summarizes the main findings, discusses the advantages and disadvantages of electrification for each vessel type, and provides recommendations for further research and sector implementation.

8. References and Appendices

Lists all sources cited and provides supplementary material, including detailed model descriptions and additional simulation results.

2 Methodology

The study combines literature review, market analysis, operational profiling, technical feasibility studies, dynamic simulations, and economic modelling.

- Literature & Market Survey: Assesses current adoption and readiness of electrification in shipping.
- Operational Profiles: Defines typical journeys and power demands for six vessel use cases.
- Technical Feasibility: Evaluates weight, volume, and integration challenges for electrified systems. For 'electrified systems' we mean that electricity is used to power the ship propulsion systems. This electricity can come from generator sets or from a battery. We studied three types of propulsion (ICE-mechanical as a reference, ICE-electric and Hybrid).
- Dynamic Simulations: Analyses system efficiency under real-world conditions.
- Economic Analysis: Uses the NavigaTE TCO model to compare costs across propulsion types.

The application of electrification of the propulsion system can happen in many ways and is very much case specific. A standard approach for each use case is taken in order to find generic answers to the potential benefits of electrification.

2.1 Generic feasibility studies

To answer the first research question, *How feasible is electrification of the ship propulsion drive system?*, the following steps are taken:

- Perform literature and market survey on current state of propulsion electrification in the existing shipping fleet
- Identify driving factors for electrification
- Assessment on ship design parameters

The market study is performed by analysis of the World Fleet Register (WFR) from Clarksons Research as a reference [4]. The vessels are filtered and grouped into the categories comparable to the applicable ship archetypes of the project.

Identification of driving factors is given from an expert opinion. Effects are given per ship archetype.

The assessment on ship design parameters is performed with MARIN's inhouse developed tool SPEC (Ship's Power and Energy Concept) [5]. This tool can provide volume, weight and capital expenditure (CAPEX) for different energy carriers and PPE system architectures (like ICE-mechanical, ICE-hybrid and ICE-electrical). The data used by SPEC are relative Key Performance Indicators (KPI), such as power densities (l/kW), relative costs (€/kW) and are based on papers, studies and data presented in symposia. The data used by SPEC can be obtained online through the Sustainable Power portal [6].

The data used in SPEC is not specific to the chosen layout of the architecture, only to the type of architecture. Hence it is a quick and powerful way to assess a multiple criteria trade-off in an early design stage, but lacking details of the applied solution.

Components that are assumed to be incorporated in the SPEC data of this study include:

- ICE's, gearboxes
- E-motors
- Gensets
- Electric distribution, switchboards, converters
- Fuel containment systems (tanks)

Mechanical, hybrid and electrical propulsion architectures are defined based on above data, where the sizing of the hybrid and mechanical propulsion architectures are based on generalised metrics derived from more detailed studies performed in the ZERO JIP project [6]. Batteries were not included in any of the architectures.

To bridge the gap between the component volumes and the actual occupied machinery space volume SPEC introduces a system placement factor. This is a factor that allows for the voids in between components (for maintenance and accessways), and possible additional space reservations as needed. The factor is set per vessel type as some vessels typically have more spacious engine rooms (larger vessels) whereas others have more tightly packed ones (small vessels and yachts). Factors between 2 and 4 are used in this project and these are estimated based on reference vessel machinery spaces.

The results of the generic feasibility study can be found in §3.

2.2 Detailed technical feasibility studies

This chapter systematically analyses the potential for electrification across different ship types by breaking down the assessment into several interrelated components. Each component addresses a specific aspect of feasibility, and together they provide a comprehensive evaluation for each vessel archetype.

Main Components of the Analysis

1. Operational Analysis

Establishes the typical operational profile for each reference vessel, including the sequence of tasks, environmental conditions, and power requirements (propulsion, payload, and auxiliary).

This forms the foundation for all subsequent technical and economic evaluations, ensuring that the analysis reflects real-world vessel usage.

Each vessel's operational analysis is introduced at the start of its respective section (e.g., General Cargo Vessel, Harbour Tug, etc.).

2. Propulsion Power and Energy (PPE) Architecture Design

Defines and sizes alternative propulsion system architectures for each vessel, based on the operational profile. The main architectures considered are ICE-mechanical (reference), ICE-electric, hybrid, and, in some cases, battery-assisted.

These designs are tailored to each vessel's operational needs and constraints, enabling a fair comparison of technical and economic performance.

The architecture design process and rationale are detailed in the subsections following the operational analysis for each vessel.

3. System Part Load Efficiency and Fuel Consumption Analysis

Evaluates the operational efficiency and fuel consumption of each PPE architecture over the defined operational profile, using quasi-static and, for some cases, dynamic simulation methods.

This quantifies the potential fuel savings and efficiency gains (or losses) from electrification, providing data for both technical and economic assessments.

Methodologies and results are presented in dedicated sections for each vessel and architecture, often accompanied by figures and tables.

4. Technical Feasibility Assessment (Weight, Volume, Integration)

Assesses whether the proposed electrified systems can be physically integrated into the vessel, considering space, weight, and layout constraints.

Ensures that technically promising solutions are also practically feasible for retrofit or newbuild scenarios.

These assessments are typically summarized in figures and discussion sections within each vessel's analysis.

5. Economic Feasibility (where applicable)

For selected cases, evaluates the total cost of ownership (CAPEX and OPEX) for each architecture, using established economic models.

Complements the technical analysis by determining whether electrification is financially viable under realistic assumptions.

Economic analysis is included for the general cargo vessel and referenced in summary tables for other vessel types.

6. Comparative Summary and Discussion

Synthesizes findings across all components, highlighting the main technical and economic trade-offs for each vessel type.

Provides actionable conclusions and recommendations for stakeholders.

Comparative results and discussions are found at the end of each vessel section and in summary tables/figures.

How the Components Come Together

- The analysis begins with a realistic operational profile for each vessel, ensuring that all subsequent technical and economic evaluations are grounded in actual use cases.
- Alternative PPE architectures are then designed and sized to meet these operational demands.
- Each architecture is assessed for efficiency, fuel consumption, and technical feasibility (weight, volume, integration).
- Where relevant, economic feasibility is evaluated to determine the business case for electrification.
- Finally, results are compared and discussed, providing a holistic view of the feasibility and impact of electrification for each vessel type.

2.2.1 Operational analysis

The operational analysis aims to provide the distribution of required power on board of the vessel over a generic operational profile. To achieve this, a typical operation of the ship is built up on a sequence of operational tasks, based on expert opinion. For each task, the environmental conditions, ship condition and task duration are provided.

Furthermore, for each task the following power requirements are estimated:

- Propulsion power
- Payload power
- Auxiliary power

The **propulsion power** is estimated based on statistical data from MARIN's databases based on the main ship dimensions. Information from the reference ship are taken into account, for example maximum ship speed and installed power. The condition of the ship (e.g. ballasted, full load) are differentiated and taken into account by change in resistance prediction. Environmental influences (e.g. sea state, confined water) are also taken into account on the predicted propulsion power. Effects of seaway are taken into account by correlation factors based on MARIN's experience. The propulsion power is the sum of mechanical power at all driving propeller shafts.

The **payload** and **auxiliary** power are based on information from the installed equipment of the reference ships, together with statistical data and expertise from MARIN on the load factors (% of usage). The sum of payload and auxiliary power provides the total required electric power demand.

From the gathered information, one or more Operational Power Profiles are created. These operational power profiles are at the early phase independent of the chosen PPE system. However, changes may apply when different propeller types are chosen. In that case, the propulsion power is updated in the calculations.

For the General Cargo Vessel an extended operational profile was set up with three different mission types. Those three mission types were evaluated on fuel consumption for each of the three power and propulsion configurations. For the other five Use Cases limited operational analyses are performed with only one or two (significant) mission type for each Use Case.

2.2.2 Electrified propulsion system architecture design

The various PPE architecture designs have been based on the operational profile, and are sized in order to achieve the typical benefits of electric or hybrid propulsion (by ensuring that low loads on engines can be covered and by choosing adequate steps in generator sizes). Engine product guides of various suppliers were used to come up with realistic engine ratings. The first results of the fuel efficiency calculations were used to refine the architectures in order to achieve the best possible performance of the hybrid and ICE-electrical architectures.

As mentioned in the introduction, to set a boundary to the electrification options, this projects focus on three application types of the electric PPE architectures:

- ICE-electric
- ICE-mechanical & ICE-electric hybrid propulsion technology (short: Hybrid)
- Battery assisted

These are always compared to the reference: ICE-mechanical.

The Power and Propulsion system topologies that are compared can also be found in Figure 2-1. In the whole study the energy carrier remains Diesel or Marine Gas Oil (MGO), i.e. no alternative fuels were assessed in this study.

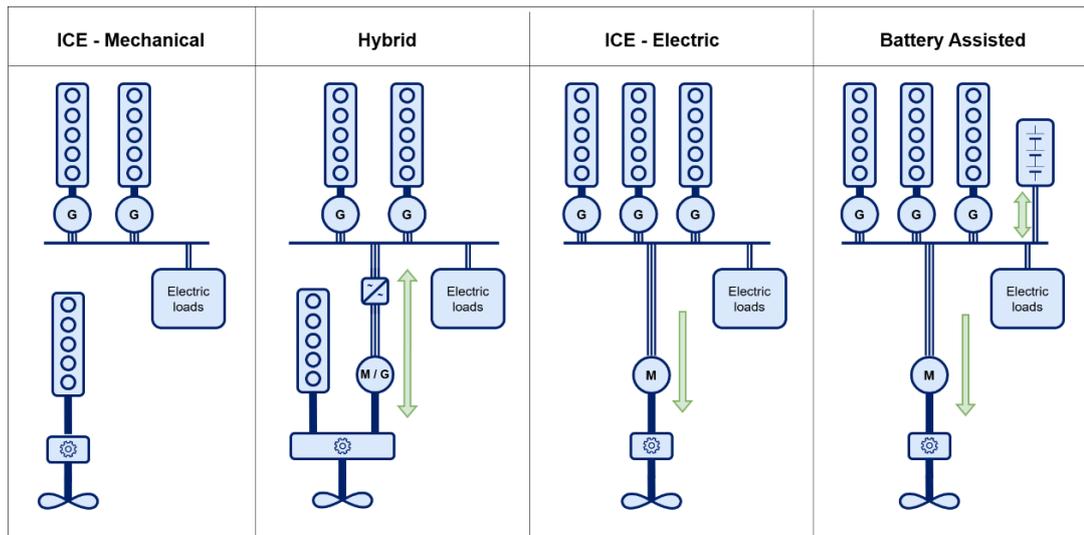
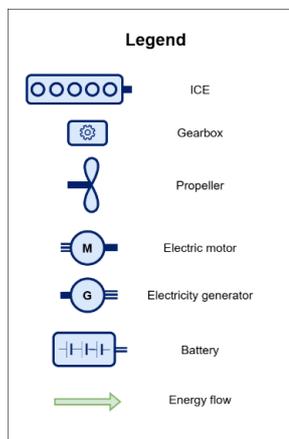


Figure 2-1: Schematic overview of Propulsion Power and Energy (PPE) system architecture types as used in this study.



ICE-mechanical is the reference topology with a ICE mechanically coupled to drive the propeller, typically via a reduction gear for the vessels in scope. The electric energy on board is supplied by Internal Combustion Engines (ICE) driven Generator Sets (gensets), and potentially a propulsion shaft generator. The number and power rating of gensets can vary. The ICE-mechanical reference architecture is provided based on the available information of the reference vessel.

ICE-mechanical & ICE-electric hybrid propulsion (hybrid) is a topology where the propulsion is provided by a combination of a mechanically connected ICE and an electric motor, where the electric energy is provided by ICE driven gensets. The number and power rating of gensets can vary. The electric load can also be supplied by using the electric motor as a propulsion shaft generator. Hence, the energy can flow from the mechanically connected ICE to the electric grid or vice versa.

The power sizing of the components is driven by the potential part load operation to be achieved in ICE-electric mode, ICE-mechanical mode and shaft generation mode. These are based on the load distribution of the operational analysis. The vessel constraints on volume and weight budget for the PPE systems are taken into account as well for selection. For some use cases, this option seemed unfeasible from the literature review and is therefore skipped.

ICE-electric is a topology with only electric motors to drive the propulsion shaft and where the electric energy is provided by Internal Combustion Engines (ICE) driven Generator Sets (gensets). The number and power rating power of gensets is based on the load distribution found from the operational analysis, market available power ratings of gensets from product catalogues, the potential space and weight availability of the reference vessel.

Battery assisted topology is used to research potential effects of the battery system on fuel consumption and full battery-electric propulsion. The battery can store electric energy supplied by the gensets and provide it to the onboard electric power distribution to supply electric loads and propulsion. In this research, the battery is provided only as part of the ICE-electric architecture. It is applied for only 1 use case. The sizing of the battery system is made based on the energy requirement from the operational profile.

The selected PPE architectures for each use case are described in more detail per use case in section 4. The battery assisted architecture is discussed in section 5.1.

2.2.3 System part load efficiency in quasi-static calculations

The PPE architecture designs are being assessed for operational efficiency over the operational power profiles. This type of analysis have been performed by both MARIN and TNO. MARIN has performed the part-load efficiency and fuel consumption analysis for all created architectures for all use cases. TNO focussed its battery modelling and analysis on the ICE-electric architecture for the General Cargo Vessel only. This vessel was selected because it represents a large group of vessels and was of particular interest to stakeholders. Both methods for quasi-static efficiency and fuel consumption calculation are described below.

2.2.3.1 Methodology description for quasi static efficiency and fuel consumption calculations

The calculations regarding quasi static fuel efficiency estimation are performed using the MARIN Efficiency Calculator (MEC) software tool. The MEC tool offers various ways to support evaluation and optimisation of the power load distribution among the PPE systems for a specific architecture. For the Green Deal project, the tool is used to calculate fuel consumption, and therefore efficiency, of the different architectures.

MEC is a steady-state system evaluation (analysis) tool. It calculates fuel consumption using provided propulsion power predictions and known operating conditions or operational profiles. The calculation model looks at operational profiles to determine the need for propulsion and auxiliary power at any point in time. Vessel fuel consumption is then calculated using the specific fuel consumption characteristics of the equipment.

Fundamentally, the methodology behind the MEC tool considers three main steps:

1. Calculate the required power at distribution nodes (these could be mechanical and/or electrical);
2. Distribute the load across a combination of different power sources that offer the lowest fuel consumption for the specific load (energy management).
3. Calculate the fuel consumption based on the distributed load setpoints, actual operational part load efficiency of the energy conversion components in the PPE system.

The tool includes the PPE architectures that are defined for this research project, that are built up by generic component models for the following types of components:

- Internal Combustion Engines (ICE)
- Electrical Motor
- Generator sets
- Mechanical transmission
- Electrical power transmission and converters (AC or DC)

These generic models are tuned using the following parameters: nominal rotation speed, nominal power and nominal fuel consumption. Part load efficiencies are calculated using predefined efficiency maps, based on literature.

The reference model is the **ICE-mechanical** architecture. In some cases, this reference has a propulsion shaft generator, or Power Take-Off (PTO), to provide electrical power to the onboard grid. In these cases, it is assumed that the vessel is equipped with a Controllable Pitch Propeller (CPP) running at constant speed to maintain the onboard net frequency.

For the **hybrid** cases, the vessel is equipped with a combined ICE-mechanical and ICE-electric propulsion that can operate in the following modes:

- ICE-mechanical
- ICE-electric
- combined ICE-mechanical and ICE-electric (boost modus)
- ICE-mechanical + PTO (Power Take-Off)

In the hybrid case, the electric equipment is expected to be able to convert the frequency of the shaft frequency in such way that the ICE-mechanical + PTO can run at variable speed.

For the **ICE-electric** cases, all the energy is provided by the gensets. The algorithm selects the most favourable genset(s) to be used based on overall fuel consumption. Both propulsion and onboard electric demand are provided by the gensets.

In all cases, the gensets are expected to run either at fixed speed with the main distribution assumed AC or variable speed with a DC distribution. This is set per case.

2.2.3.2 Methodology for determining battery efficiency and fuel consumption

TNO has a model to simulate PPE architectures that can run both in time domain as well as a quasi-static domain. In this environment it is possible to add battery models to accurately assess the battery's impact on fuel efficiency. This model is utilised to evaluate the potential of batteries specifically for the general cargo vessel.

Battery Model

The battery is one of the major components required to build the quasi-static simulation model of the PPE system. The battery model includes several tuneable parameters that can be adjusted to reflect different scenarios and conditions. These parameters are the battery capacity, which determines the total amount of energy the battery can store; the battery voltage, which affects the power output and efficiency; the initial State of Charge (SoC), which indicates the battery's charge level at the start of the simulation; and the Maximum and Minimum SoC, which define the operational limits of the battery.

By fine-tuning these parameters, researchers can simulate a wide range of conditions and optimise the battery's performance within the powertrain system.

This simulation model combine elements of the quasi-static approach and dynamic modelling in a forward-backward simulation method. In this method, a reference speed or power is used, with the propeller output acting as feedback to update the set points of the components. This iterative process ensures that the system operates optimally under various conditions. The interaction between these elements can be clearly seen in Figure 2-2.

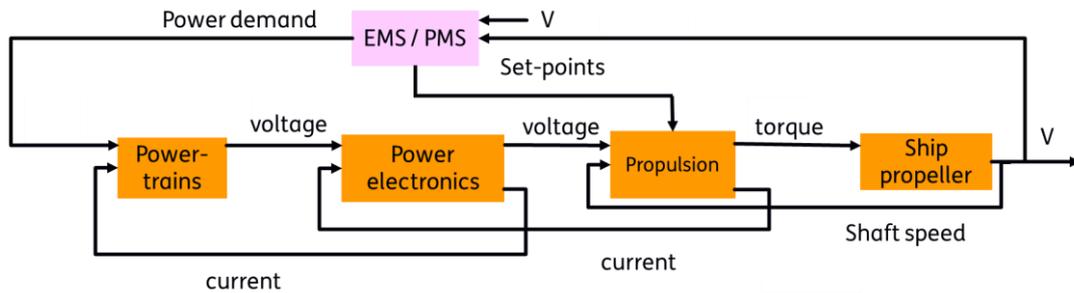


Figure 2-2: Simulation model methodology

The simulation models were developed for General Cargo Vessel for two different architectures:

- ICE-Mechanical Architecture: This model is used as a reference to access the impact of incorporating batteries on-board vessels.
- ICE-Electric Architecture: This model incorporates the battery and other electric components to assess their impact on fuel efficiency.

The results from the evaluation of battery usage for general cargo vessel can be found in the results section 5.1.2.

2.2.4 System efficiency and control performance in a dynamic time domain assessment

As stated by the research question *Can the electrification of the propulsion line benefit from higher system efficiency in dynamic operation conditions by improved control strategies?* the interest is to understand potential benefits from dynamic response and control behaviour of the PPE system. In order to research this, the behaviour of the PPE system cannot be studied in the quasi-static domain, but has to be solved in the time domain. In particular, the dynamics caused by seaway are of interest as they can be present over a long time over the vessel's journey and hence can have a significant effect on the total fuel consumption.

The dynamics experienced by the PPE systems originate from the hydrodynamic load variations of the sea acting on the hull. The resulting movements and added resistance of the vessel causes torque variations at the propeller. The experienced torque of the propeller and the actuated torque by the main drivers of the PPE system balance each other in equilibrium conditions, or cause acceleration or deceleration of the propulsion shaft. This will result in the actual shaft speed the propeller and main drivers of the PPE system experience. From the speed and torque of the propeller, the thrust can be calculated that will find balance with the vessel resistance to achieve a vessel speed, while the torque and shaft speed will provide the operational loading condition of the PPE system.

To assess how the vessel dynamics in seaway interfere with the PPE system dynamics and control, both the ship and PPE system were modelled for one ship type. The ship and propeller model include hydrodynamic performance models and reacts on the provided sea state. The torque on the propulsion shaft is transferred to the dynamic PPE model. Within the dynamic PPE model the required torque is allocated to the prime movers, i.e. propulsion engine and/or propulsion motor. The electric power is added and the required electric power is allocated to the available sources.

For this assessment of the effect of seaway on the fuel consumption of the vessel, a hydrodynamic model is created by MARIN using MARIN's time domain simulation framework aNySIM-XMF. Within this framework, several solvers of hydrodynamic systems, such as a seaway calculation, ship resistance and propeller thrust calculations, can be coupled. A dynamic model of the PPE system is created in MARIN's vZEL environment. This is a MATLAB-Simulink based, time domain simulation that consist of modules representing the main components of the PPE system architecture. A coupling is created that makes the models update simultaneously and let them interact.

Since this modelling requires much more effort than the quasistatic performance modelling, this has been performed for 1 use case only. Based on the interest from the stakeholder group, the number of vessels in this group and recent developments in the sector, the general cargo vessel use case has been used for this purpose.

The results of this study can be found in paragraph 5.2.

The hydrodynamic simulation modelling approach

Manoeuvring causes speed variations of the ship. It also may cause the ship to sail under a drift angle and/or make the ship turn. Therefore, manoeuvring has a strong effect on the propeller inflow velocity field, which has a strong impact on the propeller loading (i.e. the propeller thrust and torque). For this reason the movement of the vessel in seaway conditions and the effects on the inflow of the propeller are calculated at first for all conditions in the frequency domain with the use of MARIN's SEACAL tool. The results are stored in a database. In the time domain simulation, this database is used to solve the motion equations of the vessel, based on a force and moment summation.

In the time domain simulations, the vessel can be sailed virtually. The manoeuvring motions are initiated by the helmsman (or the autopilot) in the form of rudder setpoints and/or changes in telegraph setting. This results in a change in speed or heading, or the performance of a specific manoeuvre like a turning circle or a zigzag manoeuvre. Heading keeping or track keeping is also considered as manoeuvring. In that case the rudder actions have the purpose to counteract disturbances that are caused by the waves. Track keeping has been applied for the use case in this project.

The model is made available in the form of a Functional Mock-up Unit (FMU). This type of model can be used as a black box for other simulation environments such as the PPE modelling in MATLAB Simulink. Furthermore, it is used to exchange it with TNO, such that they could make use of it in their quasi-static battery assessment.

The details of the ship and propeller simulation model and all included sub-models as well as the Functional Mock-up Interface (FMI) are described in Appendix B.

2.3 Economic feasibility

To compute the total cost of ownership for the general cargo vessel, TNO uses a version of the NavigaTE TCO model, developed by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping [7].

The model is applied to the use case of the General Cargo vessel for 3 architecture types, ICE-Mechanic, hybrid and ICE-electric. This vessel type is selected in analogy of the detailed models before: Based on the interest from the stakeholder group, the number of vessels in this group and recent developments in the sector. With the TCO model, an estimation is made of the costs of the vessel to be bought and operated. In this way, the additional CAPAX costs and potential OPEX savings of the electrification options are quantified over the lifetime of the vessel and seen in comparison to the total costs of the vessel.

2.4 Overview of performed analysis

An overview of the analysis per ship type and architectures in scope of the project is provided in Table 2-1.

Table 2-1: Stages performed per use case.

Use Case	PPE Architecture	Generic Feasibility & design impact	PPE Architecture design	Virtual Fuel Consumption comparison Tests		Total Cost of Ownership
				Quasi-Static	Dynamic	
General Cargo Vessel	ICE Mechanical + PTO	Y	Y	Y	Y	Y
	ICE Electric	Y	Y	Y	Y	Y
	ICE Electric + Battery	-	-	Y	-	-
	Hybrid	Y	Y	Y	-	Y
Harbour Tug	ICE Mechanical	Y	Y	Y	-	-
	ICE Electric	Y	Y	Y	-	-
	Hybrid	Y	Y	Y	-	-
Offshore Supply Vessel	ICE Mechanical	Y	Y	Y	-	-
	ICE Electric	Y	Y	Y	-	-
	Hybrid	-	-	-	-	-
Crew Tender Catamaran	ICE Mechanical	Y	Y	Y	-	-
	ICE Electric	Y	Y	Y	-	-
	Hybrid	Y	Y	Y	-	-
Dredger Vessel	ICE Mechanical	Y	Y	Y	-	-
	ICE Electric	Y	Y	Y	-	-
	Hybrid	-	-	-	-	-
Mega Motor Yacht	ICE Mechanical	Y	Y	Y	-	-
	ICE Electric	Y	Y	Y	-	-
	Hybrid	Y	Y	Y	-	-

In line with the selection of one type of vessel for the execution of the dynamic simulation, we chose the same vessel type for the TCO: the general cargo vessel use case. This selection is based on the interest from the stakeholder group, the number of vessels in this group and recent developments in the sector.

3 Generic feasibility study

The study is started with the generic feasibility study. This part includes retrieving information on the existing applicability of electrification, identifying driving factors for electrification as well as a generic assessment on ship design parameters.

Together they are used to answer the first posed research question:

- *How feasible is electrification of the ship propulsion drive system ?*

3.1 Literature and Market survey Current State of Electrification

At first, a brief literature survey is performed to find founding for the current research. The market survey aims to find the share of electrification in the propulsion drive line of vessels for the 6 archetypes of ships within the Green Deal project [3].

3.1.1 Literature survey

Technical impact

Implementation of an electrified powertrain poses technical and safety challenges. It involves choice and implementation of a suitable architecture for the ship type and size, and can include port infrastructure as well. Variables that are included in selecting this suitable architecture include the size and configuration of the existing vessel (in case of retrofiting), the number of primary and auxiliary engines, the available space on-board, the ship's operational profile, and the possibility of modifying the existing ship architecture.

Other research studies from literature indicate the potential impact of electrification to emissions and GHGs. For example, Moon et.al. [8] in their study, estimate that retrofiting 6323 domestic ships under 1000 gross tonnage (4800 tugs, 1439 passenger ships, 51 general cargo, 18 tankers, 14 Ro-Ro and 1 bulk carrier) to full electric vessels in the US, would reduce the domestic shipping GHG emissions by up to 73% by 2035 from 2022 levels. Anmar et.al. [9] analyse three propulsion systems for container ships, comparing two mechanical propulsion systems, a dual-fuel propulsion system, and a hybrid propulsion system. This study identifies the most efficient and cost-effective propulsion system as a step towards "green" transport in container shipping. The environmental results show that the hybrid propulsion system is the best option, with 52%, 63.7%, and 30.4% reductions in NO_x, SO_x, and CO₂ emissions respectively, compared to a conventional system. In economic terms, the hybrid system is the most cost-effective system proposed for container ships in terms of upcoming regulations, with levelized energy costs (LCOE) of 0.07 USD/kWh [9].

Environmental impact

Shipping electrification could significantly reduce the environmental impact when compared to traditional maritime transport. The potential benefits as per common literature include reduction in GHG emissions, reduction in air pollutants, reduced noise pollution and increased energy efficiency. In the marine industry, considering the major ship emission types, four environmental impact categories are generally proposed: Global warming potential (GWP), Acidification potential (AP), Eutrophication potential (EP) and Photochemical ozone creation potential (POCP) [10].

GWP accounts for the total emissions from greenhouse gases that tend to insulate heat energy in the atmosphere such as CO₂, CH₄, N₂O, in *kg CO₂-eq*. The AP quantifies the amount that each emission gas contributes to acid rain, and is measured in *kg SO₂-eq*. EP refers to the nutrient enrichment of aquatic environments, which impacts water quality by promoting excessive plant growth. EP is measured in *kg N-eq*. PCOP refers to the process of smog formation in the lower layer of Earth's atmosphere, by photochemical oxidation of volatile organic substances (except CH₄) and NO_x. PCOP is measured in *kg CH₄-eq* [11].

Byongug Jeong et.al., [10] in their study, assess the environmental impact potential via a lifecycle impact assessment (LCIA) for the 4 impact categories mentioned above. According to their results, using batteries instead of diesel engines was revealed to reduce 35.7% of the GWP, not 100%: this is because the environmental impacts associated with the energy production and transport contribute substantially to the total impacts. For the other three potentials with batteries, better results were observed with the decrease of the AP by 77.6%, the EP by 87.8% and the PCOP by 77.2%, when compared to conventional ICE mechanical propulsion (Note: this study doesn't mention which Tier of the IMO standards are considered for the conventional ships). Despite the emission reductions, the fact that the batteries are still subject to producing a huge amount of emissions particularly with the GWP should be noted. This paper continues to argue that the level of emissions heavily depends on the type and method of energies consumed for the electricity production and their logistics. It is key to note that [10] focused on demonstrating environmental advantages for small ships engaged in short route services and cannot be directly extended to all sea-going vessels.

Byongug Jeong et.al. [12] in another research, try to answer the fundamental question on whether electric battery powered ships can ultimately be a promising solution for future maritime environmental protection. One of their conclusions from this study was that the battery-powered ships operating in countries with high reliance on fossil-based energy resources contribute to much greater environmental impacts than the same ships dispatched to countries with a high level of renewable energy sources.

Based on the available literature and research, it is clear that the environmental impact mainly depends on the choice of the ship (size, capacity) and its corresponding sailing profile and route, along with the source of production of electric power, which finally could contribute to an overall positive effect.

3.1.2 Market survey

From the literature survey, the archetype of the vessel and sailing profiles are found important when considering electrification options. TNO performed a market study to assess the current state of electrification of ships in the Netherlands, which is described below.

[Applicability of electrification per ship archetype](#)

The 6 types of vessels under initial consideration in the Green Deal Electrification [3] topic are given in section 1.3 and a brief overview is shown in Figure 3-1.



Figure 3-1: Ship archetypes [3].

To assess the current electrification status of the above-mentioned archetype ships, TNO used the World Fleet Register (WFR) from Clarksons Research as a reference [4]. The WFR contains the details of all ships currently sailing in the world including ship size, power type, ship status, engine and auxiliaries' specifications, and more. The WFR categorises ships into the following power types:

Table 3-1: Categorisation of ships in the following power types according to Clarkson's World Fleet Register.

Mechanical power	
Diesel 2-stroke	Vessel that uses a 2-stroke diesel engine(s) linked directly to propeller shaft(s) to drive propulsion
Diesel 4-stroke	Vessel that uses a 4-stroke diesel engine(s) linked directly to propeller shaft(s) often via gears to drive propulsion
Steam turbine	Vessel that uses steam turbine(s) to drive vessel propulsion
Gas turbine	Vessel that uses gas turbine(s) to drive vessel propulsion
Steam reciprocating	Vessel with steam reciprocating main engine
Electrical power	
ICE or Diesel electric	Vessel with ICE or diesel engine(s) connected to electrical generator(s) to create electricity that powers electric motors which in turn drive main propeller(s) and/or thruster(s)
Hybrid Mechanical / Electrical	Vessel with ICE or diesel engine(s) and diesel generator(s). Power is transferred to propeller shaft(s) via gears either through direct mechanical connection or electrically through Power Take In (PTI) motors
Combined	Vessels that use a combination of power sources to drive propulsion. Mainly combined propulsion includes gas or steam turbines
Batteries and diesel	Vessels that use batteries to power main propulsion alongside diesel engines or diesel generators (sometimes referred to as "Hybrid") NOTE: In order to distinguish with "Hybrid Mechanical / Electrical" vessels, "batteries and diesel" are referred to as 'Vessels with Hybrid Power' in the remainder of the report.
Batteries propulsion	Vessels powered solely by electricity generated by batteries
Fuel cell and battery	Vessels powered by both fuel cell and batteries
Fuel cell, battery and diesel	Vessels that use fuel cell and batteries to power main propulsion alongside diesel engines or generators

Please note the difference in the power types mentioned in Table 3-1 and the convention for this report. All mechanical power types fall under “ICE Mechanical Propulsion”. The electric power types are defined as per Table 3-2. This new naming convention will be followed in the remainder of the report.

Table 3-2: Naming convention correlation of WFR and used in this report.

WFR naming convention	Naming convention in this report
diesel electric	ICE Electric Propulsion
Hybrid Mechanical/Electric	Hybrid ICE Electric Propulsion
Combined	
Batteries and diesel	
Batteries propulsion	Battery Electric
Fuel cell and battery	Fuel Cell Electric (not used in remainder of report)
Batteries, diesel and fuel cell	Battery supported (ICE only)

The WFR includes a total number of 109714 ships registered as of 17th June 2024. Out of this, a total of 3707 ships falls under the “Electrical power” type including the fuel cell / battery / diesel category. This works out to 3.38% of ships in the fleet that are “electrified”. Table 3-3 shows the percentage of fleet electrification over the years from the WFR.

Table 3-3: Percentage of shipping electrification (status June 17, 2024).

Year	Total Ships	“Electrified” Ships	% Electrified
1868 to 2014	85,904	2,259	2.63
2015 to 2024	23,810	1,448	6.08
Ships on Order	6,173	663	10.74

Source: Clarksons Research

Based on the 6 categories of ships being considered in this study, the electrification % based on power type and category from the WFR (as of 9th July 2024) is shown in Table 3-4.

Table 3-4: Electrification percentages based on power type for selected ship types (status June 17, 2024),

1	General cargo + MPP	Mechanical	Diesel Electric	Hybrid Mech./Elec.	Combined	Batteries & Diesel	Batteries propulsion	FC & battery	Batteries, diesel and FC	% Electrified
All	19327	19263	40		2	22				0.33
LOA 90 to 130 m	4597	4573	17			7				0.52
2	Tugs	Mechanical	Diesel Electric	Hybrid Mech./Elec.	Combined	Batteries & Diesel	Batteries propulsion	Fuel Cell & battery	Batteries, diesel and fuel cell	% Electrified
All	22446	22307	96	10	1	17	15			0.62
LOA 20 to 40 m	19628	19536	54	9	1	16	12			0.47
3	Offshore supply	Mechanical	Diesel Electric	Hybrid Mech./Elec.	Combined	Batteries & Diesel	Batteries propulsion	Fuel Cell & battery	Batteries, diesel and fuel cell	% Electrified
All	1290	1051	209	2		28				18.53
LOA 70 to 100 m	457	292	138			27				36.11
4	Crew transport vessel	Mechanical	Diesel Electric	Hybrid Mech./Elec.	Combined	Batteries & Diesel	Batteries propulsion	Fuel Cell & battery	Batteries, diesel and fuel cell	% Electrified
All	1428	1402	4			15	6	1		1.82
LOA 15 to 35 m	418	409	1			5	2	1		2.15
5	Dredgers	Mechanical	Diesel Electric	Hybrid Mech./Elec.	Combined	Batteries & Diesel	Batteries propulsion	Fuel Cell & battery	Batteries, diesel and fuel cell	% Electrified
All	2144	2007	131			5			1	6.39
LOA 110 to 140 m	187	158	29							15.51

Source: Clarksons Research - There is no data on superyachts in the WFR.

The key points from the data listed in Table 3-4 are:

- The specific ranges of the Length Overall (LOA) included in the table are an approximate range for the 6 Green Deal ships considered in this study.
- The electrification % ranges significantly: 0.33% to 18.53% for the different ship types under consideration, taking into account all vessels. This percentage range changes from 0.52% to 36.11% when considering only the sample set of ships corresponding to the ship sizes based on the sailing profiles considered in table 2.5 of the Green Deal report [3].
- Offshore supply ships are the most electrified ship type at 18.53% and 36.11%.
- Dredgers are the second most electrified ship type at 6.39% and 15.51%.
- The most widely adapted power type for electrification is Diesel Electric (ICE-electric).
- The second most widely used power type is Batteries and diesel (vessels with hybrid power) type.
- Pure batteries propulsion is the third power type with relatively larger fleet incorporation, mainly used for Tugs and Crew transport vessels.

Based on the current state of electrification and available sailing profiles (from the source [3]), a matrix to show the possible electrification options is created. The matrix is shown in Table 3-5.

Table 3-5: Matrix of possible electrification options (Legend: Grey = Default, Green = Yes, possible, Yellow = Yes, low in numbers).

Electrification Matrix	Ship Types	Sailing Profiles	Electrification Options					
		Characteristics	ICE Mechanical Propulsion	ICE Electric Propulsion	Hybrid ICE Electric Propulsion	Battery Electric	Fuel Cell Electric	ICE & Fuel Cell Electric Propulsion
Reference Vessel	I SSTV (General Cargo / Multipurpose)	<u>Speed:</u> 12 to 18 kts <u>Power range:</u> 700 kW to 10 MW <u>Size:</u> 112m L, 18.2m B <u>Range:</u> >3000 NM <u>Zones:</u> Transit 55% (13 kts) Manuevers 10% (5 kts) Port 35%	Grey	Green	Green			
	II HTB (Tug)	<u>Speed:</u> 10 to 14 kts <u>Power range:</u> 2 MW to 5 MW <u>Size:</u> 32m L, 12m B <u>Range:</u> ? <u>Zones:</u> Transit 25% (12.5 kts) Towing 25% (4 kts) Waiting/Port 50% (0-2 kts)	Grey	Green	Green	Green		
	III OTV - Goods (Offshore Supply)	<u>Speed:</u> 15 kts <u>Power range:</u> 4 to 6 MW <u>Size:</u> 82m L, 17.5m B <u>Range:</u> ? <u>Zones:</u> Transit 45% (14.5 kts) Manuevers 25% (2 kts) Port 35%	Grey	Green	Green			
	IV OTV - People (Crew Transport Vessel)	<u>Speed:</u> 20 to 25 kts <u>Power range:</u> 1 to 3 MW <u>Size:</u> 25m L, 9m B <u>Range:</u> 100 NM <u>Zones:</u> Transit 40% (23.5 kts) Manuevers+Loading 10% (5 kts) Port 50%	Grey	Yellow	Green	Green	Yellow	
	V LOWV (Dredger)	<u>Speed:</u> 12 kts <u>Power range:</u> 2 to 15 MW <u>Size:</u> 125m L, 28m B <u>Range:</u> >500 NM <u>Zones:</u> Transit 22% (16 kts) Dredging 31% (2 kts) Dumping by pump 12% (1 kts) Dumping through doors 14% (1 kts) Unloading at quay 12% Port 10%	Grey	Green	Yellow			Yellow

The matrix consolidates the sailing profiles for the ship types from [3] and the currently available ships based on power type as per the WFR. All the vessel types have a standard mechanical propulsion option available, and it is highlighted with “grey” in the matrix. The “green” highlight indicates that there are already a number of vessels with that power type existing in the market, and thereby translates to easier implementation for the particular ship type. The “yellow” highlight indicates a low number of available vessels within that power type.

Obstacles on the road towards electrification

As discussed in the previous section, there has been a growth in the electrification of ships in the past 10 years and also in new vessels being built. Nevertheless, this growth is slow and only a small percent of the total fleet is electrified. This indicates that there must exist a set of challenges that prevent a larger deployment of electrified ships. This section aims to list the key challenges present.

The challenges can be broadly divided into different categories, spread across a number of political, economic and technological factors [13]. This study focuses on the technological factors that pose a challenge to electrification of ships, and also aims to evaluate the total cost of ownership (TCO) for these ships along with the possible emission reduction capabilities.

These factors can be divided into the following [14]:

1. Development of the main and auxiliary systems, by using electrical power sources adds to the complexity of the system architecture.
2. Retrofitting of current ships is not always economically feasible and needs further analysis.
3. A smart power electronics interface and power managing system would be required, in order to ensure operation of the electrified ships around their minimum emissions operation point for all possible loading scenarios.
4. Another bottleneck for fleet electrification is the availability of infrastructure in ports in order to ensure cold-ironing interface capability.

3.2 Driving factors of propulsion electrification

Choosing for electrification is not necessarily based on the single metric of fuel efficiency, it is in fact a multicriteria analysis. This section provides a list of aspects which are considered to be drivers or holding back electrification of the ships' propulsion line. They are addressed qualitatively, based on expert opinions. Volume, weight and capital expenditure will be calculated in the next section. Table 3-6 summarises the pros and cons.

Fuel consumption and system efficiency

The fuel consumption is one of the main factors to apply electrification in the propulsion line. As a basis, the vessel operation is seen as a cloud of operational conditions, from which design optimization to a single design operational point will not provide the best overall solution. Operation of high power equipment at low operational loads will result in low efficiency. With the use of electrification of the propulsion train, the required power can be combined with the onboard electric power and distributed over various sources. This distribution can be allocated such that the running equipment can run on at high efficiency. Deficit of applying electrification compared to ICE-mechanical propulsion is the addition of more energy conversion stages. This results in lower system chain efficiency. The effect of load distribution must be greater to find net benefit. This topic is studied in much more detail in the remainder of the study.

Capital expenditure

The capital investment to be made for electrification is usually significant. For ICE-electrical all power first must be converted to electricity, which requires a significant investment into the electrical grid.

For ships that operate with a large electrical payload and auxiliary system, ICE-electric PPE architecture can reduce the total amount of installed ICE power as propulsion and payload power not necessarily are required simultaneously. In that case, the investment costs may reduce again.

For hybrid options, the balance between ICE-mechanic and ICE-electric propulsion is delicate. It can lead either to higher or lower total installed power and resulting investment costs.

ICE-hybrid is also more expensive than ICE-mechanical as it still requires additional components (like a more complex gearbox with power take-off/take-in and a motor/generator). An indication of the capital expenditure is given in the next sections.

Maintenance

When designed well, maintenance costs can be reduced when ships are electrified. This is because the total running hours of the installed machinery reduce, particularly running hours at low load. As a Diesel-mechanic PPE system typically has multiple engines operating: an auxiliary generator set is running, as well as the propulsion engine set, and combined with a generator for the bow thruster (which only runs shortly). When electrifying, this can more efficiently be arranged by one or two engines which can provide multiple services. In low load propulsion conditions, the ship can be powered by a single generator set. In Diesel-hybrid a similar effect is obtained by using the power take-off on the gearbox to provide the auxiliary load. Furthermore, maintenance costs for an electric propulsion motor are expected to be lower.

Air pollutants

Due to the improved loading of machinery (see previous paragraph) not only the maintenance costs can be reduced but also the emission of various air pollutants may be reduced (like NO_x, PM, VOC, CO). It must be noted that the emission of pollutants in the first place strongly depends on the machinery and after-treatment systems installed.

Operational availability

For the electrification of vessels that have large payload consumers, the installed electric power generation can be distributed to more equipment. Furthermore, the availability of an electric propulsion and distribution system can be higher as a failure of a single generator set may only reduce the available power, rather than the complete loss of functionality. Electric propulsion motors show very high uptimes. A Diesel-hybrid architecture can also have an improved availability, but losing a main engine can still have a large impact on the operability of the vessel. Power electronics can also break down, just as mechanical counterparts. Electric reconfiguration and redundancy supply is however easier to implement. Electrification may also require more complex control and safety systems. Especially for hybrid configurations. However, this is generic available technology. For ICE-electric, this is typically not more complex than existing AC power distribution for onboard systems.

Ship arrangement

The flexibility of a ICE-electric PPE system is greater in terms of layout, as the placement of the main generating sets is no longer to be close to the shaft line. The electric motors are also much smaller per unit power they can provide compared to the ICE-mechanic propulsion engines, providing more freedom in the arrangement and aft ship design for both internal arrangement as well as hydrodynamic design for the flow towards the propeller. This may result in an optimised lay-out of the vessel, better propulsive efficiency and a better weight distribution of the vessel (and running trim), which may compensate partly for the increased weight of the electric architecture.

Electrification may also require more space and weight budget for multiple generator sets and switchboard rooms. The latter require other operational conditions than the classic machine room.

Refit flexibility

From an energy transition perspective there is also an advantage: the electric architecture allows a (part) changeover to other power systems, without having to change the electric distribution or the propulsion train.

For example, by replacing one generator set by a battery system, fuel cell or generator set on an alternative fuel. Of course, the necessary energy carrier storage systems and supporting systems must still be in place. In order to provide the potential refit flexibility, precautions may be considered. For example, space reservations for additional electric power equipment.

Drive characteristics

The electric motor provides a high torque availability over the complete operating range, and the flexibility to run temporarily at higher torques. They can run at speeds significantly above the speed at which max torque (or power) is reached, with constant power output and run at very low speeds compared to ICEs. Electric motors can reverse their operational direction and passively run without de-clutching. Control of the electric motor output is typically quicker or more precise than control of a diesel engine. These characteristics make electric propulsion engines suitable for example as a boost modus, in heavy dynamic operations like DP or temporary high (over)loads like ice breaking. Also matching with propeller design can make use of the electric motor characteristics, making them more efficient or applicable in a wide range of operational conditions. Furthermore, the created torsional vibrations are much less compared to diesel engines making them easier to integrate in the drive line.

Noise and vibration

Well-designed ICE-electrical systems typically have lower noise and vibration compared to ICE-mechanical as generator sets have better sound proofing possibilities (e.g. selection of flexible mounts based on fixed speed operation, added enclosure) and is always uncoupled from the propeller shaft and thrust bearing. Also the location of the system can be located such that the noise levels in accommodation are lower.

Table 3-6: Advantages and disadvantages of the 3 electrification options, simplified to a plus (+) or minus (-) based on expert opinion.

	ICE-mechanical propulsion	ICE-hybrid propulsion	ICE-electrical propulsion
Fuel consumption and efficiency	+/-	+/-	+/-
Capital expense	+	-	- -
Maintenance	-	+	+ +
Air pollutants	+/-	+ ¹⁾	+ ¹⁾
Operational Availability	-	+	+ +
Ship Arrangement	-	-	+ +
Refit Flexibility	-	+	+ +
Drive characteristics	+/-	+	+ +
Noise and vibration	-	+	+ +

1) Strongly depends on installed equipment and aftertreatment solutions

3.3 Feasibility of propulsion line electrification from ship design perspective

Ships are limited to carry their cargo up to the max allowed water displacement respecting their stability criteria and draught marks. Space onboard is limited up to the exterior of the ship. Space and weight needs to be shared between cargo (payload), construction and systems (lightweight) and consumables (fuel, water).

In order to understand the impact of changing the propulsion architecture on the ship design, the estimated volume and weight for hybrid and ICE-electric systems are compared to ICE-mechanical architecture. In order to apply one of the electrified drivelines, sufficient space needs to be available in the machine space to avoid reducing space for the cargo. The same applies to the weight, as the ship is limited to its designed watermarks of displacement.

Changing the type of architecture also includes a different system efficiency, resulting in a difference in fuel volume and weight at fixed endurance of the vessel. By estimating the total required volume and weight of the systems and fuel together, the feasibility of applying such system design for the specific vessel use case is being checked. Next to the ship related parameters also the cost aspect is checked (CAPEX). This is a first rough indication but shows the order of magnitude to be incorporated. More details on the cost aspects are added in section 6.

The feasibility of the electrification on weight budget and volume reservation for hybrid and ICE-electric PPE architectures compared to ICE-mechanic are assessed for:

- General cargo vessel
- Harbour tug
- Offshore supply vessel
- Crew tender vessel
- Trailing suction hopper dredger
- Mega motor yacht

The study is performed with MARIN’s tool SPEC and based on generic data, and made specific for the use case reference vessels. Batteries were not included. See section 1.3 for more details on the reference vessels. More information on the methodology can be found in chapter 2.1.

3.3.1 Short Sea Transport Vessel

For the three identified technical solutions an indicative weight, volume and capital expenditure (CAPEX) are provided in Figure 3-2 and Figure 3-3. It is clear that the Diesel ICE Electric technology requires the most weight and volume, and also has the highest CAPEX.

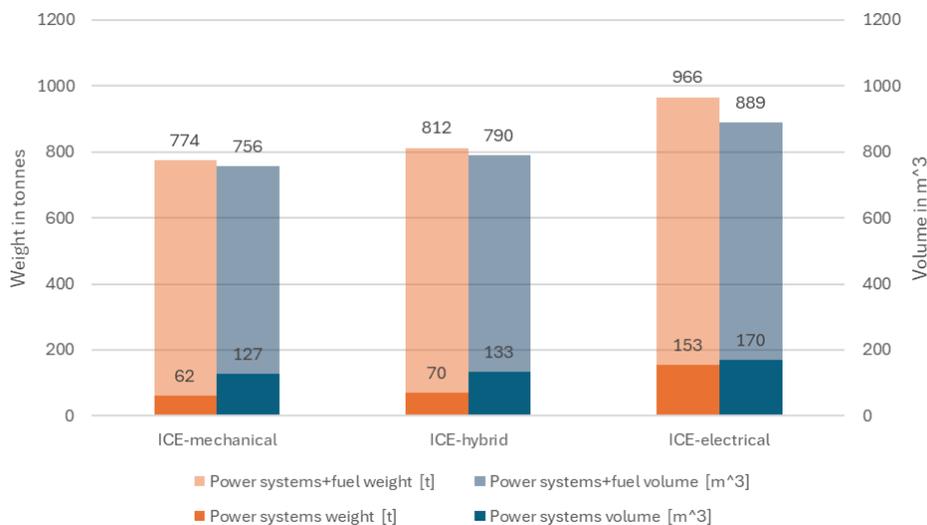


Figure 3-2: Weight and volume for fuel (incl. containment) and power systems for the General Cargo Vessel.

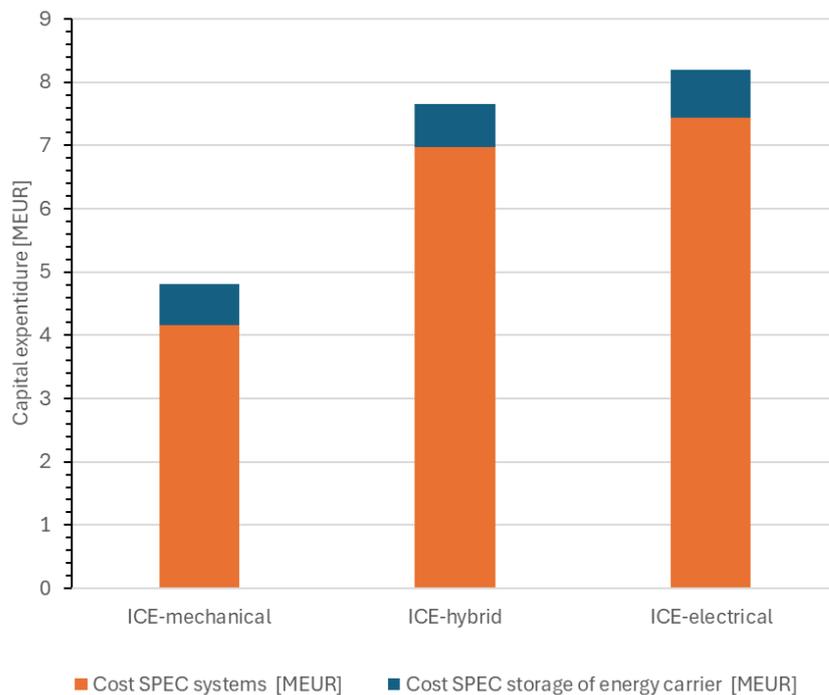


Figure 3-3: Capital expenditure of fuel storage tanks and power systems for the General Cargo Vessel

Impact on the ship design

When putting the technology in perspective of the reference vessel, an assessment of the impact on the ship’s main properties is made. The results in Figure 3-4 show that changing the vessel to ICE electric or hybrid propulsion reduces the payload capacity of the vessel by 2.3% or 0.5% respectively.

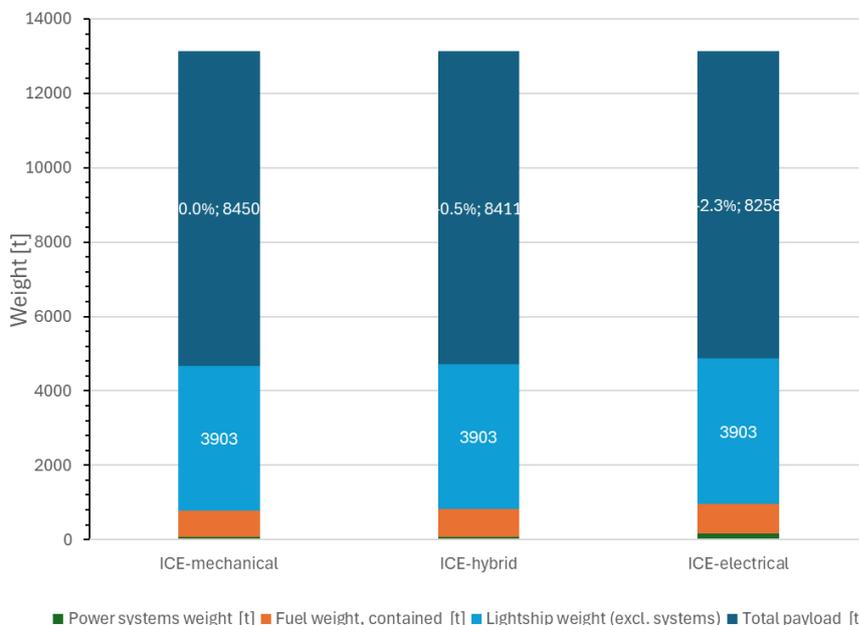


Figure 3-4: Weight distribution and variation in payload per technology for the General Cargo Vessel

When considering the volume, the machinery space is likely to have sufficient volume to accommodate ICE-electrical or hybrid propulsion. This is shown in Figure 3-5. An estimated system placement volume to system volume ratio of 3 was used.

Which means for every 1 m³ of power system volume, 4 m³ is reserved for system placement. This can be walkways, maintenance areas and such. It should be noted that non-PPE (Propulsion, Power & Energy) components may also be installed in the machinery space volume, like HVAC, freshwater systems, etc. These are not included in the analysis. Nevertheless, a large volume appears to be available.

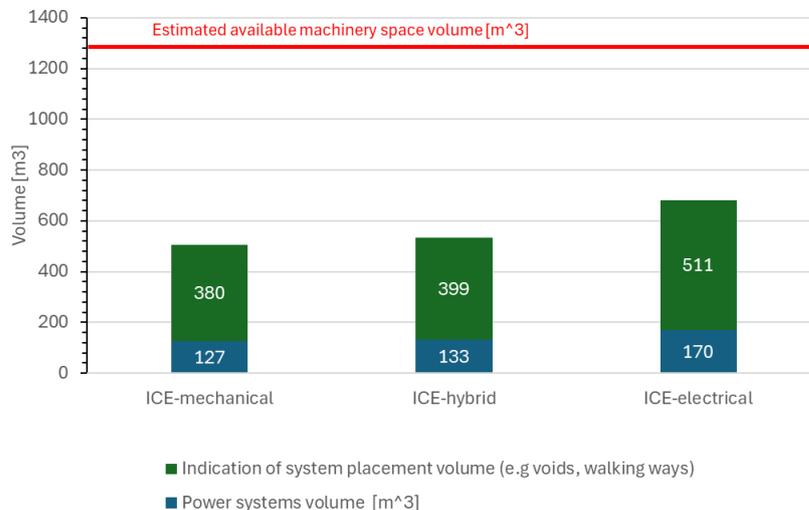


Figure 3-5: Volume of power system incl. the system placement volume for the Short Sea Transport Vessel

3.3.2 Harbour tug

For the three identified technical solutions an indicative weight, volume and CAPEX are provided in Figure 3-5 and Figure 3-7. It is clear that the Diesel ICE Electric technology requires the most weight and volume, and also has the highest CAPEX. It is also apparent that the fuel is a relatively small portion of the total system. The power systems are dominant in this use case. It must be noted that weight, volume and CAPEX only consider the power systems: including switchboards, converters, gearboxes, electric machines and main machinery (generator sets or propulsion engines). Fuel tanks are also considered in the CAPEX but are only a fraction of the total costs.

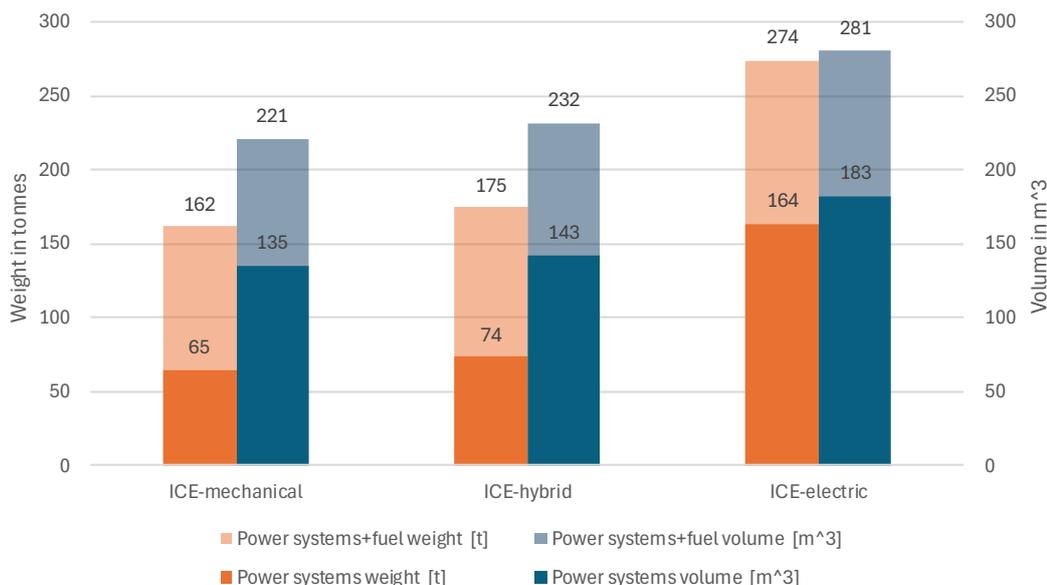


Figure 3-6: Weight and volume for fuel (incl. containment) and power systems for the Harbour Tug.

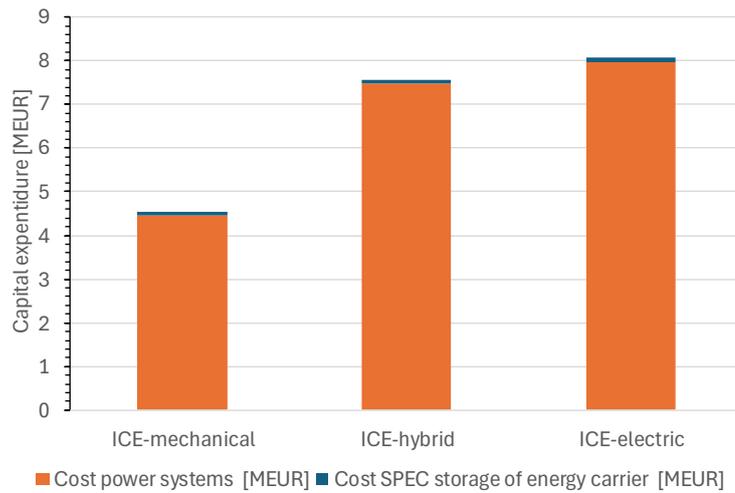


Figure 3-7: Capital expenditure of fuel storage tanks and power systems for the Harbour Tug.

Impact on the ship design

The required systems volume with respect to the available machinery space was considered. Weight is not considered an issue for this vessel type because it sails at low speed. For this a system placement volume ratio of 2 was used, which means that for every 1 m³ of power system volume, 2 m³ is reserved for system placement. The result is given in Figure 3-8. This shows that the ICE-electrical architecture may not fit within the current machinery space. Especially when considering that the machinery space may also contain non-PPE equipment, which is not considered in this calculation. The hybrid architectures will fit within the available machinery space as it is only slightly larger than the direct architecture. Choosing for a DC grid and variable speed generators may reduce the overall weight and volume of the system [15].

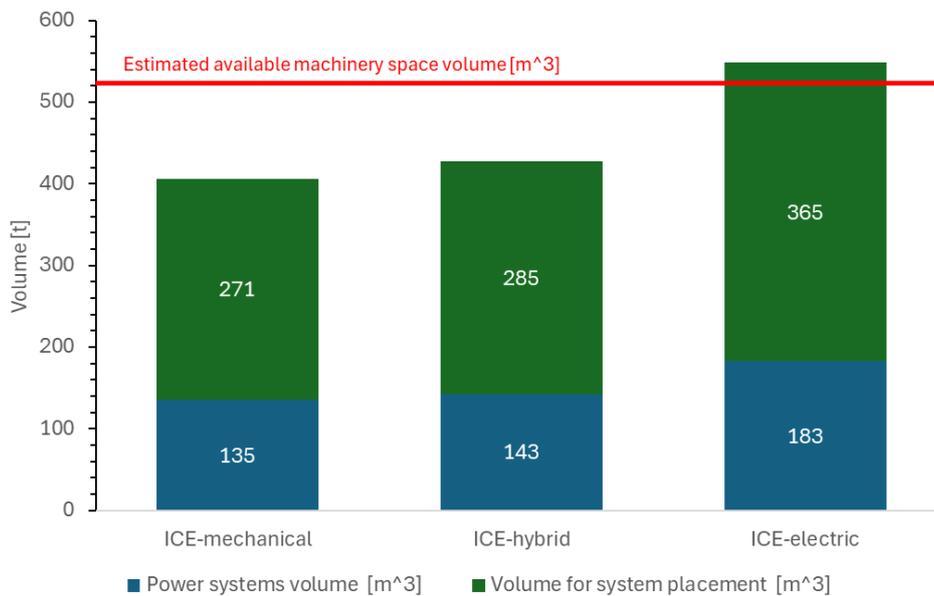


Figure 3-8: Volume of power system incl. the system placement volume for the Harbour Tug.

3.3.3 Offshore supply vessel

The feasibility check on volume and weight for the Offshore Supply Vessel was performed for ICE-electric and hybrid architecture and compared to ICE-mechanic. Although no specific architecture is created for the hybrid version of the use case (see Table 2-1), a generic model was available to consider all three architectures.

An indicative weight, volume and CAPEX are provided in Figure 3-7 and Figure 3-10. It is clear that the Diesel ICE Electric technology requires the most weight and volume, and also has the highest CAPEX. For the ICE-mechanical and the ICE-hybrid the power systems are about 50% of the weight, for the electric the power systems are at least twice as heavy than the fuel. As earlier presented in Table 3-4, electrification is more common than hybrid propulsion, but CAPEX and volume are not the only considerations here (more on that in Chapter 4). Furthermore, the weight, volume and CAPEX only consider the power systems: including switchboards, converters, gearboxes, electric machines and main machinery (generator sets or propulsion engines). Fuel tanks are also considered in the CAPEX but are only a fraction of the total costs.

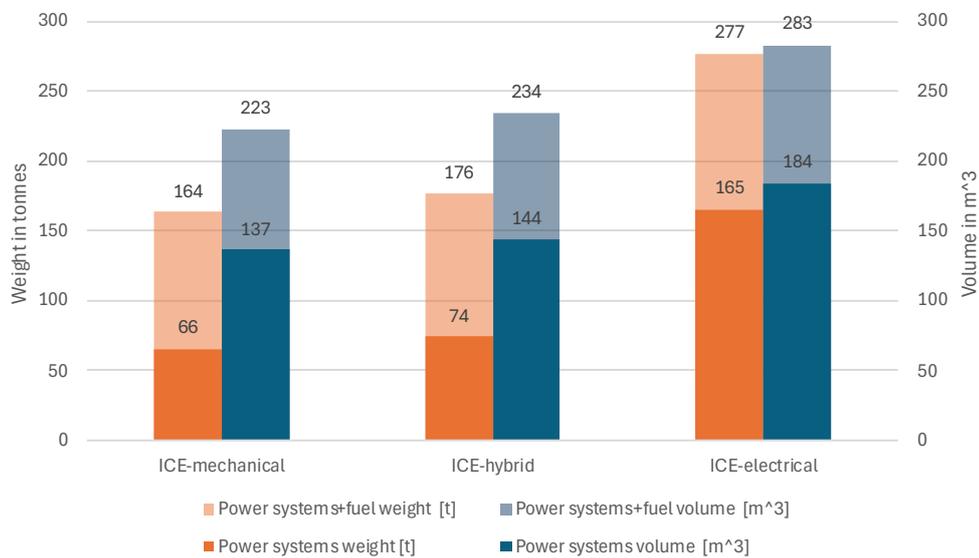


Figure 3-9: Weight and volume for fuel (incl. containment) and power systems for the Offshore Supply Vessel.

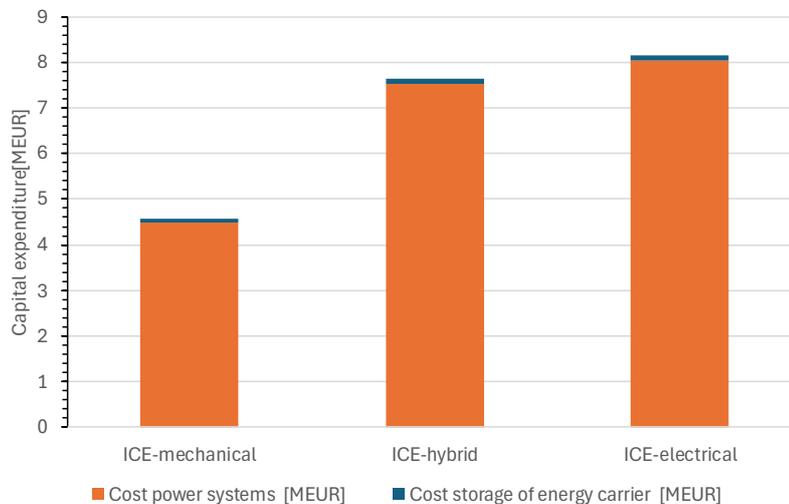


Figure 3-10: Capital expenditure of fuel storage tanks and power systems for the Offshore Supply Vessel.

Impact on the ship design

The required systems volume with respect to the available machinery space was considered. For this a system placement volume ratio of 3 was used, which means that for every 1 m³ of power system volume, 3 m³ is reserved for system placement. The result is given in Figure 3-11, from which it is clear that there is sufficient of space available in the machinery space for all architectures.

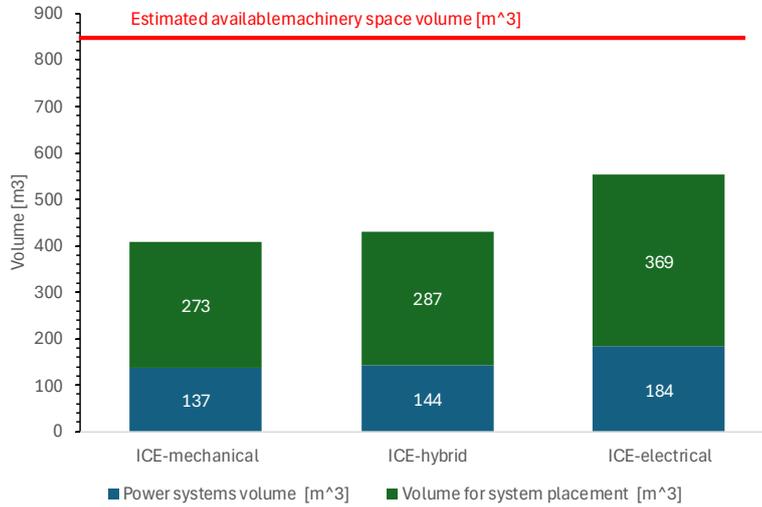


Figure 3-11: Volume of power system incl. the system placement volume for the Offshore Supply Vessel.

3.3.4 Crew tender vessel

For the three identified technical solutions an indicative weight, volume and CAPEX are provided in Figure 3-12 and Figure 3-13. It is clear that the Diesel ICE Electric technology requires the most weight and volume, and also has the highest CAPEX. It is also apparent that the fuel is a relatively small portion of the total system. The power systems are dominant in this use case. It must be noted that weight, volume and CAPEX only consider the power systems: including switchboards, converters, gearboxes, electric machines and main machinery (generator sets or propulsion engines). Fuel tanks are also considered in the CAPEX but are only a fraction of the total costs.

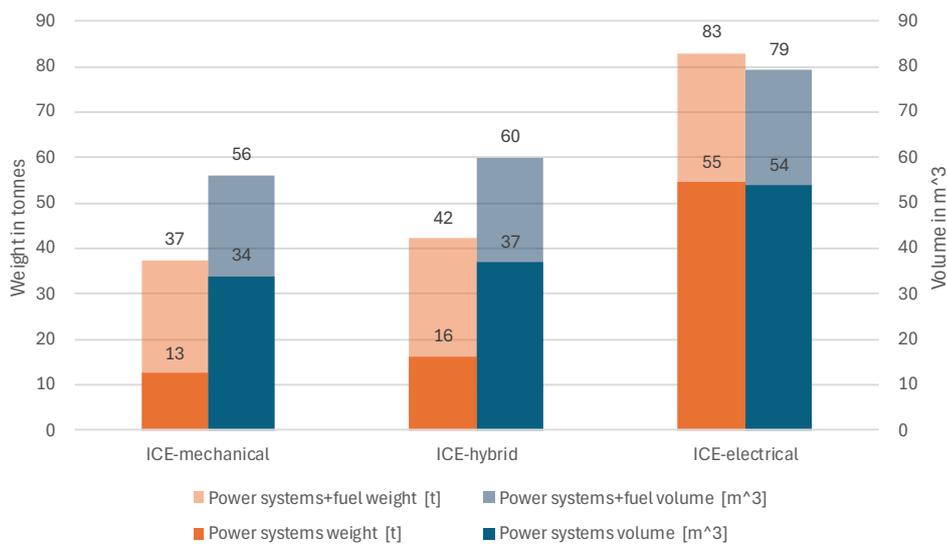


Figure 3-12: Weight and volume for fuel (incl. containment) and power systems for the Crew Tender Catamaran.

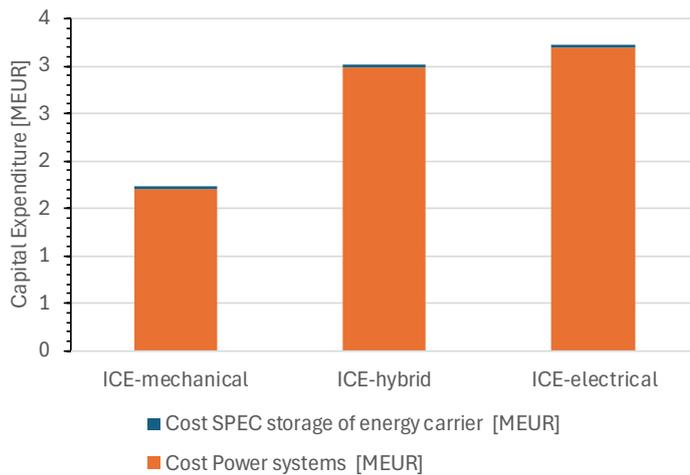


Figure 3-13: Capital expenditure of fuel storage tanks and power systems for the Crew Tender Catamaran.

Impact on the ship design

The required systems volume with respect to the available machinery space was considered. For this a system placement volume ratio of 1.5 was used, which means that for every 1 m³ of power system volume, 1.5 m³ is reserved for system placement. This is already very tight, as most machinery spaces have more volume for maintenance, access., etc.. The result is given in Figure 3-14. This shows that the ICE-electrical architecture will not fit within the current machinery space. The available machinery space is an estimate from literature [16].

For this type of vessel, the weight impact might even be more critical than the volume impact, as the ships are very sensitive to additional weight. The weight impact was assessed by calculating what fuel weight can be carried on-board provided that the ship does not exceed its design displacement and that the operations are kept as is. The result is shown in Figure 3-15. This shows that also the ICE-mechanical architecture cannot make the design endurance, which has to do with modelling inconsistencies⁷. However, the difference between the different architectures is more important: when designing a ICE-electrical architecture, all the available weight goes into the power system, and there is hardly any fuel available, thus making the concept not feasible given the set constraints. Also ICE-hybrid reduces the available range, but it is still in the same order of magnitude.

As this vessel is very critical in weight, a DC electrical distribution including variable speed generators may reduce the overall weight and improve the numbers for ICE-electrical.

⁷ The reference weight of the power system (Diesel-mechanical) is 12.6 tonnes according to the SPEC-tool. Given the fixed lightship weight of the vessel, the weight available for fuel is then calculated as a result. However, the real power system weight of the reference vessel might be a few tonnes lighter, as it is not a very accurate calculation. This can easily give an extra day of range to all options.

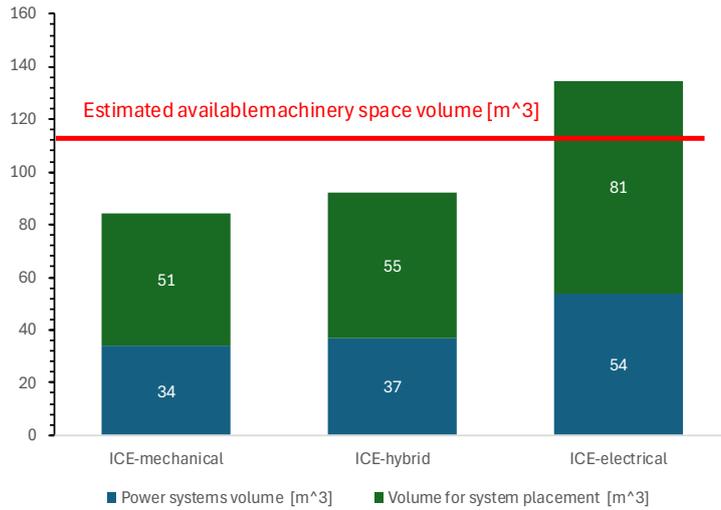


Figure 3-14: Volume of power system incl. the system placement volume for the Crew Tender Catamaran.

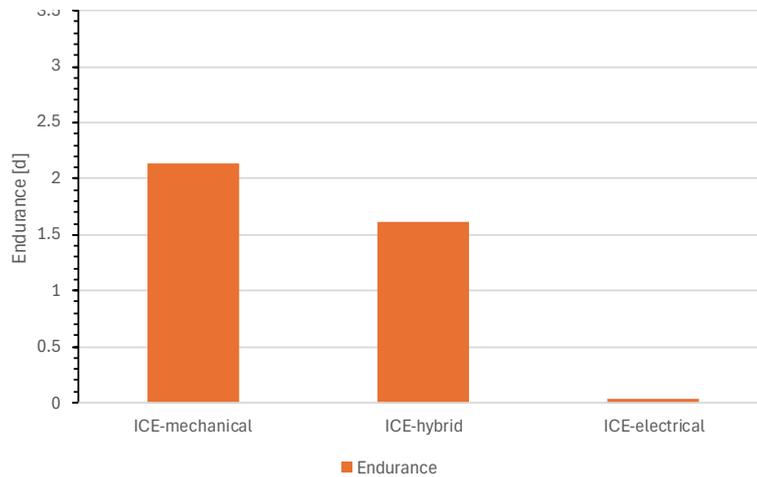


Figure 3-15: Resulting endurance of each architecture when keeping operations fixed.

3.3.5 Trailing suction hopper dredger

For the three identified technical solutions an indicative weight, volume and CAPEX are provided in Figure 3-12 and Figure 3-13. The Diesel ICE electric technology requires the most weight and volume, and also has the highest CAPEX. The fuel storage space is still dominant in all three solutions. It must be noted that weight, volume and CAPEX only consider the power systems: including switchboards, converters, gearboxes, electric machines and main machinery (generator sets or propulsion engines). Fuel tanks are also considered in the CAPEX but are only a fraction of the total costs.

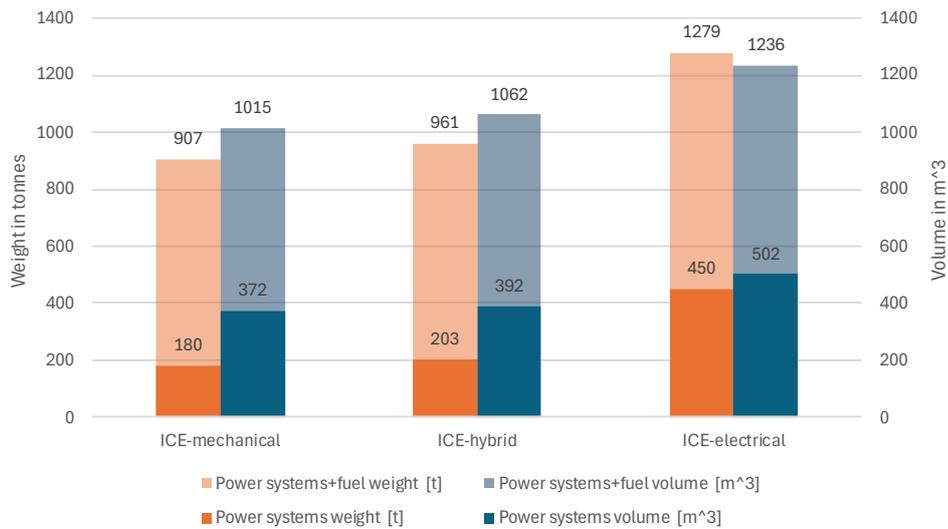


Figure 3-16: Weight and volume for fuel (incl. containment) and power systems for the Dredger.

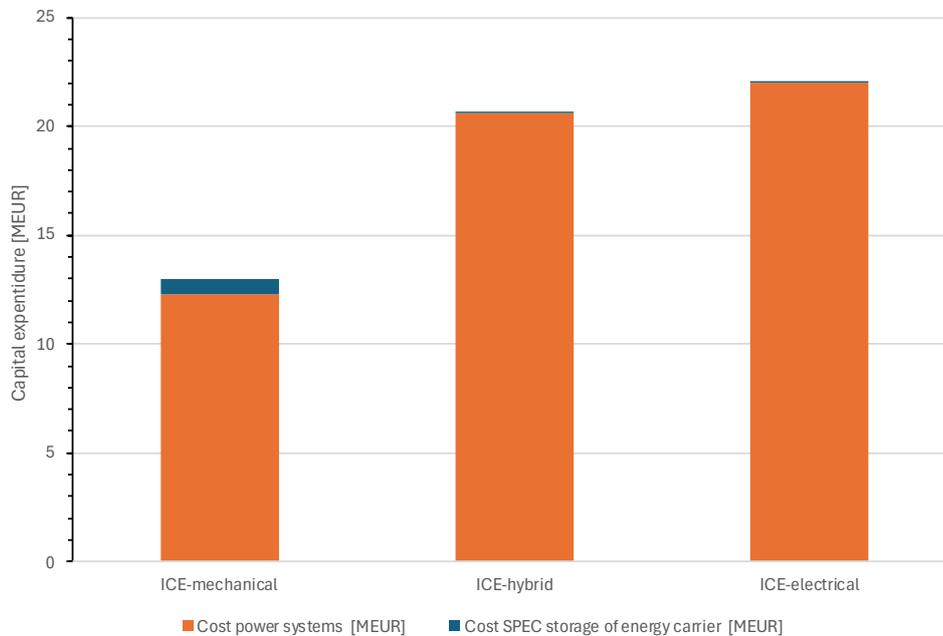


Figure 3-17: Capital expenditure of fuel storage tanks and power systems for the Dredger.

Impact on the ship design

The required systems volume with respect to the available machinery space was considered. For this a system placement ratio of 3 was used. Meaning that for every 1 m³ of power system, 3 m³ is reserved for placement. This is similar to the other large vessels. It is a reservation for maintenance space, access ways. Figure 3-18 shows that estimated machinery space volume is this still significantly larger than the PPE system. The available machinery space was estimated from the General Arrangement of Trailing Suction Hopper Dredger of the reference case. Its machinery space also features large repair areas/workshops, hydraulic spaces, a substantial power-take off for the pumps. Nevertheless, based on these available volumes the impact on the ship design of hybrid or full electric appears not too significant from a weight/volume perspective.

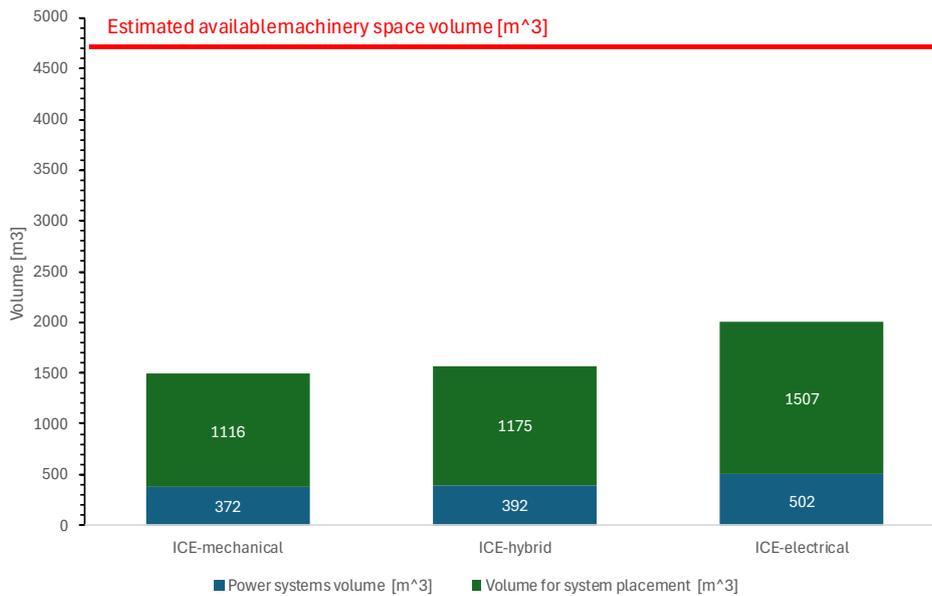


Figure 3-18: Volume of power system incl. the system placement volume for the Dredger.

3.3.6 Mega motor yacht

For the three identified technical solutions an indicative weight, volume and CAPEX are provided in Figure 3-19 and Figure 3-20. The Diesel ICE electric technology requires the most weight and volume, and also has the highest CAPEX. For the mechanical and hybrid propulsion the fuel storage is the most substantial part of the PPE weight, but for the electric solution the system weight is dominant. For the CAPEX it is shown that the system cost is dominant, and that the fuel storage system cost has an insignificant contribution.

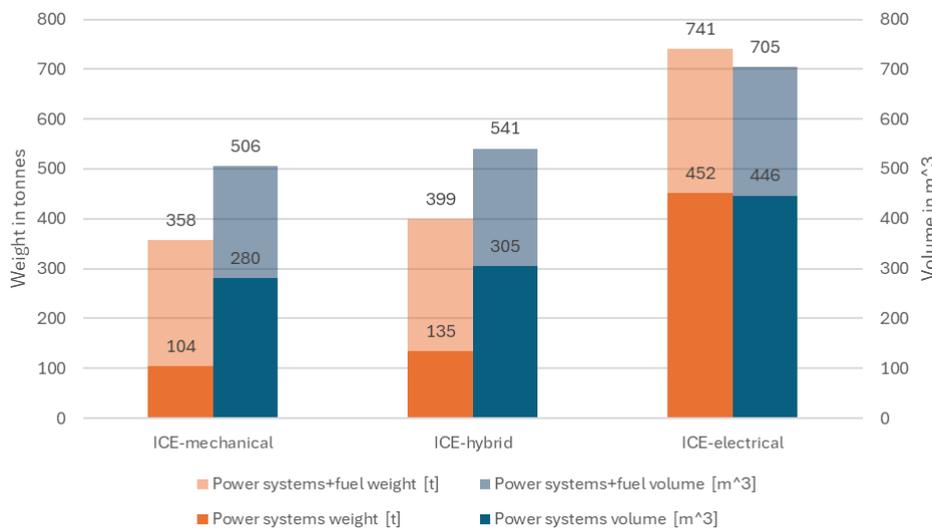


Figure 3-19: Weight and volume for fuel (incl. containment) and power systems for the Mega Motor Yacht.

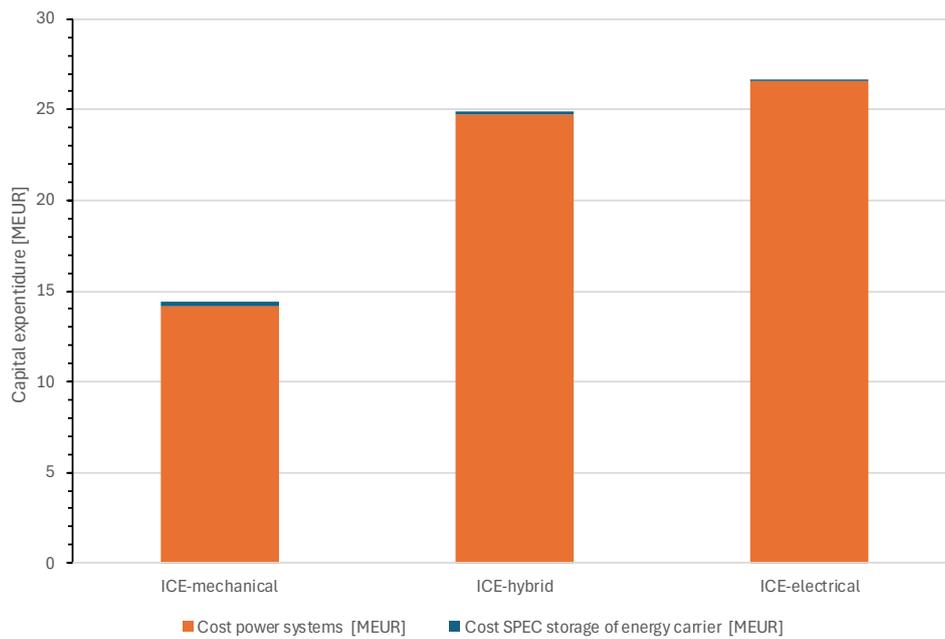


Figure 3-20: Capital expenditure of fuel storage tanks and power systems for the Mega Motor Yacht.

Impact on the ship design

The required systems volume with respect to the available machinery space was considered. For this a system placement ratio of 2 was used. Meaning that for every 1 m³ of power system, 2 m³ is reserved for placement. This is similar to other motor yachts, which typically have a tight machinery space (in order to maximize interior volume). This placement ratio is to account for access and maintenance space. Figure 3-21 shows that the estimated machinery space volume is a tight: only the mechanical and hybrid architectures seem feasible. The electric architecture requires almost 400 m³ of additional volume. It must be noted this analysis only gives an indication of the required space, an actual design study may show a more favourable result. Moreover, the available machinery space volume varies from vessel to vessel. The 1000 m³ reference machinery volume is not the same for all yachts in this class. Nevertheless a substantial impact from electrification in terms of volume is expected for this vessel type.

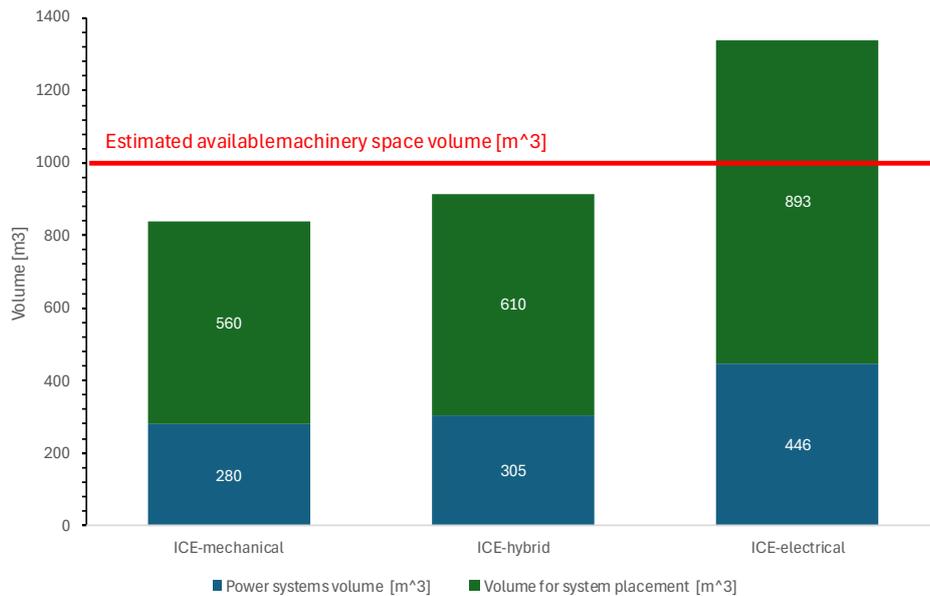


Figure 3-21: Volume of power system incl. the system placement volume for the Mega Motor Yacht.

3.4 Conclusions from the generic feasibility study

The generic approach taken to assess the feasibility of electrification of the ship propulsion for the selected archetypes indicates that electrification is dependent on the application type. Dredgers and offshore supply vessels show significant shares of electric propulsion. The majority of which is ICE-electric. Also tugs show some market share.

Different drivers are acting to apply electrification.

The following topics are discussed and they have different contributions per vessel archetype:

- Fuel consumption and efficiency
- Capital expense
- Maintenance
- Air pollutants
- Operational Availability
- Ship Arrangement
- Refit Flexibility
- Drive characteristics
- Noise and vibration

Generally addressed, the ICE-electric propulsion is given the most benefits on the listed items. The costs however, are expected to score worst. This is where the ICE-mechanical reference is scoring highest.

In more detail, the size and weight impact of applying hybrid or ICE-electric propulsion systems are estimated based on key figures obtained from published numbers in literature. This is matched against the available space in the vessel. Since this is particular for the ship design, the results are provided per use case specific reference vessel.

General conclusions are:

- Hybrid system topologies show a limited increase in weight and volume around 5-10%.
- ICE-Electric system topologies show a significant increase in weight and volume around 10-20%.
- The CAPEX of the power system is increased by 70-90% for hybrid and electric vessels. Thus substantial OPEX savings are required to maintain a business case for electrification.
- For the short sea transport vessel the impact of electrification seems limited regarding the additional weight and volume of the systems, especially compared to the impact on the cargo carrying capacity.
- For the harbour tugboat the additional volume required by electrification seems most critical, the ICE-electric propulsion system is over the limit regarding the estimated available volume in the machinery space. It could mean an overall different hull design is needed.
- For the offshore supply vessel electrification seems feasible regarding weight and volume.
- For the crew tender vessel electrification seems unfeasible regarding space and weight requirements. This vessel is very limited in volume and critical on displacement; additional weight has big penalty on the propulsion power of the fast (semi-)planning vessel.
- For the dredger vessel the impact of electrification from seems limited from a weight and volume perspective. These vessels already have large machinery spaces with substantial auxiliary/payload power requirements.
- For the mega motor yacht the impact of electrification is substantial. A hybrid architecture is still feasible, but full electrification appears unfeasible with the tight machinery space available on this vessel.

4 Detailed feasibility studies

The previous chapter has investigated electrification based on open literature and main rules of thumb that could be derived from the open literature. The ship use cases were used to provide specific values and investigate potential regarding volume and weight.

This chapter will further investigate the designs by creating the PPE architectures and sizing main components. These can then be used to investigate the part-load efficiency of the total energy chain.

The chapter will focus on answering the following research questions as stated in the introduction:

For which ship types and operations is electrification advantageous? Can electrification of the propulsion line benefit from lower fuel consumption over a typical operational profile by load distribution compared to a ICE-mechanical solution?

4.1 Introduction

This chapter gives insight into the feasibility and potential benefits of electrification for the different use cases considered within the Green Deal electrification report.

The feasibility is split into the following topics:

- Naval architectural feasibility
- Operational efficiency
- Other benefits

For each vessel archetype, use case specific electrification alternative designs of the PPE architecture are made.

Generic applicable operational profiles have been created, based on typical vessel journeys and expert opinion. These were provided to the market via the stakeholders for feedback. For each use case an indication of fuel savings were calculated per ICE-electrical or ICE-hybrid architecture, based on an evaluation over the defined operational profiles. The objective of this approach is to calculate possible savings due to sizing of propulsion engines and generators in order to improve the operational load distribution of components and hence the efficiency of the total Propulsion and Energy system. To this extent MARIN evaluated the feasible electrified naval architectures, developed propeller and component models, and analysed the efficiencies of these configurations in a quasi-static calculation.

TNO complemented the model of MARIN and focused on analysing the effects of implementation of a battery pack in the Short Sea Transport Vessel. This is reported in chapter 5. The results of the analysis done by MARIN will be discussed in detail in the following sections per design use case.

4.2 Short Sea Transport Vessel

4.2.1 Operational analysis

The operational power profile and load distribution of the Short Sea Transport Vessel is performed for 3 different missions, each at a different season. This is to take into account the effects of rougher sea state conditions during wintertime for the propulsion and varying conditions for the HVAC and reefer containers (payload).

Propulsion power

Propulsion power is estimated for ballast and full load conditions in calm water, sea state 3 and sea state 6.

Payload and Auxiliary Power

Payload consumers are associated with the cargo or more generally, how the vessel makes its money. In this use case we assume that part of the cargo has to be cooled (reefer). Other payload equipment includes deck cover cranes, ballast water treatment and ballast water distribution system. The total power of the installed payload consumers is defined as 450 kW, but the actual average usage is assumed between 10-45% per defined operational task.

The auxiliary consumers concern navigation, rudder, lighting, heating and ventilation, galley, general cooling etc. The total installed power of the auxiliary power consumer is defined as 300 kW, but the actual average usage is assumed between 50-80% per defined operational task.

Operational profiles

The operational profile of the Short Sea Transport Vessel consists of a route from Dutch port of Rotterdam in the Netherlands, to Norwegian port of Bergen, to the Canadian port of Halifax, and vice versa, requiring an autonomous range of 7,000 [NautMiles] without re-fuelling.

As mentioned, the seasonal effect has been captured by assessing power requirements for:

- Operation I - Typical Cargo Transportation Voyage – Spring/Autumn
- Operation II - Typical Cargo Transportation Voyage – Winter
- Operation III - Typical Cargo Transportation Voyage – Summer

Figure 4-1 shows the profiles of the consumed Propulsion, Payload Power, Auxiliary Power, and the Total Power for Operation I – Spring/Autumn.

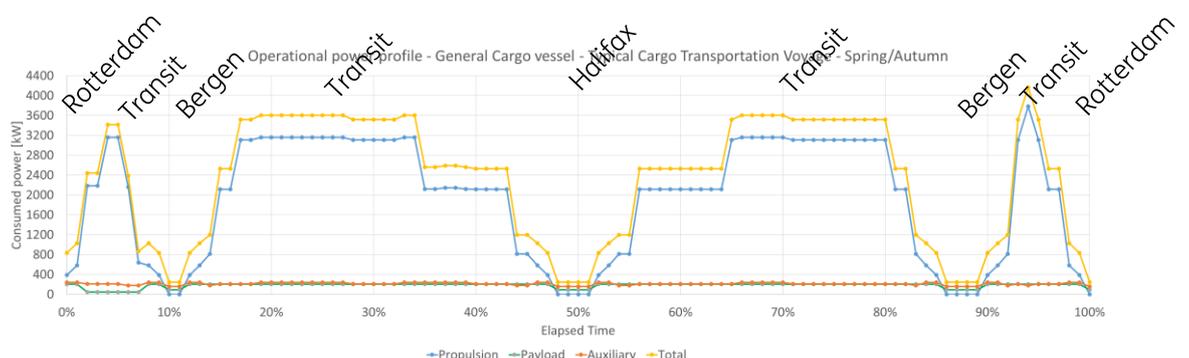


Figure 4-1: Operational power profile for the Short Sea Transport Vessel – Operation I - Typical Cargo Transportation Voyage in Spring/Autumn.

The operational power profiles for the other two seasons are very comparable and shift some percentages, hence not repeated. The comparison of results between the seasons can be seen in the power distribution profile as given in Figure 3-2.

The total amount of Consumed Energy for Mission Type I is 1952 [MWh]. The Consumed Energy differs from the amount of consumed diesel, because between those two is the Total Efficiency of the Energy-to-Power plant.

The total estimated amount of consumed Energy for Mission Type II is 2167 [MWh], which is 215 [MWh] more than for a typical Spring or Autumn voyage. This corresponds to an approximate extra diesel consumption of 60 [Metric Tons] per voyage, assuming a total average efficiency of 37% (Fuel-to-Consumers).

The total amount of consumed Energy for Mission Type III is 1882 [MWh], which is 70 [MWh] less than for a typical Spring or Autumn voyage, corresponding to an approximate lower diesel consumption of 17 [Metric Tons] per voyage, assuming a total average efficiency of 37% (Fuel-to-Consumers).

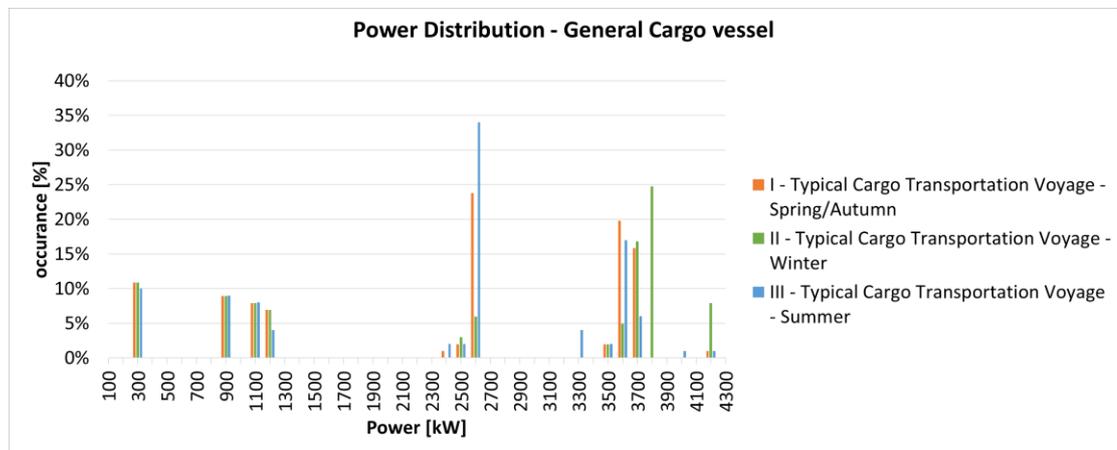


Figure 4-2: Power distribution of the Short Sea Transport Vessel obtained from 3 different seasonal conditions.

Summary Mission Profiles

The results of the Operational Analysis for the PPE system of the Short Sea Transport Vessel are shown in Table 3.3. The total consumed energy differs for the Mission Types. The most demanding is the Winter Mission and the least demanding is the Summer Mission, based on change in propulsion requirement while maintaining the same ship speeds over the profiles. The auxiliary and payload power did not change significantly over the different profiles. A change in propulsion power can be expected at later stage when more details and different concepts of the propeller are taken into account.

Table 4-1: Summary of the vessel PPE particulars and mission types of the Short Sea Transport Vessel

Reference vessel	Displacement - Fully Loaded [metric tons]	Max Speed - Fully Loaded [Kts]	Autonomous Range [NautMiles]	Installed power prime movers [kW]	Power and Propulsion Architecture
Short Sea Transport Vessel	13,120	13.5	7,000	4500	ICE-Mechanical – PTO (Power Take-Off)

Reference vessel	Operation	Consumed Energy [MWh]
Short Sea Transport Vessel	I - Typical Voyage - Spring/Autumn	1,952
	II - Typical Voyage – Winter	2,167
	III - Typical Voyage – Summer	1,882

4.2.2 Architectures

The different architectures, ICE-mechanical, hybrid and ICE-electrical that were analysed are shown in Figure 4-3.

The ICE-mechanical architecture is the reference architecture. It features a single main propulsion engine of 4000bkW and two small auxiliary engines of 270 kWe to provide electrical power to the ship’s grid. It is sized to provide reefer power. In transit the Propulsion Shaft Generator (PSG) can also supply power to the auxiliary grid.

Application of the PSG in parallel to an auxiliary genset is justified by:

- reduce total running hours of the auxiliary genset equipment and hence maintenance cost
- apply less strict fuel oil combustion from the main propulsion engine
- potentially reduce total fuel rate by operating the engines on a more efficient working point

In order to provide the power to ship’s grid with the PSG, the engine is running at constant speed to provide a fixed frequency to the AC distribution board. i.e., no frequency converter is applied between the PSG and distribution grid. The propulsion thrust is controlled by changing the pitch of the Controllable Pitch Propeller (CPP).

The hybrid architecture features a smaller propulsion diesel engine (3000 bkW) compared to the reference case, which is supported by an Electric Shaft Machine (ESM) of 1200bkW. In contrary to the reference case, the ESM is also able to apply power to the propulsion shaft. Hence, larger auxiliary generator sets are installed (2x 900kWe) to supply the electric energy to auxiliary, payload as well as propulsion power to the ESM in case it is running as ICE-electric.

Application of the hybrid solution is justified by:

- smaller Propulsion Diesel Engine (PDE) to have a more efficient load during part-load or economical transit operations, while ESM to provide additional power to reach max propulsion power demands.
- ESM to provide electric power to the grid to reduce running hours of the auxiliary gensets and improve the efficiency of the PDE
- ESM to provide mechanical power for propulsion for the low speed operations to avoid low load running of the main engine.

The total installed genset power is relatively high and chosen to run the ESM as propulsion motor and providing auxiliary and payload power to the vessel. Two medium sized gensets are chosen for more optimal load distribution, and it is still expected to fit in the vessel design.

The ICE-electrical propulsion architecture features four generator sets of 3x 1300kWe and 1x 600 kWe, allowing the generators to run with significant load and beneficial loading points at various power requests. A gearbox is connected to the Electric Propulsion Motor (EPM) of 4000kW output to select a high speed / lower torque motor compared to a direct drive e-motor in order to reduce the size and cost of the electric system. This will yield a lower efficiency compared to an architecture without gearbox, but is typically preferred due to lower investment costs. The ICE-Electrical architecture is fitted with a fixed pitch propeller (FPP), because the electric propulsion allows the technical feasibility for it. In this architecture a ducted propeller is applied to make more benefit during the low speed vessel operations.

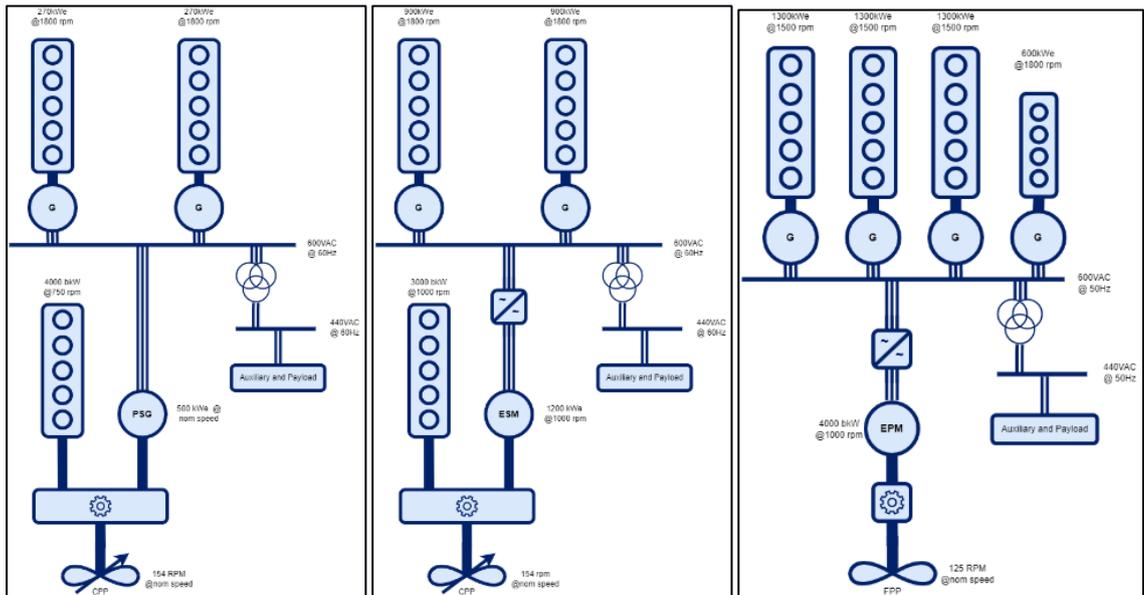


Figure 4-3: Overview of the Short Sea Transport Vessel architectures, from left-right: ICE-mechanical, ICE-hybrid and ICE-electrical.

4.2.3 Feasibility from fuel efficiency perspective

All architectures are evaluated over the defined operational profile, including an optimization scheme for component allocation and using the part-load efficiency of the main components. The results of this quasi static analysis are shown in Figure 4-4. Overall, all architectures have a similar fuel consumption over the entire operational profile.

Figure 4-4 provides an overview of both input to the calculations as well as output. The top graph of Figure 4-4A shows the speed profile of the vessel from the operational analysis. The second graph of Figure 4-4B shows the calculated total power from the operational analysis. Differences occurred when the propulsion type has changed from CPP to FPP. The payload and auxiliary power are kept constant. The ICE-mechanical architecture is shown in red (referred to as MechArch CPP), the hybrid architecture is given green (referred to as HybridArch FPP) and the ICE-electric architecture is shown in blue (referred to as ElecArch CPP).

The first output of the calculation is given by the third graph in Figure 4-4C which shows the conversion efficiency from diesel fuel chemical energy to the sum of propulsion, auxiliary and payload energy for each point in the operational profile.

The final output of the calculations is given by the fourth graph in Figure 4-4D which shows the total fuel consumption rate for each time step. This is a combination of the input power and the system efficiency. The integrated result over the whole profile gives the total fuel consumption per trip, which has been numerically provided in the legend Figure 4-4D.

The mechanical propulsion shows the highest efficiency in the transit conditions, but the lowest at low speeds. This is due to the low engine efficiency at low load conditions. The hybrid configuration has the benefit of higher system efficiency at part load compared to the ICE-mechanical case. Overall it has a more stable, but lower efficiency compared to the ICE-mechanical architecture. The ICE-electric architecture shows lower efficiency over the whole range, due to its additional power conversions and relative lower genset efficiency.

Overall, the ICE-electrical architecture has a slightly lower fuel consumption. This is seen in Figure 4-4D and tabulated in the legend, which shows a 0.6% reduction in fuel consumption. However, this is in the order of the accuracy of the analysis. Although the efficiency is lower, the total fuel consumption reduction originates from the lower propulsion power requirement for the ICE-electrical architecture due to the application of the FPP, as is reflected in Figure 4-4B.

In other words, the efficiency loss by the electric conversions in hybrid and ICE-electric architectures are fully compensated by improving the loading of the equipment in part-loads over the whole operational profile. This is of course heavily depending on the distribution of the loading or the sailing vs harbour time.

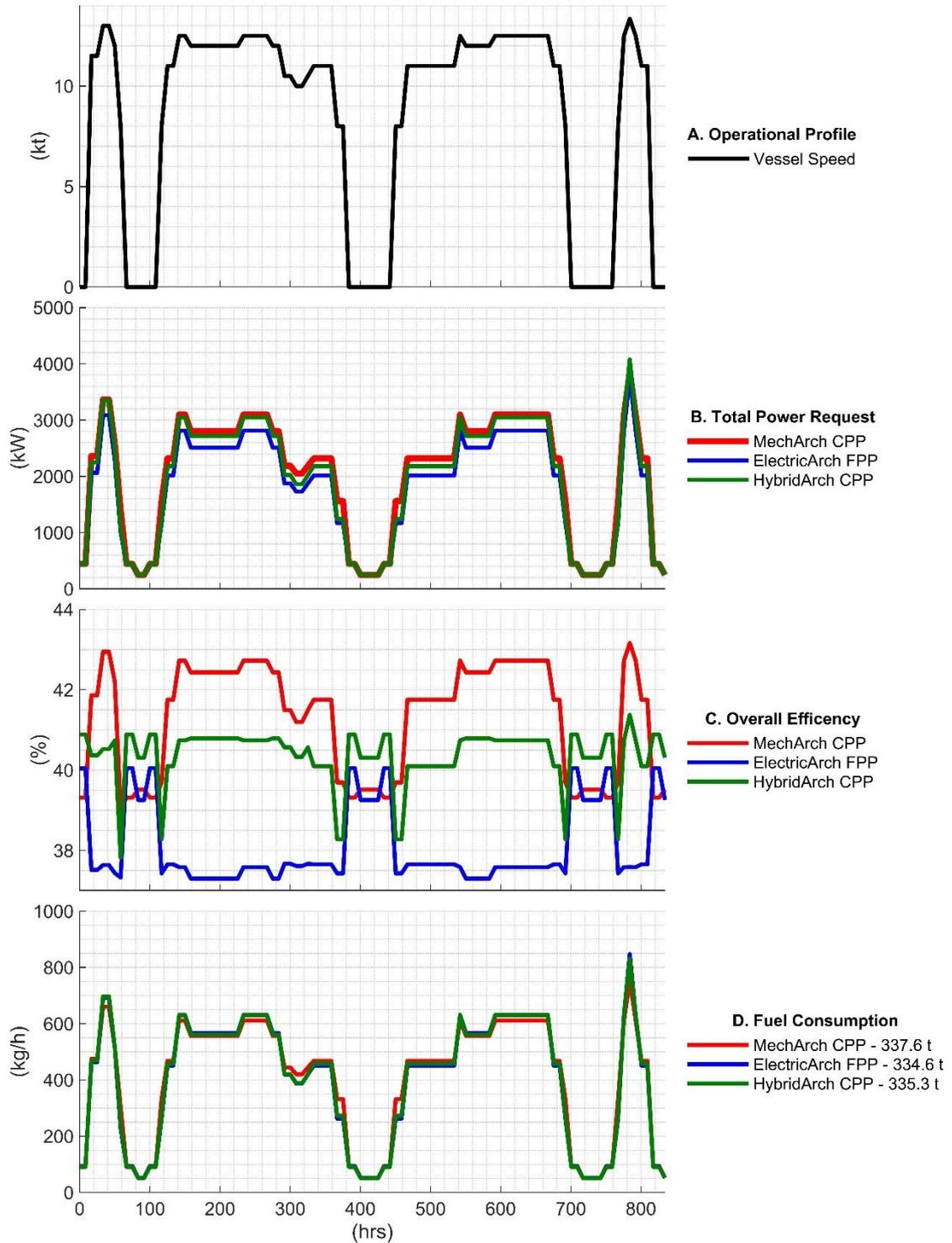


Figure 4-4: Input and output of the quasi static calculations for the Short Sea Transport Vessel. Red – ICE -Mechanical, Green – Hybrid, Blue – ICE-Electric. From top to bottom: (A) input speed profile as obtained from the operational analysis (B) Total summed power of propulsion, auxiliary and payload power (C) total system efficiency from fuel rate input to total power request (D) total fuel consumption rate, total over profile is provided in the legend.

4.2.4 Discussion

Based on the performed quasi-static analysis there is not a very strong incentive for electrifying a general cargo vessel.

The main long transits take most of the energy to propulsion, which is most efficient with ICE-mechanical solutions. Also the auxiliary and payload systems are relatively small, where the benefit of electrification does not easily pay off. The vessel lay-out is well suited to direct propulsion. None the less, for smaller vessels with reduced installed power or other niches, a range of vessel sizes can still benefit from the electrification.

Due to the large amounts of energy consumed, batteries as main energy source are typically not relevant for this ship type. They could assist in standby operations however, especially for the hybrid case, to reduce running hours of the gensets and further reduce low load operations and reduce emissions during harbour operations.

4.3 Harbour Tugboat

4.3.1 Operational profile

The tug boat operation consist of sailing towards a tugging job, perform the (un)berthing assistance and sail back. Secondly, the specific use case (Azimuthing Stern Drive tug) is also able to escort vessels on a harbour entrance or towards sea. In this way, the tug is assisting at the guided ship's speed and creating side forces with both thrusters and dynamic lift.

Two operational profiles are created:

- Operation I - Typical tug job – in harbour near quay operation
- Operation II – Typical tug assistance job – receiving vessel from port entry to quay operation

Propulsion power

To address the propulsion power over speed for the harbour tug, only a single vessel draught is used based on statistical information from comparable vessels within the MARIN database. The main propulsion power differences by the tug are when it is in either pushing or pulling condition at very low vessel speeds or while assisting. This could be performed at several propulsion settings. For simplicity in this use case, only part load (50%) or full load (100%) are used for (un)berthing assistance and one additional propulsion load (40%) for the escorting assistance to create the loading profile. For its own berthing, and manoeuvring 5-15% propulsion power is assumed. Since the vessel is operating in confined waters, no additional environmental loads are assumed.

Payload and auxiliary power

To perform the tugging operation, hydraulic or electric systems are used to operate the winches. These are part of the payload power. Average loads up to 150kW are assumed. The tug is also equipped with firefighting installation, but this is not used in the typical mission profile as it is seldomly used. The auxiliary loads consist of the nautical and hotel services, next to other generic operating systems such as bilge and cooling water systems. The loads are assumed to vary between 40-80kW.

Mission profiles

Two missions are defined for the Harbour Tug. Mission type I consists of five quay operations and Mission Type II consist of a vessel assistance job and two quay operations.

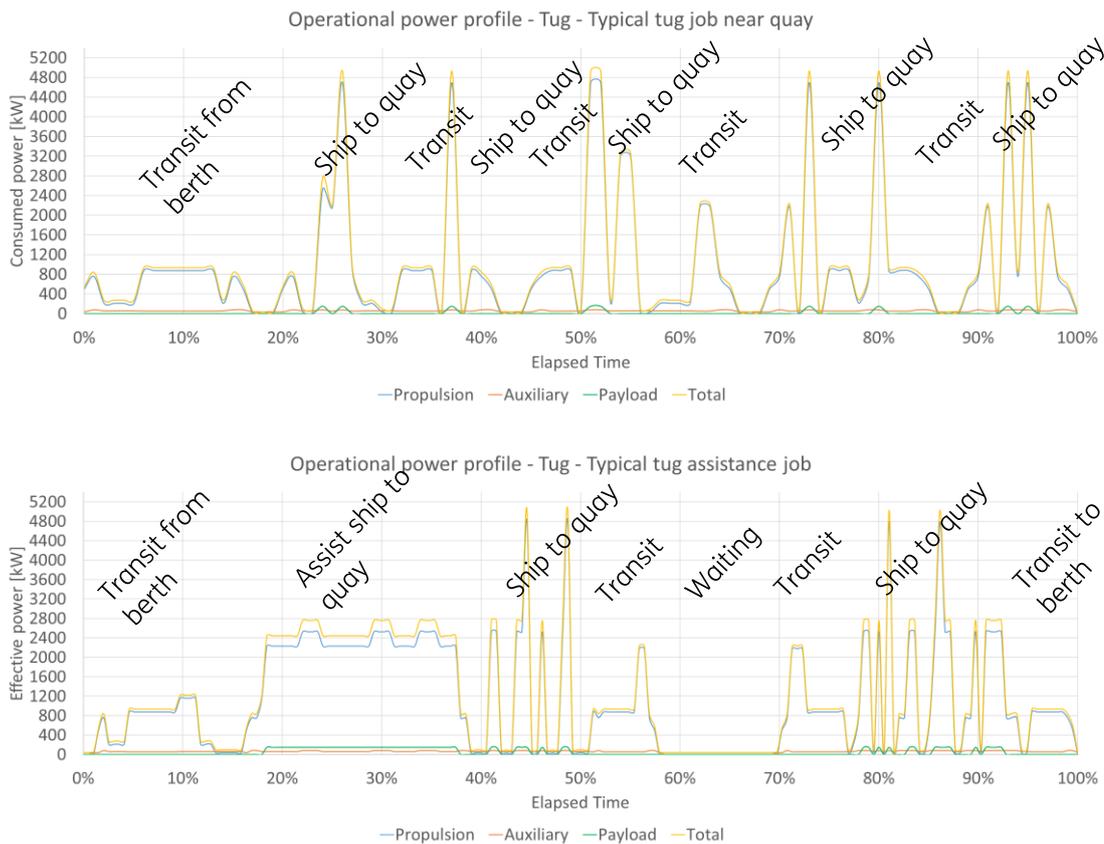


Figure 4-5: Operational power profiles for the tug of a typical tugging job with near quay operation (top) and a including a vessel assistance job (bottom).

The power distribution of both operations of the Harbour Tug Boat are shown in Figure 4-6.

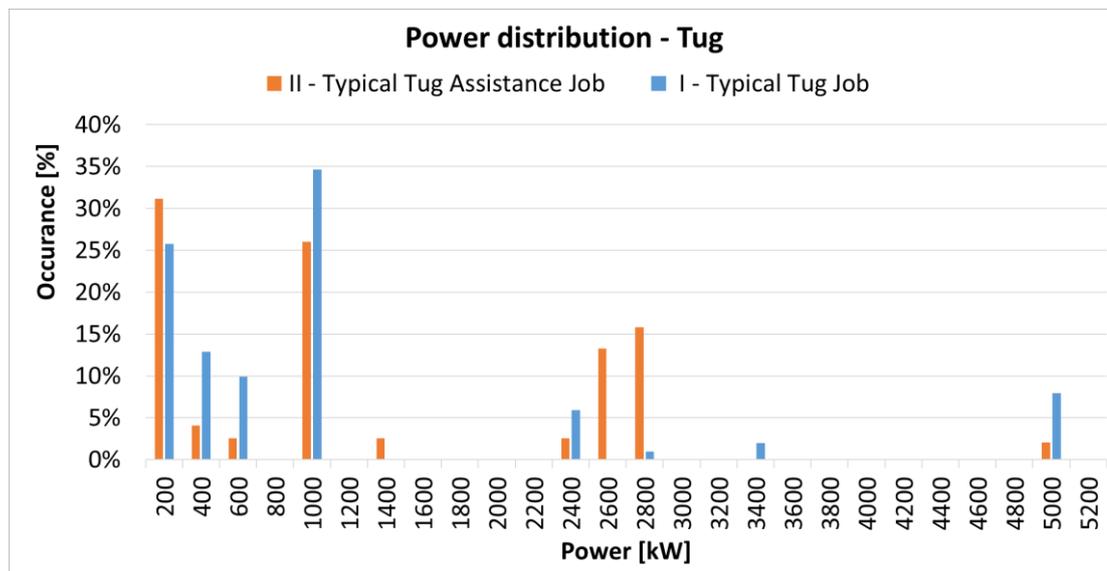


Figure 4-6: Distribution of power - Harbour Tug Boat – operation I and II.

Both missions are scaled to represent 12 days of autonomous operation (no fuel bunkering). Although operation I has a higher distribution of time at the max output power, operation II has a 18% higher energy demand due to the longer period of assisting.

The power and Propulsion particulars of the Harbour Tug Boat are shown in Table 4-2.

Table 4-2: Vessel PPE Particulars and Mission Type of the Harbour Tug Boat

Reference vessel	Displacement - Fully Loaded [metric tons]	Max Speed - Fully Loaded [Kts]	Autonomous Range [NautMiles]	Installed power prime movers [kW]	Power and Propulsion Architecture
Harbour Tug	800	13.5	49	5,300	ICE-Mechanical

Reference vessel	Mission Type	Consumed Energy [MWh]
Harbour Tug	I - Typical Tug Job	298
	II - Typical Tug Assistance Job	355

4.3.2 Architectures

The different architectures, ICE-mechanical, ICE-hybrid and ICE-electrical that were analysed are shown in Figure 4-7.

The ICE-mechanical architecture is the reference architecture. It features two large main engines (2x 2525 bkW) and two small auxiliary engines (2x 150kWe).

The ICE-hybrid architecture features smaller propulsion engines (2x 1725bkW) and significantly larger generator sets (2x 880 kWe + 1x 99kWe). The Electric Shaft Machine (ESM) can provide the remaining propulsion power to sum the total power equally to the reference case, as max power for bollard pull is a major design constraint.

Considerations in the hybrid design are:

- Combination of auxiliary and propulsion loads (reduced running hours)
- Installing a smaller main diesel engine, used more at higher loads
- Using the ESM to boost temporarily or dynamically assist the main diesel engine
- Using the ESM to propel the vessel at low speeds and transits
- Using the small generator set for 0 speed operation waiting / loitering

The ICE-electrical architecture may further improve the above depending on the actual operation loads and conditions. As many tugs feature azimuth propulsors, a full electric propulsion system can be placed in a favourable layout, enhancing the ships stability.

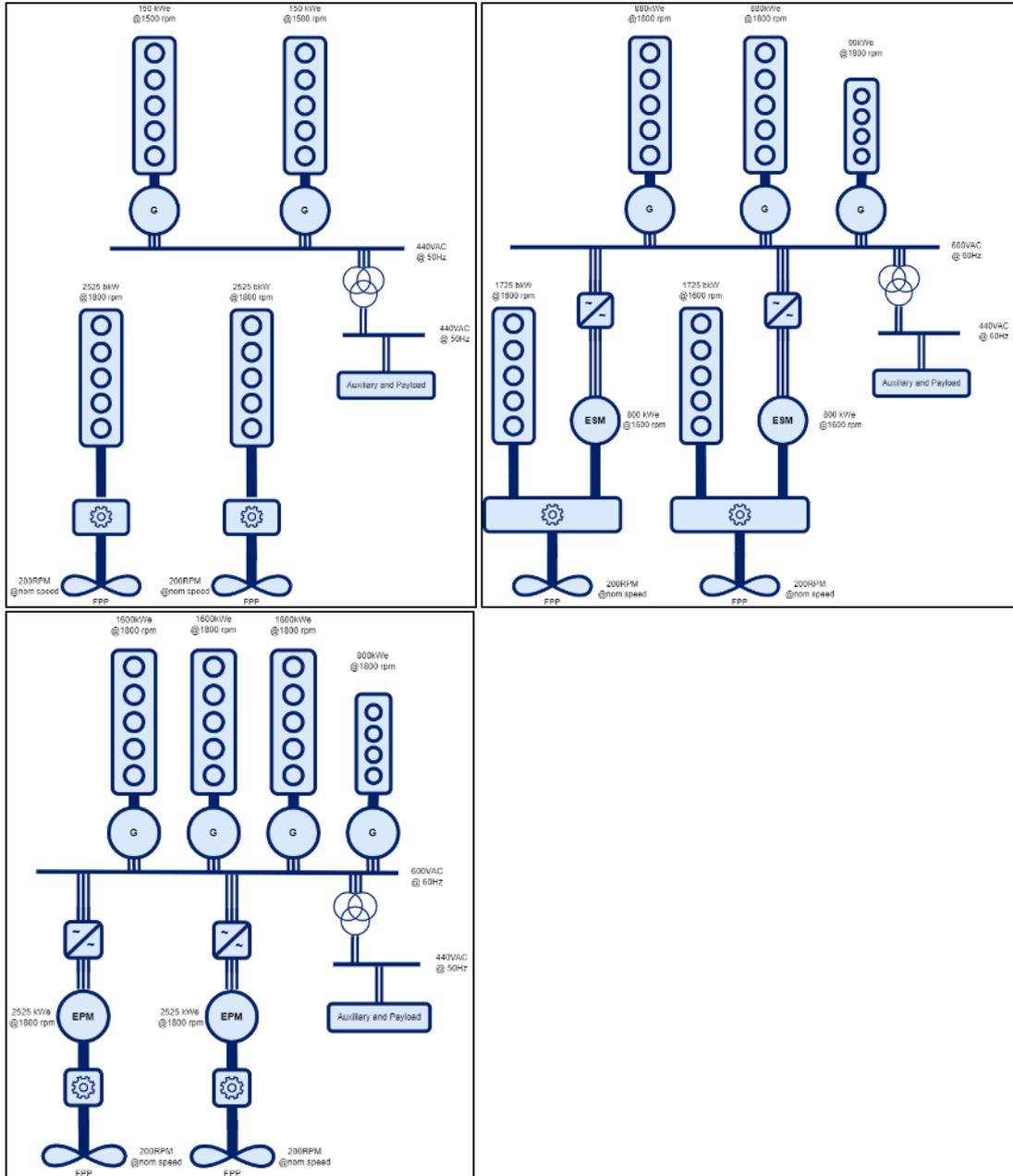


Figure 4-7: Overview of the Harbour Tugboat architectures: ICE-mechanical (top-left), ICE-hybrid (top-right) and ICE-electrical (bottom).

4.3.3 Feasibility from fuel efficiency perspective

The performance of all 3 architectures of the Tugboat are compared over the defined operational profile. The results of this quasi static analysis are presented in Figure 4-8.

Since the propulsor and payload is not changed for this use case, there is no difference in the power demand as shown in Figure 4-8B. No difference in support power for the different systems are taken into account.

Since the installed power of the tugboat is dimensioned for the max bollard pull, which is only requested occasionally, a lot of time the vessel is in low or part load conditions. For the mechanical propulsion architecture, this results in (very) low peaks in efficiency.

The hybrid and electric versions have a much higher efficiency in these cases, as can be seen in Figure 4-8C.

Since the energy during the low load tasks is low, the effect on fuel consumption is limited. Overall, the harbour tugboat has a reduced fuel consumption due to electrification. ICE-hybrid and ICE-electrical architectures are more efficient in the zero to low speed range that the vessel frequently operates in. As seen in Figure 4-8C the ICE-mechanical architecture has a very low efficiency (<30%) when the vessel speed is very low. Please note that this is in the boundary of the theoretical model of the ICE efficiency, and differences with practice may arise. The largest reduction in fuel consumption is obtained by the ICE-hybrid architecture, which reduces 5% with the selected architecture components and operational profile. The ICE-electrical savings are relatively small (<2%).

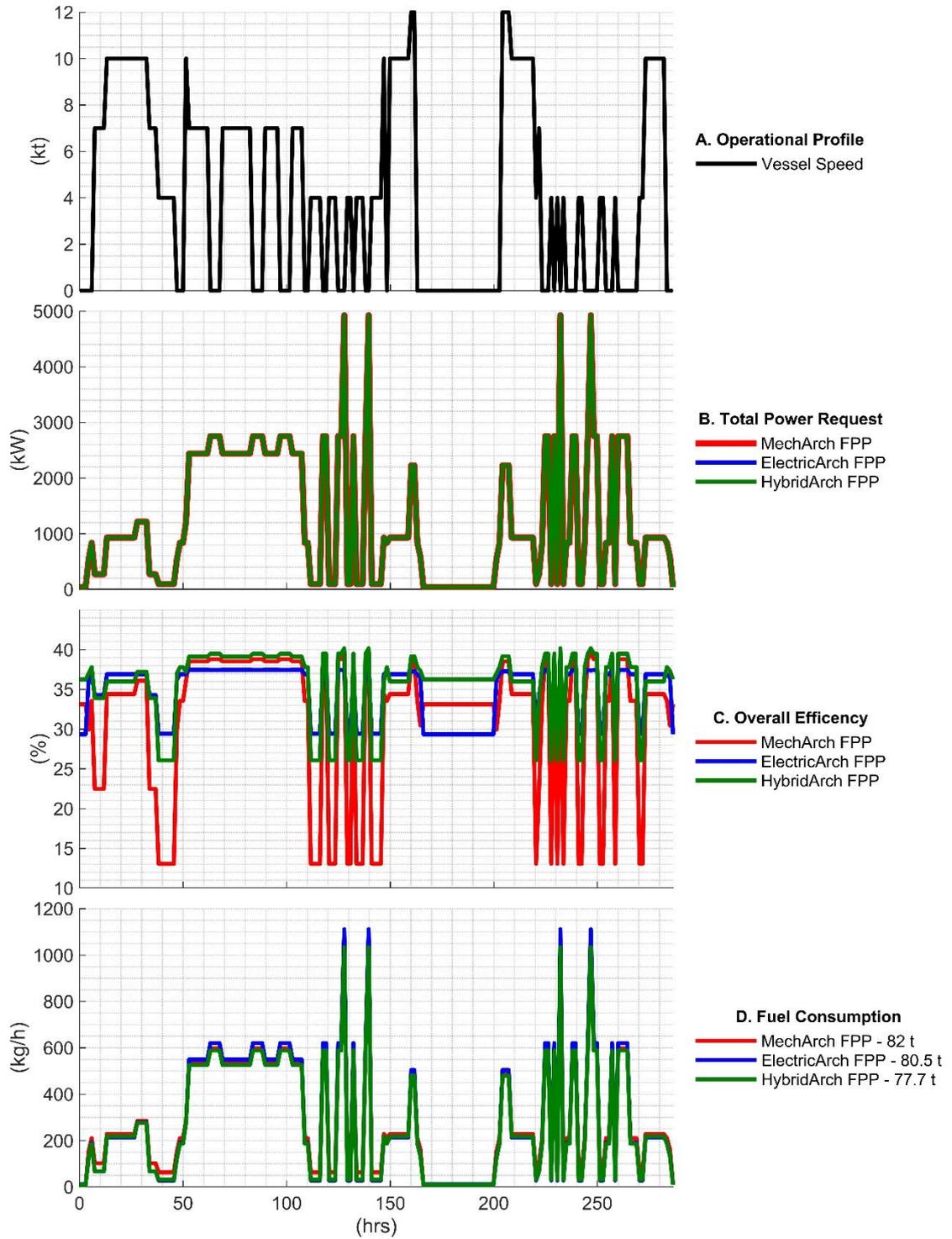


Figure 4-8: Input and output of the quasi static calculations for the Harbour Tug. Red – ICE-Mechanical, Green – Hybrid, Blue – ICE-Electric. From top to bottom: (A) input speed profile as obtained from the operational analysis (B) Total summed power of propulsion, auxiliary and payload power (C) total system efficiency from fuel rate input to total power request (D) total fuel consumption rate, total over profile is provided in the legend.

4.3.4 Discussion

The wide operational profile and payload systems of the harbour tug seems to be promising for electrification. Electrification could be beneficial for the rapid dynamic (support) of the main propulsion and especially temporarily over-capacity of an electric motor. Avoiding the low-load operations for the main engine could also improve the rating of the engine and reduce maintenance intervals.

Arrangement can be a challenge in the limited space of the harbour tug. Noise and vibrations in the accommodation challenges could possibly be reduced by making use of isolated generator sets.

Once an electric system is chosen for (partial) propulsion load, also the main winches can be made electrical, which is helpful for the control and efficiency compared to hydraulic systems.

In addition a battery system could be added to have low speed sailing without running combustion engines (with the associated running costs) and to potentially recover electricity from electrical constant tension winches. A DC grid and variable speed generator sets could be studied to further improve the efficiency of the ICE-electrical architecture. Earning back the investment is not evident from the current investigation. Making use of temporarily over-capacity of the electric motor could opt for installing even a smaller ICE in the hybrid case, which may improve slightly.

4.4 Offshore Supply Vessel

4.4.1 Operational profile

The typical mission of the Offshore Supply Vessel consists of sailing loaded towards a platform, unload near the platform using dynamic positioning and some payload equipment and sail back in ballast draught.

Propulsion power

The cargo capacity of the Offshore Supplier is substantial (DWT = 2900 [MT] versus Δ Loaded = 5800 [MT]). Therefore two drafts are used to obtain the vessel speed – propulsion power relation one for Unloaded/Ballasted condition both in calm water. Constant seaway corrections apply for events in other weather conditions. The propulsion power estimations are based on simplistic admiralty coefficient approximation, which is sufficient for this type of vessel for feasibility verification.

For (un)berthing and manoeuvring events, 10-15% average propulsion power is assumed. For the quasi static assessments of fuel consumption, corrections are made for the type of propulsor. The reference ship is assumed to have fixed shaft lines with CPP for DP performance. Hence corrections are made for the low speed conditions. With changing PPE architecture, other assumptions are made for the propulsion power. This is further addressed in the relevant section of the report.

Payload and Auxillary power

The only payload system identified are deck cranes and onboard pumps to load or unload cargo (e.g. drilling sand). These are assumed to have an average used combined power usage of 540kW during off-loading. The auxiliary power consist of the nautical and hotel services, next to other generic operating systems such as bilge and cooling water systems. The loads are assumed to vary between 200-300kW.

Mission profiles

The created mission profile consist of loading on shore, sailing to the destination (~2 days or 700nm), unloading and sail back. This would be a rather long trip, but it could also consist of several shorter trips with a total comparable endurance. The Event and Power Distribution Graphs of a typical offshore supply voyage (Mission Type I) of the Offshore Supply Vessel are shown in Figure 4-9 and Figure 4-10.

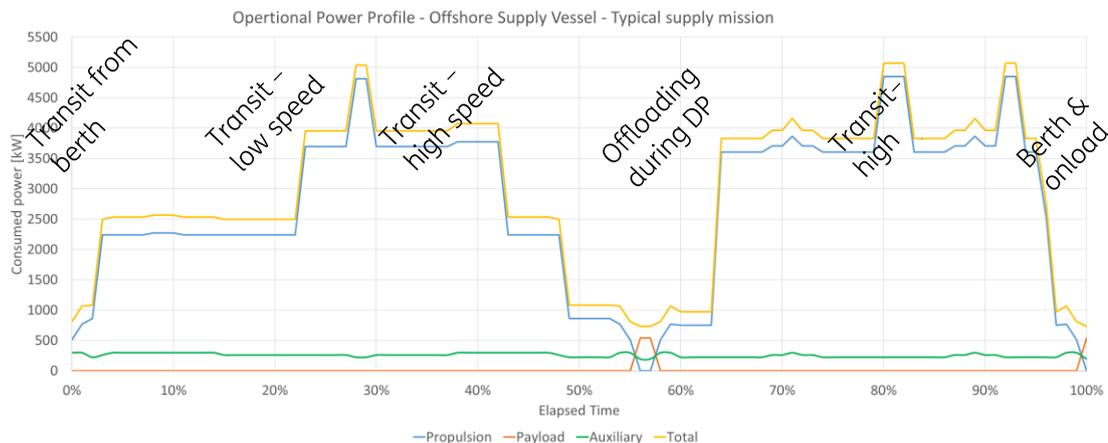


Figure 4-9: Generic operational power profile from a typical offshore supply voyage of an offshore supply vessel.

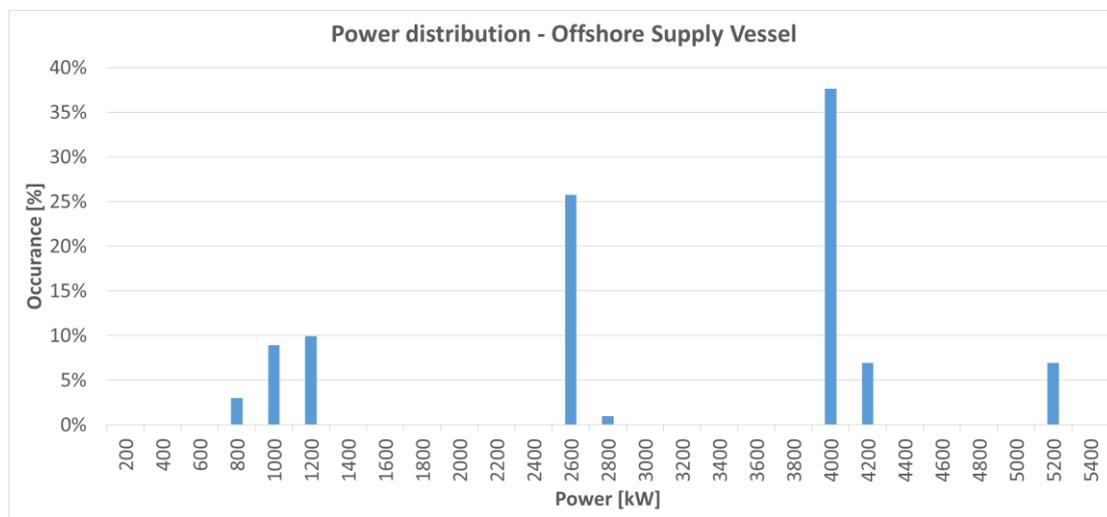


Figure 4-10: Power distribution of a typical offshore supply voyage of the Offshore Supply Vessel

The Power and Propulsion particulars of the Offshore Supply Vessel are shown in Table 4-3.

Table 4-3: Vessel PPE Particulars and Mission Type of the Offshore Supply Vessel

Reference vessel	Displacement - Fully Loaded [metric tons]	Max Speed - Fully Loaded [Kts]	Autonomous Range [NautMiles]	Installed power prime movers [kW]	Power and Propulsion Architecture
Offshore Supply Vessel	5800	14.5	1272	6000	ICE-Mechanical

Reference vessel	Mission Type	Consumed Energy [MWh]
Offshore Supply Vessel	I - Typical Offshore Supply Voyage	361

4.4.2 Architectures

For the Offshore Supply vessel, two different architectures are made: ICE-mechanical and ICE-electrical, shown in Figure 4-11. A hybrid architecture was not designed as the market survey in section 3.1.2 shows electrification is already applicable to the offshore supply vessel, but nearly all are ICE-mechanical architecture. It was considered to be common applicable for this ship type.

There is an explanation for this observation. As the hybrid architecture requires a complex and large system close to the long direct driven shaft lines and there is hardly any low speed operation to benefit from ICE-electric mode. While ICE-electric architecture can benefit from improved weight and load distribution by gensets and apply azimuthing thrusters that have small footprints and improved manoeuvrability especially in DP, this architecture clearly fits better for electrification compared to hybrid propulsion.

The ICE-mechanical features two large main diesel engines (2x 3000 bkW) and three equal-sized generator sets (3x400bkW). The propulsion is via a Controllable Pitch Propeller (CPP) in a duct on a fixed shaft line to have proper DP performance. The generator sets are sized to apply the load during off-loading of the cargo with DP (electric power to bow thrusters).

The ICE-electrical architecture features four medium sized generator sets (4x 1400kWe) for combined propulsion and payload power and one smaller generator set (1x 800kWe) used during the lower loads without propulsion. The propulsion is changed to an azimuthing thruster with Fixed Pitch Propeller (FPP) in a nozzle, that benefits manoeuvrability for the DP performance.

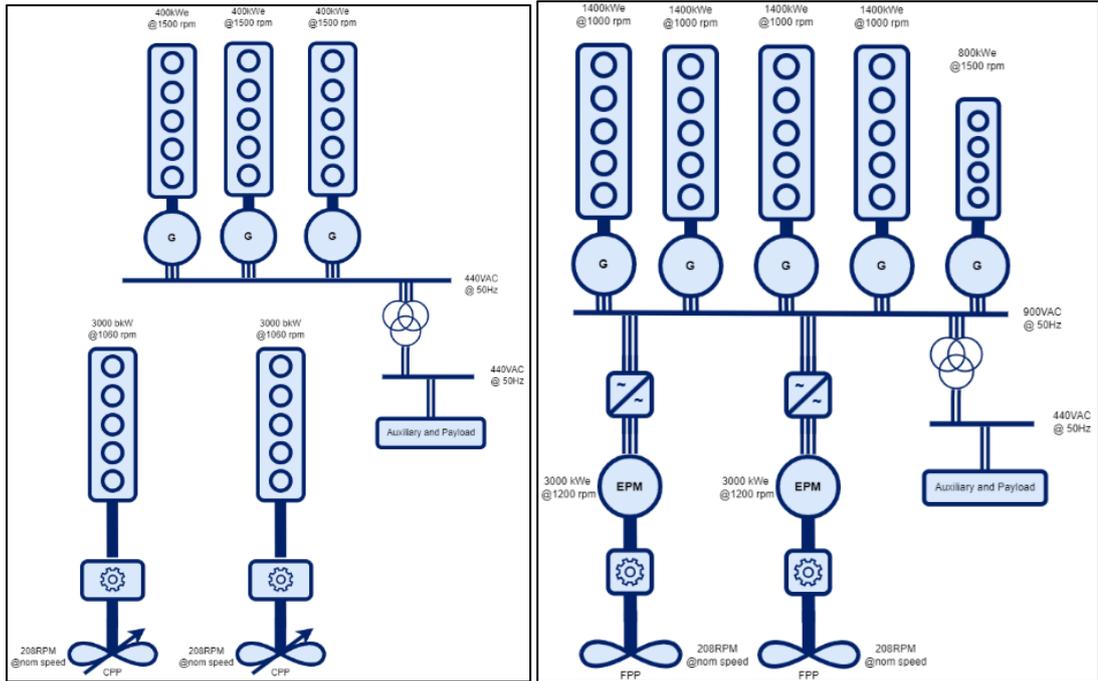


Figure 4-11: Overview of the Offshore Supply Vessel architectures, ICE-mechanical (left) and ICE-electrical (right).

4.4.3 Feasibility from fuel efficiency perspective

The performance of the 2 architectures of the Offshore Supply vessel are in estimated over the operational profile from Task 2. The results of this quasi static analysis are presented in Figure 4-12.

Since the ICE-electrical architecture can make use of a different propulsion type, this reduces the required power significant as can be seen in Figure 4-12B.

The ICE-electric configuration shows a stable operational efficiency, as the load can be matched against the number of running gensets. Only at the highest loads, the ICE mechanical solution scores better, but the vessel is only expected to use this power seldomly.

Overall, the ICE-electrical architecture has the lowest fuel consumption. This is seen in Figure 4-12D. This is partly due to the improved efficiency in the operations, especially in the zero to low speed region, but it is mostly due to the difference in requested power (Figure 4-12B). This is lower for the ICE-electrical architecture as it features an FPP. The total reduction in fuel consumption is 7% compared to ICE-mechanic. This confirms the viability of this architecture option to the vessel archetype as found in the market survey in section 3.1.2.

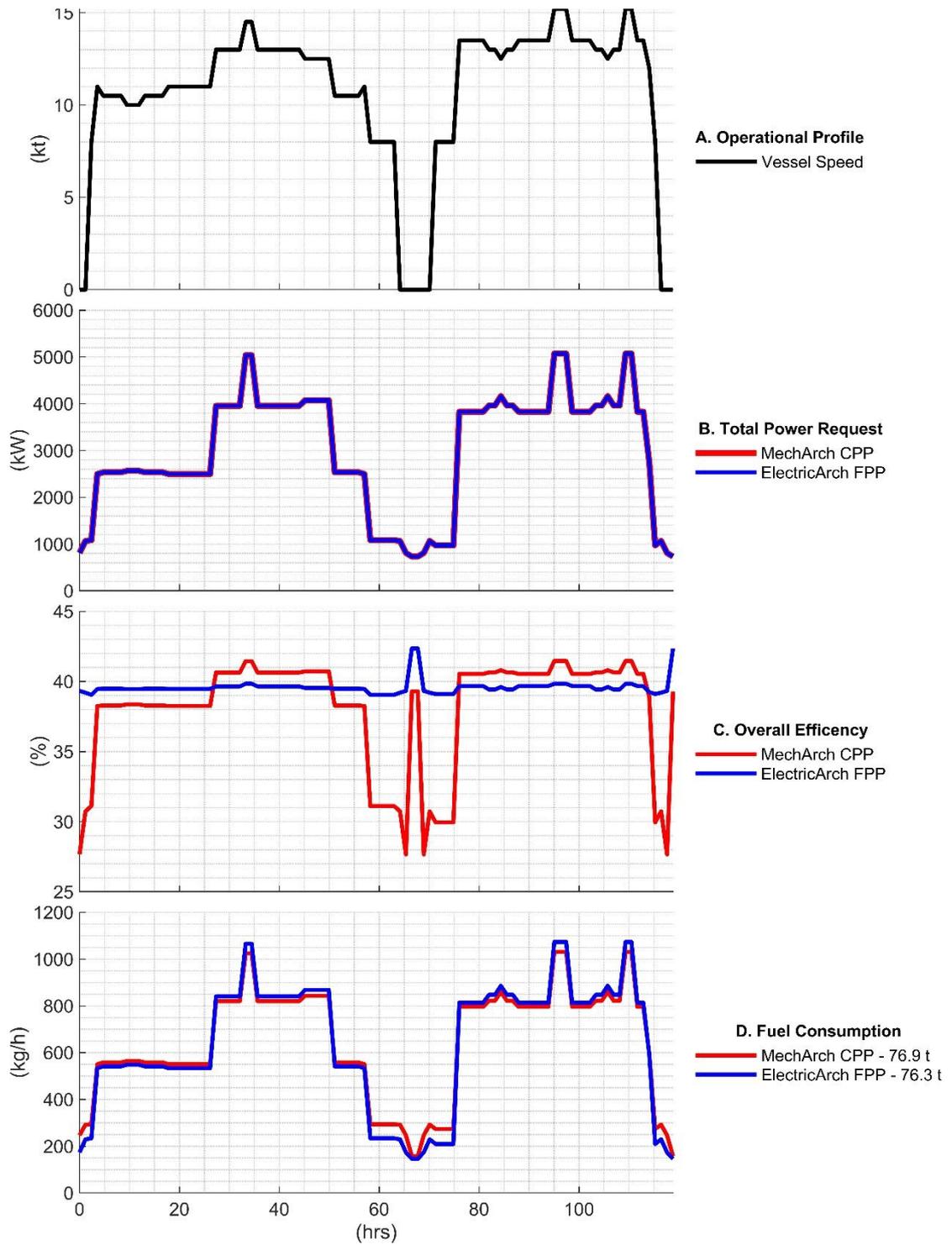


Figure 4-12: Input and output of the quasi static calculations for the Offshore Supply Vessel. Red – ICE -Mechanical, Blue – ICE-Electric. From top to bottom: (A) input speed profile as obtained from the operational analysis (B) Total summed power of propulsion, auxiliary and payload power (C) total system efficiency from fuel rate input to total power request (D) total fuel consumption rate, total over profile is provided in the legend.

4.4.4 Discussion

Electrification seems suitable for the Offshore supply vessel. This is not directly because of its operational profile, but rather due to its operational requirements (like DP and forward position of machinery space). However, some improvements in fuel reduction have been found. The more diverse the operational profile or DP conditions are, the more benefit can be expected from the electrification.

The offshore supply vessel further benefits from electric propulsion from a lay-out perspective: typically these vessels have their superstructure and accommodation located far forward, leaving the remainder of the vessel free for payload. This typically results in a very long shaft line as the machinery space is located further forward (where there is space for integrating exhausts stacks). By going to a ICE-electrical configuration this can be uncoupled and the integration of the shaft line is no longer an issue as the electric motors can be situated aft.

Offshore supply vessels may also have dynamic positioning (DP) requirements, for which a ICE-electrical architecture is also an advantage by means of redundant capacity. In this case a battery system further improve to avoid having generator sets running in idle / low load as spinning reserve, load levelling and ramp assist during heavy DP conditions. For the same reasons, DC grids and variable speed generator sets can be of interest. This would also further improve the efficiency of the electric distribution.

4.5 Crew Tender Catamaran

4.5.1 Operational analysis

The typical mission of the crew tender catamaran is to bring personnel to several offshore locations, stay in the area to pick up people and sail back to shore. The difference in loading condition is nihil, since the main payload are people who will be transferred to off-shore locations as well as brought back to shore.

Propulsion power

The fast catamaran type vessel is known to have a semi-displacement semi-lift characteristic and hence a more complex vessel speed – propulsion power relation. An analysis is made of several model tested catamarans from the MARIN test database and made non-dimensional. The result is used to estimate the power requirement for the reference vessel and match it with max vessel speed and installed propulsion power. However, the vessel type is sensitive for displacement variations, no separate propulsion power estimation are made different loading conditions, as they are assumed in the same order of magnitude and accuracy of the predictions. While transferring people from and to the offshore work locations, 10% of propulsion power is assumed to be applied to keep the vessel pushed against the boarding location.

Payload and auxiliary power

The sum of payload and auxiliary power for this vessel is assumed to vary between 60 and 100kW.

Mission profile

The typical mission consists of some long high speed transfers to and from the operational area, shorter transports to different drop-off point, manoeuvring and berthing around the drop-off points (propulsion used to push against the disembarkment location) and some low speed transfer in the area for crew pick-up.

The Operational Power Profile of a typical offshore crew transfer voyage of the Crew Transfer Catamaran is shown in Figure 4-14 and the accompanying total power distribution is given Figure 4-14.

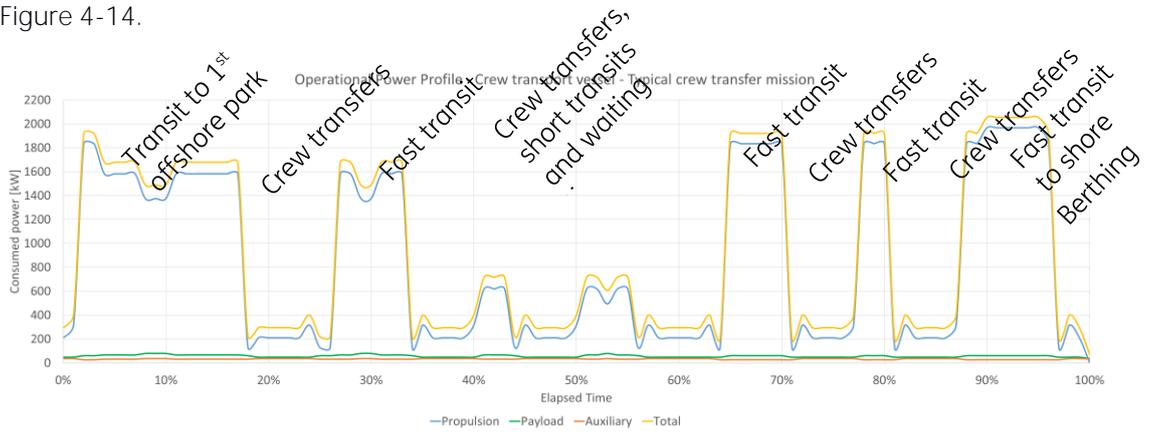


Figure 4-13: Generic operational power profile for a typical crew transfer mission.

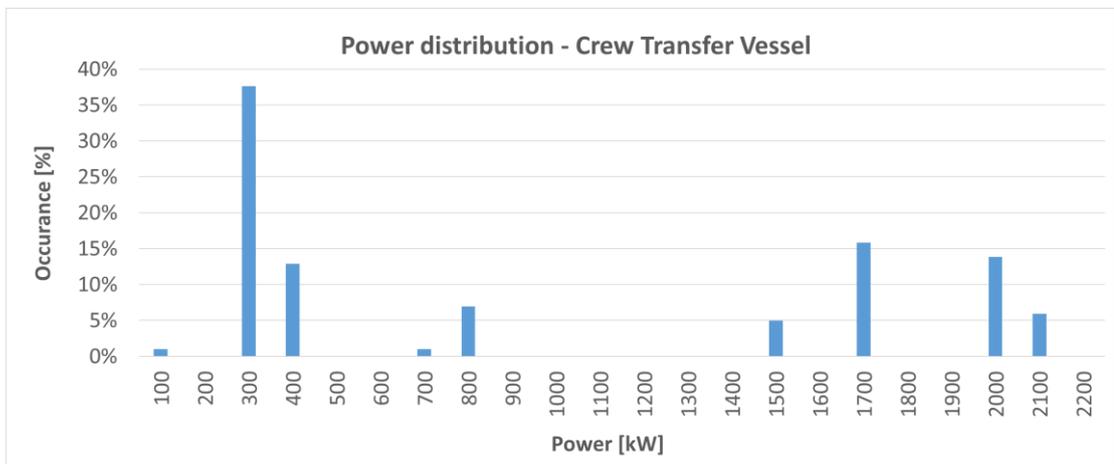


Figure 4-14: Power distribution of a typical crew transfer voyage of a Crew Transfer Catamaran

The Power and Propulsion particulars of the Crew Transfer Catamaran are shown in Table 4-4.

Table 4-4: Vessel PPE Particulars and Mission Type of the Crew Transfer Catamaran.

Use case ID	Reference vessel	Displacement - Fully Loaded [metric tons]	Max Speed - Fully Loaded [Kts]	Autonomous Range [NautMiles]	Installed power prime movers [kW]	Power and Propulsion Architecture
OTV.GDNL.4	Crew Tender Catamaran	90	23.5	770	2400	ICE-Mechanical
Use case ID	Reference vessel	Mission Type				Consumed Energy [MWh]
OTV.GDNL.4	Crew Tender Catamaran	I - Typical Offshore Crew Transfer Voyage				76

4.5.2 Architectures

The different architectures, ICE-mechanical, ICE-hybrid and ICE-electrical that were analysed are shown in Figure 4-15. All architectures have the same propulsion type, a fixed shaftline with gearbox and an open Fixed Pitch Propeller. The ICE-mechanical features two high speed main engines (2x 1100 bkW) and two small auxiliary engines (2x 80kWe). The engines are designed for max speed of the fast vessel.

The ICE-hybrid architecture features two slightly smaller main diesel engines (2x 950bkW) and bigger generator sets (2x 220kWe). The ESM (2x 200bkW) can operate as a power take-off/take-in (PTO/PTI) and is placed on the gearbox to allow the main engine to supply the auxiliary grid and vice versa. The ESM is relatively small, since there is limited space available and the vessel performance is sensitive for total weight and weight distribution. The ESM is sized to supply the main electric loads during normal operating conditions. It can furthermore be used in the idling situations, like (un)loading and waiting times. For top speeds, it can boost the main diesel engine, while it might also assist in accelerations and dynamic loading.

The ICE-Electric architecture makes use of 4 smaller generator sets (4x 600 kWe). This is such that they (might) be equally accommodated in the demi-hulls of the Crew tender catamaran.

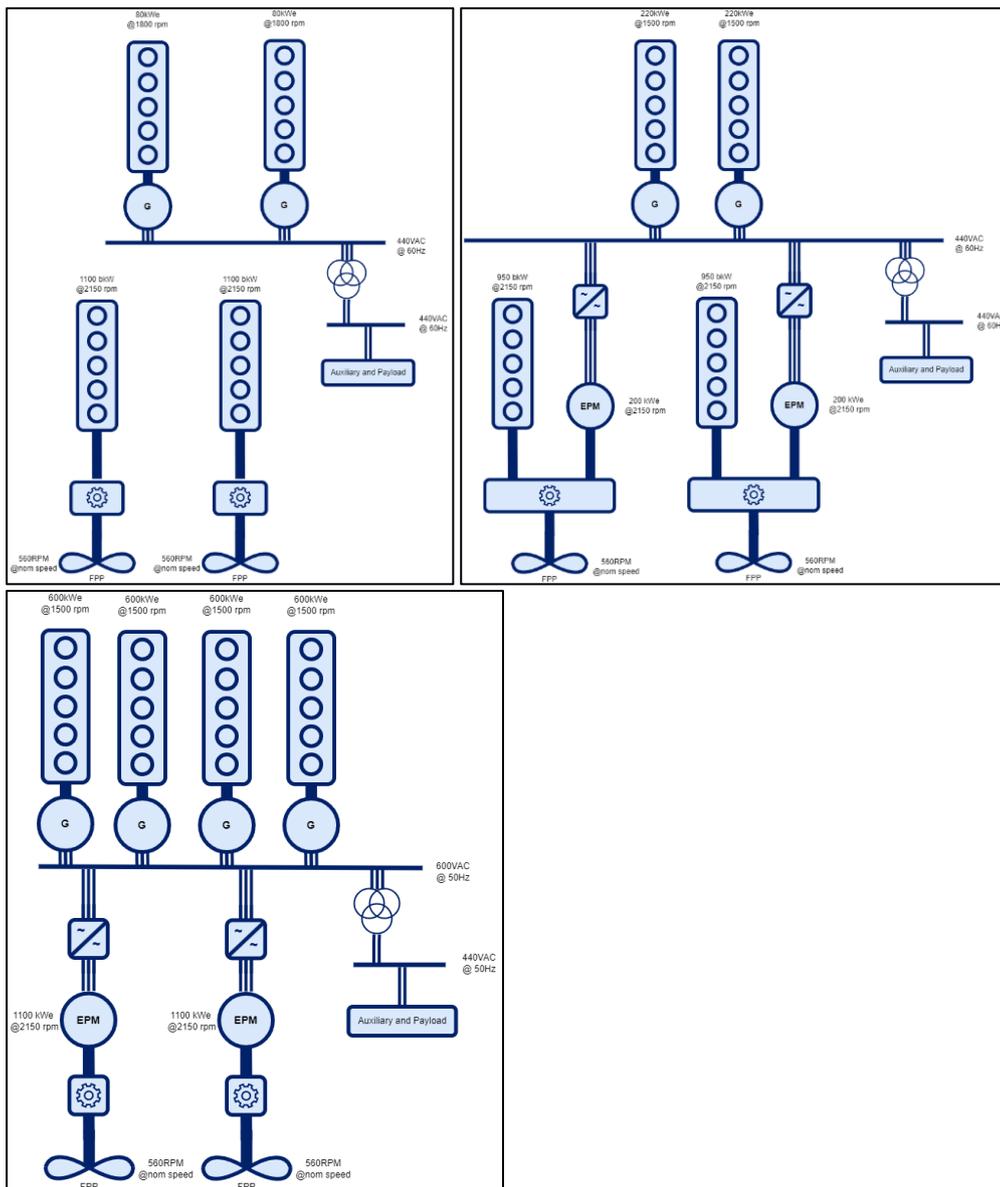


Figure 4-15: Overview of the Crew Tender Catamaran architectures: ICE-mechanical (to-left), ICE-hybrid (top-right) and ICE-electrical (bottom).

4.5.3 Feasibility from fuel efficiency perspective

The 3 architectures of the Crew tender vessel are compared for efficiency and total fuel consumption over the defined operational profile. The result of this quasi static analysis is given in Figure 4-16..

As all architectures make use of the same propulsion (FPF), no effect of weight (distribution) is taken into account and auxiliary and payload power were kept constant, no differences are obtained on the required power, as depicted in Figure 4-16B.

Differences are only obtained by the differences in partial loading and system efficiency in this quasi-static analysis. This is given in Figure 4-16C. It can be clearly seen that the ICE-Electric architecture shows a more stable efficiency. Especially during part load.

The hybrid configuration cannot benefit as much in low-load, as the propulsion load is still too high during crew transfers. It is also unlikely to stop the main diesel engine in such an event for the hybrid configuration.

All architectures have a similar fuel consumption as seen in Figure 4-16D. Overall, the electrical architecture has a slightly reduced fuel consumption (-1.7%), due to a higher efficiency in relatively longer part-load operations. But the absolute fuel savings are relatively small, making the benefits from electrification not substantial. The ICE-hybrid architecture actually shows a very slight increase of fuel consumption compared to ICE-mechanical propulsion. This is likely due to a combination of the selected components of the hybrid architecture, and the energy management system which was not able to load the engine optimally. It was not possible within the scope of the project to further optimise this. And as can be concluded from the previous section, volume and weight will be very challenging for the ICE-Electric propulsion.

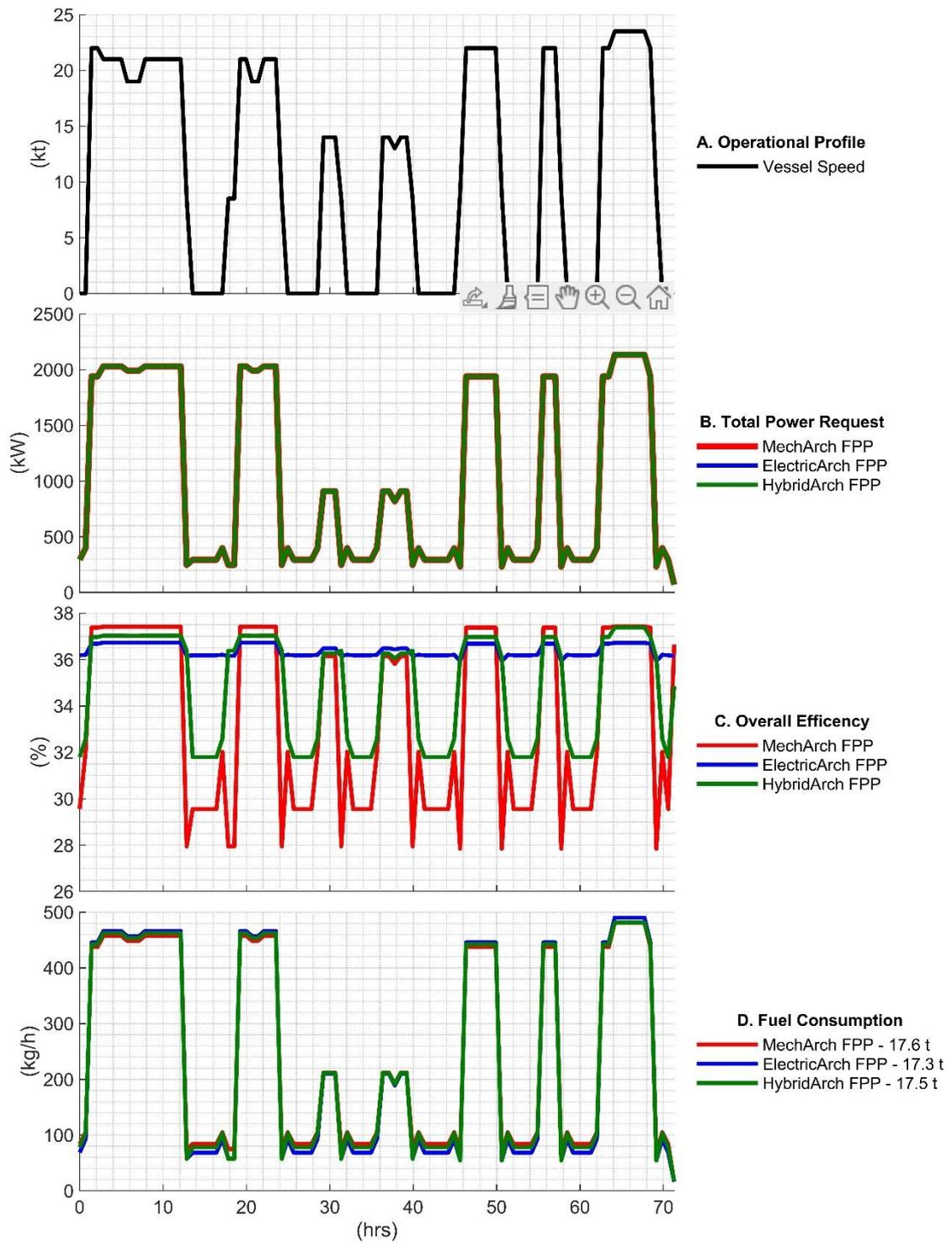


Figure 4-16: Input and output of the quasi static calculations for the Crew Tender Catamaran. Red – ICE -Mechanical, Green – Hybrid, Blue – ICE-Electric. From top to bottom: (A) input speed profile as obtained from the operational analysis (B) Total summed power of propulsion, auxiliary and payload power (C) total system efficiency from fuel rate input to total power request (D) total fuel consumption rate, total over profile is provided in the legend.

4.5.4 Discussion

A clear advantage for the Crew Tender Catamaran to go for (hybrid-)electric propulsion is that the operational profile of the ship show a wide spread. The ship spends a lot of time manoeuvring (the Berthing event takes place >20% of the total operational time, see report of Task 2). Moreover, the loads are very cyclic, meaning short times of high speed, then longer times of low speed. Electric architectures can be designed to handle these peaks better, resulting in longer lifetime of the machinery. There are only few non-propulsion consumers so from the point of combining loads there is less reason to go electric. If for a larger vessel a motion compensated gangway or other off- and onloading equipment would be installed, this would further promote the electrification of this vessel type.

On the contrary, the small high speed craft is very limited to weight and volume. Hence, all considerations must be checked against that. The vessel in the use case might be too small for electrification, but larger platforms that might have a lower top speed may classify easier, as deck-space can create the required volume and weight changes are relatively smaller for larger displacement vessel displacements.

An additional battery system (not in scope) is often considered for this vessel type to provide the low power needed to keep the vessel in position, for example to push against the monopile of the wind turbine.

4.6 Trailing Suction Hopper Dredger

The trailing suction hopper dredger is a specific type of the ship archetype of dredgers. These vessels are characterized with a large payload power like dredge pumps while still have own means of transportation and hence significant propulsion power.

Many powering concepts are available in the market. The fleet consist of small series and one-offs with specific capabilities for environments, cargoes and types of operation. The chosen reference ship is relative large but not the largest vessel of the fleet.

4.6.1 Operational analysis

The typical mission of the TSHD is to transit with empty hopper (hold) to the dredging areas, perform the dredging operation by its onboard pumps while controlling the vessel track with Dynamic Positioning (DP), sail full loaded to the off load location where the hopper is emptied via either:

- Mixed with water via a discharge pipe with the onboard pump with active propulsion
- Discharged with the onboard pump while moored
- Dumping the cargo by opening the hopper bottom doors.

The main diesel engines can provide both propulsion power (mechanical) as well as the payload power (electric via PTO or mechanically clutched) which consist of the onboard dredge and discharge pumps.

Propulsion power

The cargo capacity of the Trailing Suction Hopper Dredger is substantial (DWT = 22000 [MT] versus Δ Loaded = 30146 [MT]). Therefore two speed – power relations are used to obtain the propulsion power, one for fully loaded and one for Unloaded/Ballasted condition. Corrections for seaway are made based on fixed correction factors.

To predict the propulsion power over speed, the effects of changing the architecture were taken into account for the TSHD use case. This is because the propulsion type has changed from fixed shaft lines with CPP at fixed shaft speed to azimuthing thrusters with FPP at variable shaft speed (see further explanation in the next section 4.6.2) . This has a significant effect which cannot be simplified by assuming the same propulsion power. In this section, the estimated propulsion power of the reference vessel is provided.

For the ICE-mechanical reference case the speed-power relation was based on model tests of comparable ship type and size. For the electric case, the resistance prediction is kept the same, but the propulsion characteristics have been changed based on experience from comparable drive systems and calculations from known model propeller series. The result can be observed in the total power request as used in section 4.6.3.

Payload and auxiliary power

The payload systems on board of the TSHD are significant. The power is supplied by the main propulsion engines via a power take off and electrically distributed to several very large pumps and bow thruster units. During the dredging a significant amount of power is estimated to go to the dredge pumps and bow thrusters (50-60% of the installed power on average, up to 8000kW). During offloading with the onboard pressure pump it is estimated even up to 80-85% of the installed power, that is up to 10,800 kW. The auxiliary power of the vessel consists of the nautical and hospitality services, as well as ship systems like the ballast system and bilge systems. The total auxiliary power is assumed to vary between 900 and 1425 kW.

Mission profile

The estimated mission profile consist of 12 dredge jobs and 5 transits. A relocation transit is approx. 100-150nm. A dredge or discharge takes approx. 5 hours and distance between dredge and offloading is approx. 20-40nm. The final relocation is about 300nm back to the home port of the ship. An intermediate replenishment at a visiting harbour is taken into account. The total time of the mission contains 14 days of autonomy, i.e. without diesel bunkering.

It must be noted that the vessel will perform dredging operations many times repeatedly in one working location and some relocations to different projects over the year. This profile includes some relocations to represents also some of this yearly profile statistics.

The created operational power profile is given in Figure 4-17. In this figure a stacked plot is given of the Auxiliary, Payload and propulsion power to ease the readability. The sum of the three is the total power. It can clearly be seen that payload and propulsion are in the same order of magnitude and alternate in the sequence. Relocations are identified by longer propulsion usage.

Transit from port 4 dredge and unload jobs Relocation 2 dredge and unload jobs Relocation & Replenishment 4 dredge and unload jobs Relocation 2 dredge and unload jobs Transit to port

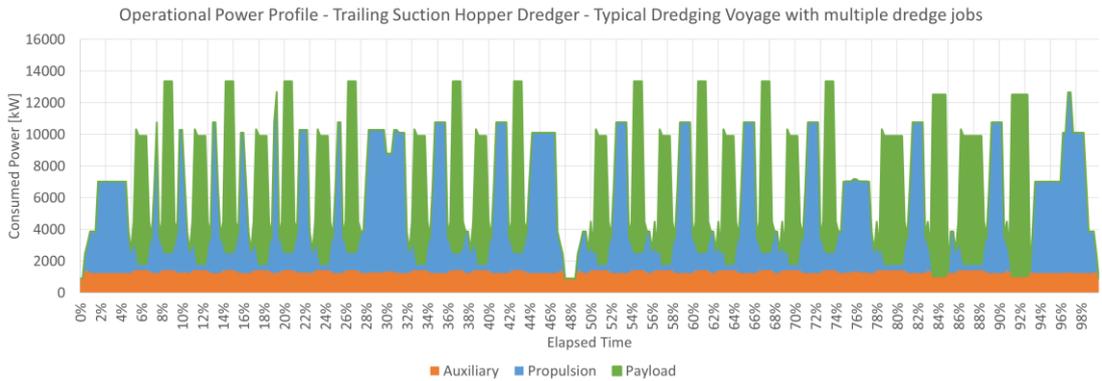


Figure 4-17: Typical operational power profile of a trailing suction hopper dredger over several dredge jobs and relocation, without intermediate bunkering.

The Event and Power Distribution Graphs of a typical dredging voyage (Mission Type I) as used for the feasibility evaluation of the Trailing Suction Hopper Dredger are shown in Figure 4-18.

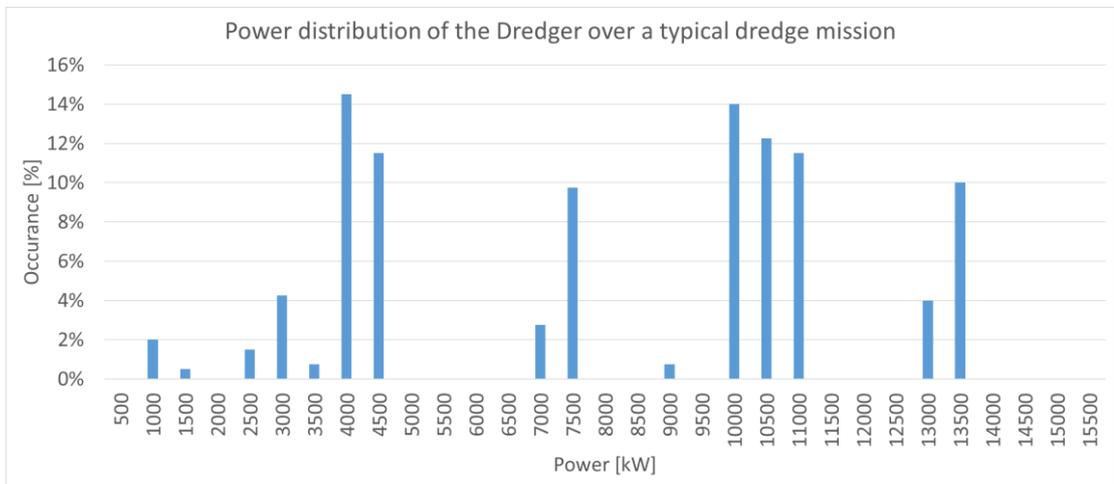


Figure 4-18: Power distribution of a typical dredging voyage of a Trailing Suction Hopper Dredger

The Power and Propulsion particulars of the Trailing Suction Hopper Dredger are shown in Table 4-5.

Table 4-5: Vessel PPE Particulars and Mission Type of the Trailing Suction Hopper Dredger

Reference vessel	Displacement - Fully Loaded [metric tons]	Max Speed - Fully Loaded [Kts]	Autonomous Range [NautMiles]	Installed power prime movers [kW]	Power and Propulsion Architecture
Trailing Suction Hopper Dredger	30,146	15.4	2,419	13,870	ICE-Mechanical - PTO

Reference vessel	Mission Type	Consumed Energy [MWh]
Trailing Suction Hopper Dredger	Typical dredging voyage	2,784

4.6.2 Architectures

The architectures created for the Dredge vessel use case are ICE-mechanical and ICE-electrical and are shown in Figure 4-19. A hybrid architecture was not in the scope for this use case. As seen in the operational analysis, the payload system of this vessel consists of many heavy consumers (pumps, thrusters) that are used during the vessel operations. These are fed from the electric system. Which components are used and to what load depend on the type of task.

The ICE-mechanical features two large main engines (2x 6000bkW) with a Propulsion Shaft Generator with a significant power take-off (2x 4000kWe), and one medium sized generator set (1x 1870 kWe). The vessel is propelled by 2 fixed shaft line propellers with a Controllable Pitch Propeller (CPP) in a nozzle. For the free sailing conditions, the vessel is expected to operate with the propellers at design pitch while varying the rotational speed and using the genset to provide power to the electric grid. While operating the vessel with one of the high load electric drives, the PSG will provide the electric power to the grid and the propulsion engines switch to fixed speed operation. The propulsion thrust is managed by varying the pitch of the CPP. The PSG cannot be operated at variable speed and cannot provide power to the propulsion shaft.

The ICE-electrical architecture features five medium sized generator sets (5x 2823kWe) to supply a comparable total power as is available in the ICE-mechanical architecture. The generator sets are connected to a DC-bus, such that the power conversions can have higher efficiency and the generator sets can be on variable speed to improve fuel efficiency. The propulsion is performed with Electric Shaft Machines of the same power as the ICE-Electric case (2x 6000bkW), connected to a gearbox, to reduce the size and weight of the electric motor. The nominal power of the ESM could be reduced as the vessel is not using this power for full speed sailing according to operational profile. It is kept to make the comparison one on one. For the ICE-mechanical option, the main engine power was only fully used it in combined propulsion + PTO mode during dredging.

Since the vessel is operated in DP and dynamic tracking, and making use of the flexibility of the electric drive system on the general arrangement, an azimuthing propeller is chosen with a fixed pitch propeller.

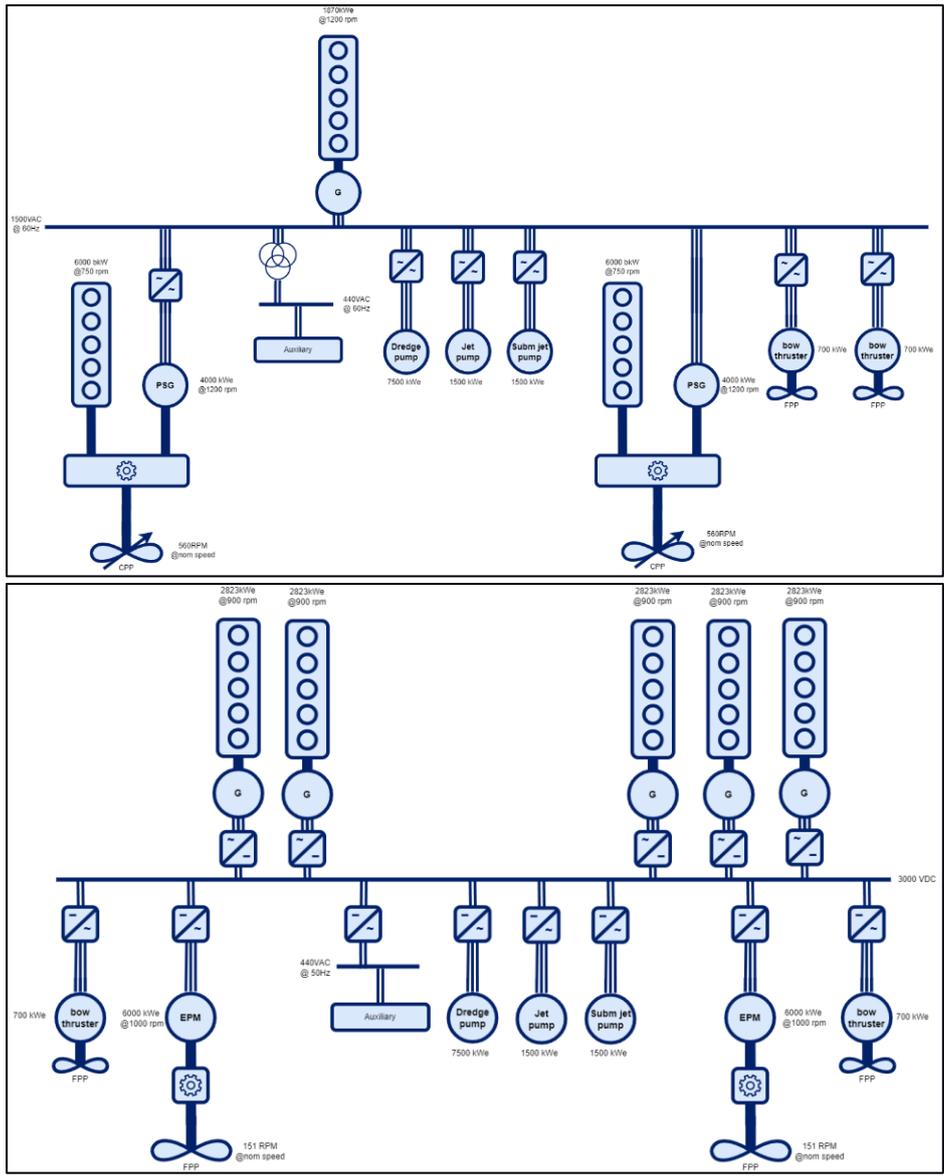


Figure 4-19: Overview of the Dredger Vessel architectures, on top: ICE-mechanical, bottom: ICE-electrical.

4.6.3 Feasibility from fuel efficiency perspective

The two architectures of the Dredging vessel of section 4.6.2 have been compared for efficiency and fuel consumption over the operational profile from 4.6.1. The results of this quasi static analysis are shown in Figure 4-20..

During dredging operations (low vessel speed, high thrust), the propulsion power demands for the ICE-mechanical propulsion with CPP at fixed speed are much higher than requested from the fixed pitch propeller connected to the variable speed electric propulsion. This can be seen in Figure 4-20B.

The ICE-mechanical architecture shows higher efficiency at transit speeds, and significantly dropping efficiency at low speeds. Increasing the load at low vessel speeds by usage of the PTO increases the efficiency again. The ICE-electrical architecture has a constant efficiency, as it matches the power demand with the running number of generators. Spinning reserve for DP operations is neglected in this case, which would worsen the results.

Overall, the results show that the Dredger vessel can obtain significant fuel savings from electrification. Figure 4-20D shows that the ICE-electrical architecture has fuel savings of 9% compared to ICE-mechanical architecture.

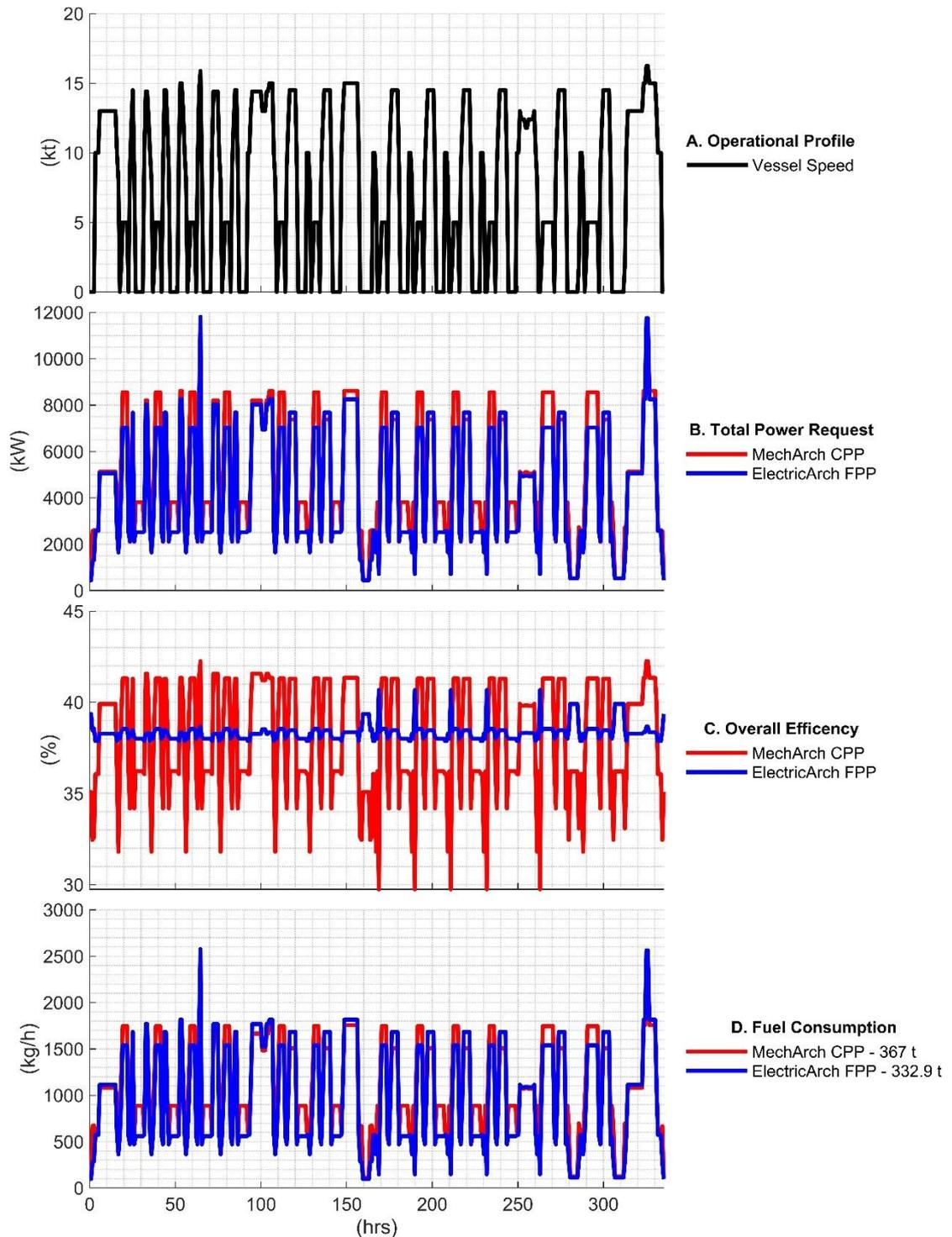


Figure 4-20: Input and output of the quasi static calculations for the Dredger Vessel. Red – ICE-Mechanical, Blue – ICE-Electric. From top to bottom: (A) input speed profile as obtained from the operational analysis (B) Total summed power of propulsion, auxiliary and payload power (C) total system efficiency from fuel rate input to total power request (D) total fuel consumption rate, total over profile is provided in the legend.

4.6.4 Discussion

Electrification is typically feasible for this vessel type as the payload loads as high or higher than the propulsion load. A large spread in the load distribution and varying cycles further benefit from electrification options. Variations Maximum propulsion and payload power are also often not required at the same time, reducing the total installed power. It can be seen that the azimuthing FPP solution seems to significantly increase the benefit of the electric drive system.

Battery systems can be considered for ICE-electrical architecture as peak-shaving could reduce the load variation on the generator sets and to act as spinning reserve. Due to the large powers involved, these battery systems may also be quite large. The vessel is typically weight constraint for the payload, i.e. the operational benefit of installing batteries should be checked against reduction in fuel cost but also to the lower payload.

4.7 Mega Motor Yacht

The Mega Motor Yacht is a typical case where the arguments of electrification are more based on comfort. These vessels are identified with a significant hotel service power, having long periods of harbour / idling time. Top speed of the vessel is an important characteristic and propulsion power is sized for, but seldomly used. Transits consist mainly on economical voyages at lower speeds, from which the operational costs may reduce by reduction of fuel costs. Various applications of hybrid and electric systems exists in the market. Hence, the focus for the feasibility study is to calculate possible benefits on the fuel consumption rather than the naval architectural feasibility.

4.7.1 Operational analysis

The typical mission used for the mega motor yacht is an exploration mission, that consist of harbour stays (crew only), transfers to travel to destination on economical speed, short transfers between several exploration locations (with guests) and stationary use of the vessel (with guests). High speed sailing only is expected very limited.

Propulsion power

The cargo capacity of the Mega Motor Yacht is limited (DWT = 460 [MT] versus a total displacement of the vessel of 4600 [MT]) and is exclusively used for people transfer and some tenders or other explorative gear. No significant changes in the vessel draught are expected. Therefore one vessel speed – propulsion power relation was used for the study. This Speed - Power curve is calculated based on statistical data from MARIN's model test database and matched with the installed propulsion power and expected top speed of the reference vessel.

For (un)berthing, manoeuvring and station keeping 5-10% propulsion power is assumed on average.

Payload and auxiliary power

The payload power of the Mega motor yacht are actually anything related to the hotel services of the guests, like hospitality services of the guests quarters and including the swimming pool, cinema or other pleasure services. The total payload power is assumed to vary between 240 and 400kW.

The auxiliary power of the yacht are the nautical services, navigation systems, crew hospitality services as well as the technical ship systems like bilge systems, cooling systems and ballast water systems. They are assumed between the range of 90-135kW.

Mission profile

The operational power profile and power distribution graphs of a typical exploration voyage of the Mega Motor Yacht are shown in Figure 4-21 and Figure 4-22.

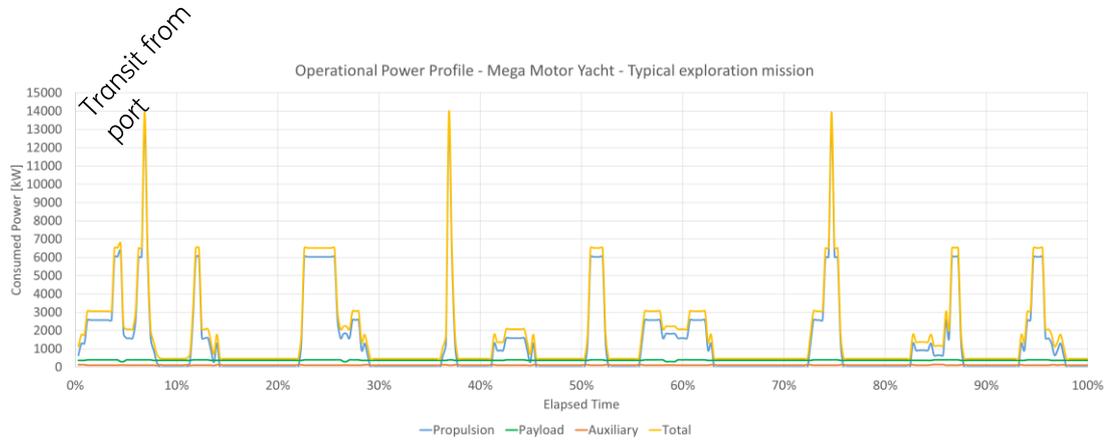


Figure 4-21: Operational power profile of a typical exploration voyage of a Mega Motor Yacht.

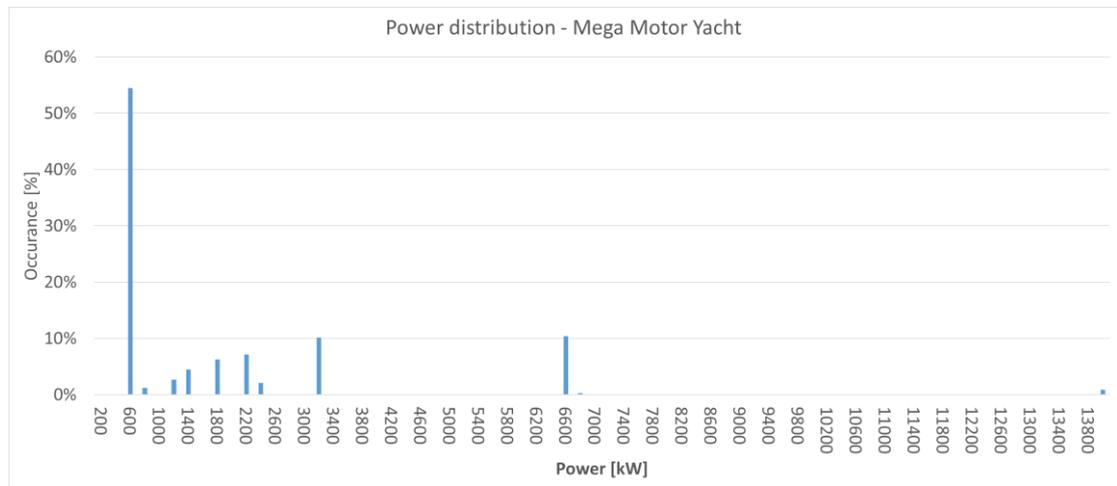


Figure 4-22: Distribution of Power Groups Mega Motor Yacht – Mission Type I - Typical Exploration Voyage.

The Power and Propulsion particulars of the Mega Motor Yacht are shown in Table 4-6.

Table 4-6: Vessel PPE Particulars and Mission Type of the Mega Motor Yacht.

Reference vessel	Displacement - Fully Loaded [metric tons]	Max Speed - Fully Loaded [Kts]	Autonomous Range [NautMiles]	Installed power prime movers [kW]	Power and Propulsion Architecture
Mega Motor Yacht	4,600	22	1,781	13,000	ICE-Mechanical
Reference vessel	Mission Type			Consumed Energy [MWh]	
Mega Motor Yacht	Typical exploration voyage			602	

4.7.2 Architectures

The three different architectures, ICE-mechanical, ICE-hybrid and ICE-electrical that were analysed are shown in Figure 4-23. The propulsion is in all architectures via a reduction gearbox, all the electric machines as the main engines are high speed. All propel the vessel with a fixed shaft line FPP.

The ICE-mechanical architecture features two large main engines (2x 7500kW) and three medium sized auxiliary engines (3x 900kWe). The ICE-hybrid architecture features three equal generator sets (3x 900kWe) and two slightly smaller main engines (2x 6500kW). An ESM is installed at each propulsion shaft that act as a power take-off/take-in (PTO/PTI). It is placed on the gearbox to allow the main engine to supply power to the auxiliary grid and vice versa. For max vessel speed, the additional propulsion power is supplied by the ESM. In this way, the total installed power is less than from the reference case, but the installed power is spread better over the users in varying tasks.

During economical sailing the ESM can also supply the electric grid with sufficient power to avoid the usage of the gensets. During low speed operations the vessel can sail fully ICE-electric, improving the comfort on board and avoiding the use of the main propulsion engines at very low load and unfavourable fuel efficiency.

The ICE-electrical architecture consists of two smaller generator sets (2x 800kWe) and three large generator sets (3x 4600kWe). The smaller sets are sized to perform the zero speed operations (hotel load / payload power) while the bigger gensets are used in case of propulsion load is added.

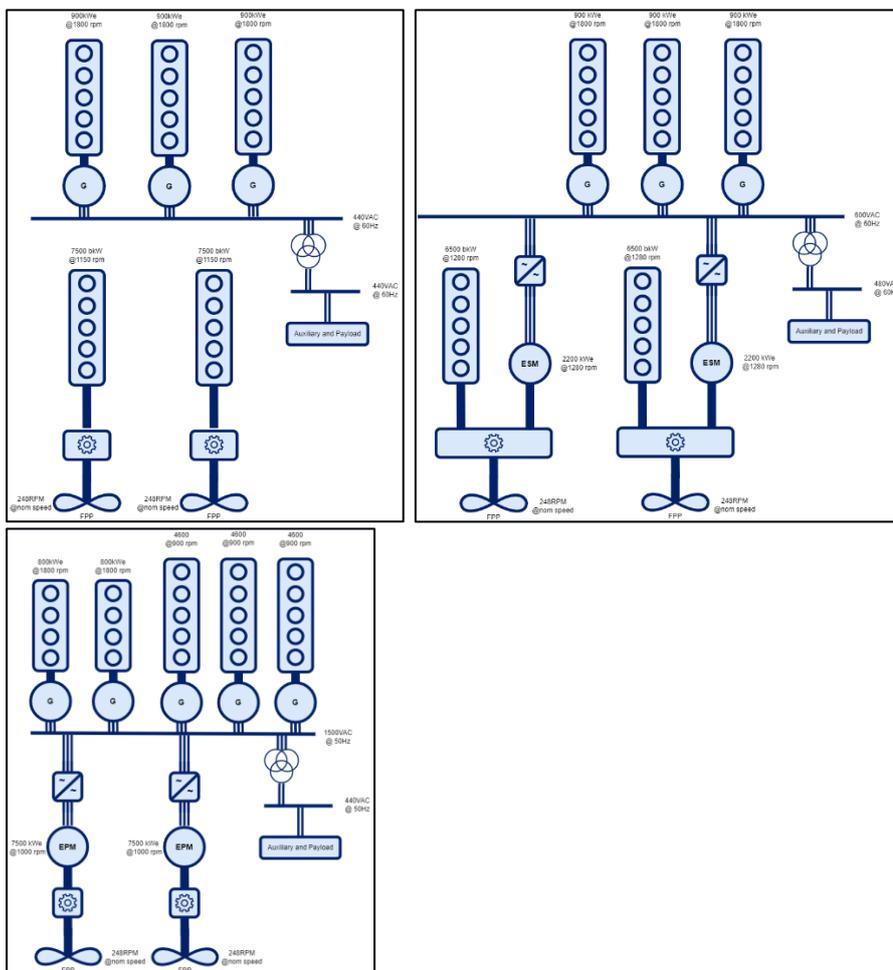


Figure 4-23: Overview of the Mega Motor Yacht architectures: ICE-mechanical (top-left), ICE-hybrid (top-right) and ICE-electrical (bottom).

4.7.3 Feasibility from fuel efficiency perspective

The architectures of the Mega Motor Yacht from section 4.7.2 have been analysed over the operational profile as defined in section 4.7.3. The results of this quasi static analysis are shown in Figure 4-24.

Since the propeller type has not been changed and the payload and auxiliary power are assumed to be the same for all 3 cases, the load profiles are exactly the same for the three architectures, as can be seen in Figure 4-24B.

The efficiency of the hybrid and electric system benefit mainly during the low speed operations. Since the main diesel engines for the ICE-mechanical architecture is sized for max speed, it is largely oversized for the low speed operations where its efficiency drops hard. This can be seen in Figure 4-24C. The ICE-electrical system has relatively constant efficiency.

The total amount of energy concerned in the low load operations is marginal, hence the total fuel consumption calculated for all architectures a very similar. From the results in Figure 4-24D the ICE-electrical has a 0.8% lower fuel consumption, because it is more efficient in the often zero to low speed range that the vessel operates in. But given the uncertainty in the modelling this is not a clear fuel saving.

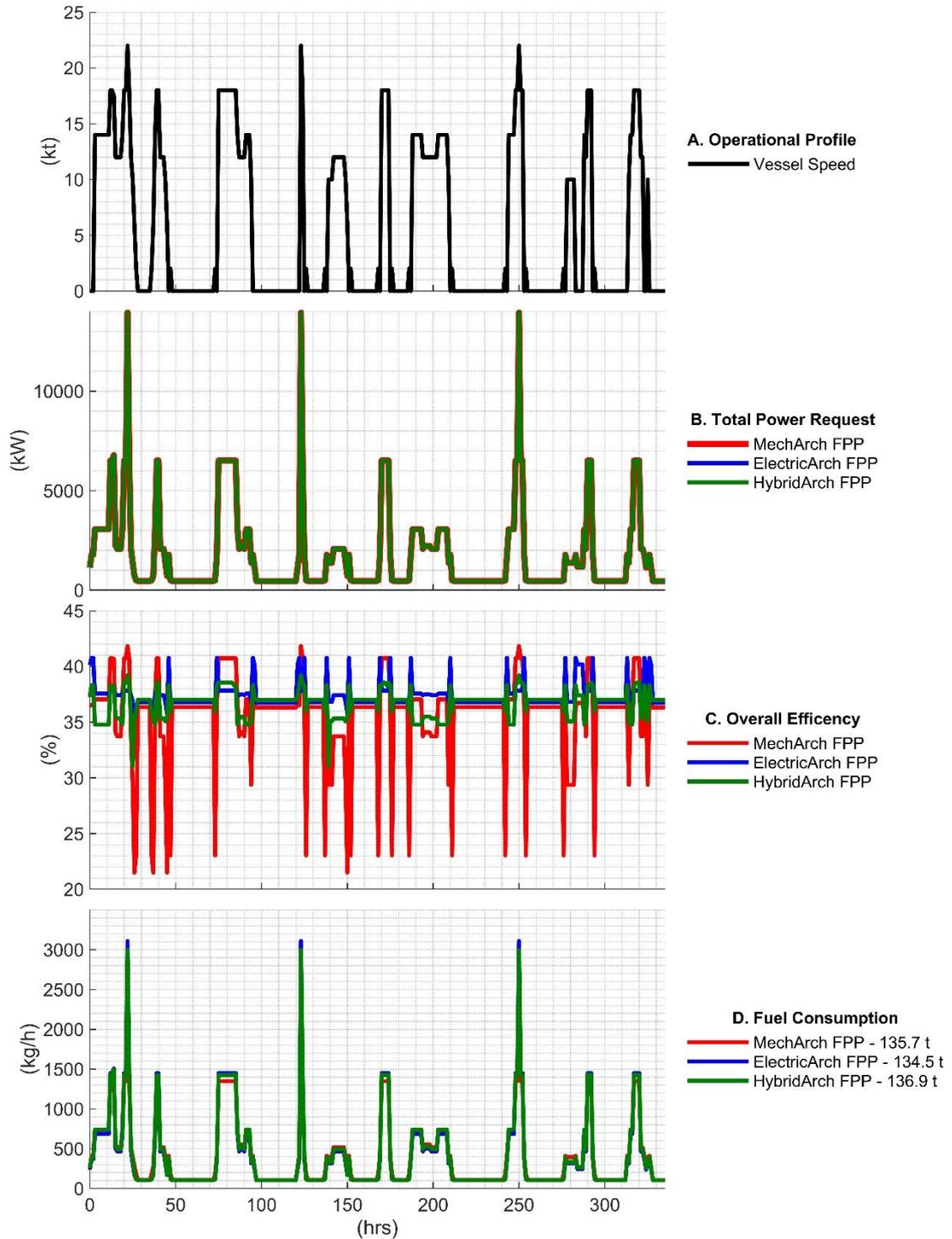


Figure 4-24: Input and output of the quasi static calculations for the Mega Motor Yacht. Red – ICE -Mechanical, Blue – ICE-Electric. From top to bottom: (A) input speed profile as obtained from the operational analysis (B) Total summed power of propulsion, auxiliary and payload power (C) total system efficiency from fuel rate input to total power request (D) total fuel consumption rate, total over profile is provided in the legend.

4.7.4 Discussion

Electrification is considered feasible for these types of vessels to have more vessel arrangement lay-out flexibility and to realise low noise and vibration levels that are often

required. PODs may be considered for large yachts like these to further reduce noise while improving manoeuvrability at low speeds. The wide operation propulsion power range also allow hybrid solutions, to further reduce the noise emissions at low vessel speeds. For the mega motor yachts, a significant base load for hotel services with high redundancy also makes a that sharing installed power in electric propulsion configurations is attractive.

Batteries may be used to offer a zero emission mode to clients when at anchor or when shore power is unavailable or to optimize loading of the generator sets.

4.8 Conclusions - Comparing the outcomes for the different ship designs

For any vessel, various advantages for electrification were identified, like reduced maintenance cost and increased flexibility. The downside is increased investment cost (CAPEX) and increased weight and volume. The latter is especially important for specific use cases (see next sub-sections). One commonly referred potential of electrification to counteract additional investment cost is to reduce fuel costs. These were calculated in this section and summarized below.

The detailed feasibility study focussed on answering the question:

For which ship types and operations is electrification advantageous?

When quantifying the fuel savings of electrification in the quasi-static approach; despite the additional power conversion losses in (hybrid) electric PPE system architectures, the total fuel consumption as seen over a whole profile of the vessel seem to be comparable or improved. For low load operations the improvements are the most significant, where the fuel consumption is already low. Non the less, significant improvements over the total profile appear for the Harbour Tugboat (5%), the Offshore Supply Vessel (7%) and the Dredger Vessel (9%). In other cases values around 0-2% are found. No fuel improvement was found for the hybrid solutions of the Crew Tender Catamaran and Mega Motor Yacht.

Given the number of assumptions in the modelling, the presented results only confirm that the Harbour Tugboat, Offshore Supply Vessel and Dredger Vessel have significant fuel savings for the given architecture and operational profiles.

In cases where CPP's are used for hybrid or mechanic architectures, a large share of the fuel savings also come from the fact that the ICE-electric can use an FPP in all cases.

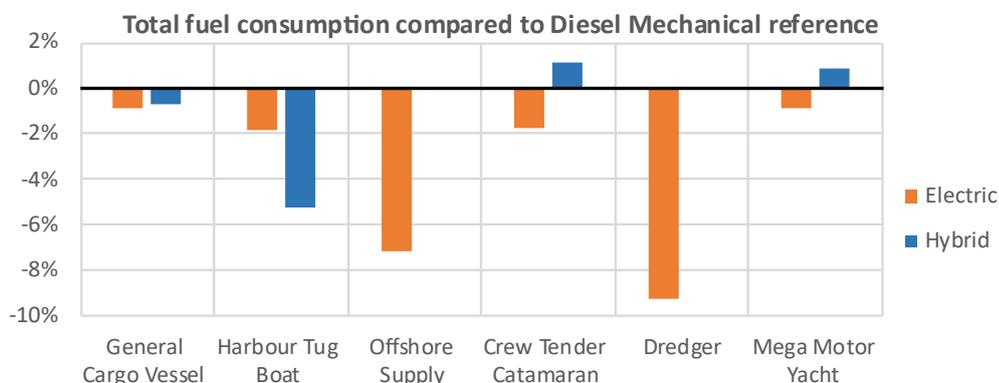


Figure 4-25: Relative comparison of quasistatic evaluation of fuel consumptions for all use cases over their respective operational profile. Note, Offshore Supply Vessel and Dredger Vessel did not have a Hybrid architecture.

The remaining use cases do not have substantial savings; this may still improve with more optimised architectures and more effective energy management. Overall, it can be concluded that very significant savings (beyond 10%) are unlikely when considering electrification for these vessels based on effective loading of components. However, the calculated fuel savings can potentially be improved by installing batteries (for some use cases), and by using a DC grid with variable speed generator sets to increase the generator efficiency.

Secondly, the following question was checked:

Can electrification of the propulsion line benefit from lower fuel consumption over a typical operational profile by load distribution compared to a ICE-mechanical solution?

Based on the system efficiency over the operational profile that was presented for each use case it can be seen that electric propulsion can indeed benefit from part load efficiency optimization compared to a ICE-machinal PPE architecture. In low load operations the benefit of ICE-electric and hybrid solutions can be significant. For high-power operations, they typically reduce in efficiency. For low load operations, the required energy and hence the fuel consumption is lower. So savings in absolute tonnes of fuel are limited. At high power the opposite counts. Therefor the spread over the load profile is the main contributing input to achieve actual fuel consumption benefits. Next to the load distribution, other benefits like the change of the propulsion layout further signify the balance for the electric propulsion.

The results presented were based on a single use case with a single operational profile for each ship archetype. The study indicates the importance of taking the complete operational profile into account in order to understand the potential of fuel savings for an electric architecture. Actual savings for a specific ship design will depend strongly on the actual operational (part)load distribution and matching architecture design. Creating a larger variation of ship use cases and a variety of operational profiles will give more understanding on the spread of the results. These statistics can confirm the potential fuel savings for the ship archetypes.

The applied method shows in order to properly estimate system efficiency, the part load efficiencies of the main components in the energy chain should be taken into account. The part load efficiencies of individual components in this study were based on theoretical models, tuned to actual realistic values at nominal power. Finding more accurate component efficiencies will significantly increase the accuracy of the numerical estimation of the fuel savings for a specific design case.

Additional benefits of the electrification, like changing the propeller type should be taken into account as they have a significant effect.

Use case specific conclusions are given in the subsections below.

4.8.1 Short Sea Transport Vessel

- From a lay-out or operations point of view there is no direct need for electrification on this vessel type. Due to the reduced electric motor size compared to the ICE, the aft ship of the vessel could be hydrodynamically optimized for a large propeller with more freedom in the gondola design.
- For the general cargo vessel, it is feasible to have hybrid or electric propulsion from a volume/weight perspective.

- The quasi-static analysis shows that all architectures have a similar fuel consumption, the dynamic calculations are inconclusive: there are benefits in specific conditions, but they are not common operational areas, thus indicating that fuel savings will not be substantial. However, only part of the sailing profile was covered. Moreover, the hybrid architecture was not analysed.

4.8.2 Harbour Tugboat

- Due to the prolonged periods of low propulsion loads, (hybrid-)electric propulsion can reduce maintenance costs of the machinery. The addition of a battery system could be beneficial for this architecture.
- ICE-electric propulsion may be challenging due to the volume taken up by the systems in the relatively small machinery space. DC-electric distribution and variable speed generators can further increase the efficiency while potentially reduce the volume required.
- The quasi-static calculations show that the hybrid architecture obtains a significant reduction of fuel consumption with 5%, the ICE-electrical savings are less than 2%. Since the propulsion layout is kept the same for the 3 architectures of the harbour tug, this fuel saving is completely achieved by better part load distribution.
- To obtain benefits for the hybrid solution, the balance between the electric motor and ICE power output for propulsion should be such that the electric motor boosts for max bollard pull while also sufficient power is available for low load propulsion. This can reduce the size of the main engine that will then have a better efficiency during the intermediate load operations.
- Tugs with electric propulsion motors also benefit from increased manoeuvrability as they can be controlled down to 0 rpm, whereas the clutch in speed of the ICE results already in significant ship speed. Electric motors further benefit from allowable temporarily over-torque that can improve the propulsion dynamics and max performance.

4.8.3 Offshore Supply Vessel

- Electric propulsion is beneficial from a lay-out point of view, keeping the aft of the vessel free for payload. Generator sets can be set more freely towards favourable position for stability, while avoiding long propulsion shafts. Furthermore, it is also advantageous when considering dynamic positioning. For this purpose an additional battery system can be used to avoid idle running hours on generator sets.
- The reserved machinery space is typically large enough for an ICE-electrical architecture.
- The analysis shows that the fuel savings from electrification are 7% for the use case. This seems realistic for the archetype, especially when more stationary or (heavy) DP operations are included. When long sailing distances are part of the operational profile, differences to ICE-mechanical propulsion are expected less significant.

4.8.4 Crew Tender Catamaran

- Electrification can be advantageous from the maintenance and lifetime perspectives as there is a lot of low loads and cyclic loads.
- Space is very limited onboard typical crew tender catamarans. Therefore, the ICE-hybrid architecture can be integrated in a typical crew tender catamaran with limited modifications, but ICE-electrical requires a large change in the ship design, possibly requiring a larger ship, increasing the propulsion energy demands. To reduce space requirements, the ICE-electric architecture could potentially benefit from DC-electric distribution and variable speed generators.

- The ICE-electrical architecture has a 1.7% fuel consumption reduction with the specified components and operational profile.
- Overall, electrification of the crew tender catamaran is not found feasible for the application in the investigated use case.

4.8.5 Dredger

- The ICE-electrical architecture saves 9% on fuel consumption based on the specific operations and defined architectures.
- The high payload powers make the vessel a good candidate for electrification. This can simplify the architecture compared to the reference vessel, as the ICE-mechanical architecture is in fact a hybrid architecture with only a power take-off and without electric motor.
- The required space for these types of systems was not considered as hybrid and electric architectures are already common for this vessel type.
- A battery system may be used for peak-shaving the irregular loads encountered by generator sets while dredging. This pack can also be used as spinning reserve functionality. The total capacity of such battery system is relatively small and with high power output (C-rate). The weight and volume requirements are relatively low. Such battery cannot be used for long periods of power supply or load levelling.
- A DC system with variable speed generators can be investigated to reduce fuel consumption further. Especially for to the high powers in payload, DC power can be of interest.

4.8.6 Mega Motor Yacht

- Electrification is often considered for mega motor yachts to have increased lay-out flexibility and to reduce noise and vibration levels.
- A battery system could be integrated when zero emission modes are required during anchoring or while moored without shore power available.
- There is a limited fuel saving found for ICE-electrical propulsion (-0.8%) but this is very dependent on the selected components and operational profile.
- The selected use case is a very large yacht with a very high installed propulsion power to achieve a high top speed for short period of time only. The results are expected comparable for smaller luxury yachts with lower top speeds. Hybrid propulsion may be beneficial to sail at lower cruising speeds without starting the propulsion ICE. However, smaller yachts are typically more space critical.

5 Dynamic simulation studies

In the first chapter, a series of research questions were posed, based on market questions. Some of these topics could be answered by generic investigation, as performed and reported in chapter 3. Some of these questions needed assessment over a typical mission profile of a specific reference ship design. These were studied and reported in chapter 4. Not yet addressed are the questions that look deeper into the electric power distribution during the operation.

In this chapter, the following research questions are addressed:

- *Can an electrified propulsion line benefit from applying battery assistance by operational load distribution?*
- *What is the impact on the ship and operational use of applying batteries in operation in and near harbour areas?*
- *Can the electrification of the propulsion line benefit from total average system efficiency in dynamic operation conditions by improved control strategies?*

The concept of how the energy flows through the PPE system is how this being optimized plays an important role to investigate these questions. Hence the implementation of an Energy Management System (EMS) and Power Management System (PMS) are required in the simulations to continue the research. Although generic strategies could be implemented, the effects are studied on a specific design of the PPE topology and therefore also on the ship use case.

For investigation on the control strategies of electrical propulsion, the behaviour of the PPE system and its components is evaluated against varying loads from sea conditions. These studies also require an adequate reaction of the components and hence a more sophisticated models compared to the ones earlier used, describing their response over time.

The application of these models requires much more effort and hence, only 1 use case specific reference vessel is being explored. The general cargo archetype is selected for this purpose, based on the interest from the stakeholder group, the number of vessels in this group and recent developments in the sector. The Short Sea Transport Vessel design use case from chapter 4 has been used for this purpose.

5.1 Results Battery Usage Assessment

In this section, we discuss the impact of including battery packs in the hybrid architectures. Our analysis focuses on the ICE-electric architecture of the Short Sea Transport Vessel.

The inclusion of a battery pack opens up new possibilities for vessel operation as described in Figure 5-1.

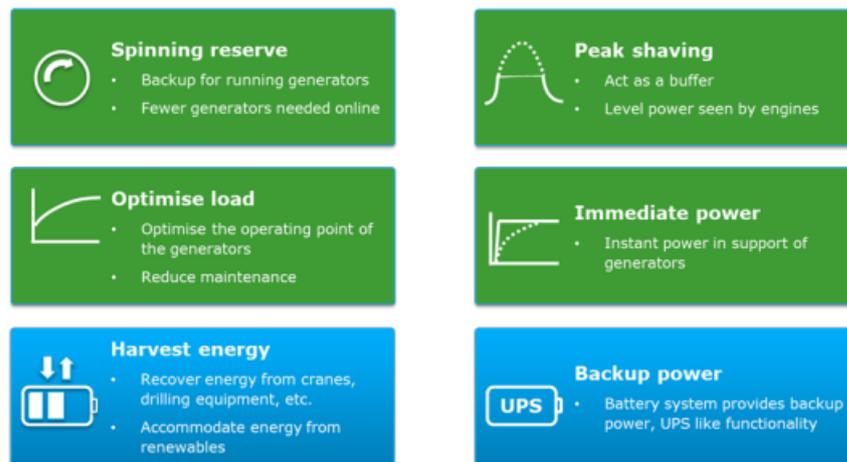


Figure 5-1: Functional roles of battery system onboard ships [17].

These functional aspects are tested through simulation of two scenarios:

- Electric sailing – Incorporation of a battery pack allows for pure electric sailing which could be beneficial especially close to coastal areas to limit local emissions.
- Generator set downsizing/removal – The addition of battery pack energy would allow for the optimisation of the generator set sizing.

We detail the process of constructing the simulation models, incorporating the battery and other components in Section 5.1.1, present the results for the two primary use cases in Section 5.1.2 and we conclude with a discussion of the findings, highlighting the benefits and potential challenges of integrating a battery into the hybrid architecture.

5.1.1 Use Case Definition

The simulation models are described in section 2.2.3. TNO added expertise on the battery modelling as well as on Energy Management Strategy to define the usage of the battery energy.

ICE Mechanical architecture

The ICE-mechanical architecture is similar to the one described in Section 4.2.2. It consists of a 4000 kW internal combustion engine (ICE) connected to a controllable pitch propeller, along with a 500 kW PTO. Additionally, electrical power can be generated by two GenSets of 270 kW each, which are connected directly to the DC bus.

The strategy for energy management is to combine the propulsion and auxiliary loads via the propulsion engine with the PTO connected for auxiliary loads. In this way, the system operates the propulsion internal combustion engine (ICE) at highest loads as much as possible. This strategy improves overall efficiency of the main propulsion by operating the ICE closest to its best Brake Specific Fuel Consumption (BSFC).

Operating the ICE at higher loads not only enhances fuel efficiency but also reduces wear and maintenance costs on the GenSets resulting in significant cost savings, as was described in the generic feasibility study of chapter 3. Through this approach the system remains efficient and cost-effective over the long term. In instances where the ICE would not be able to provide enough power for the auxiliaries, even when operated at maximum load, the GenSets are switched on one after the other.

ICE-Electric + Battery architecture

The ICE-Electric architecture as provided in section 4.2.2 remains the same in terms of the sizes of components. It consists of an electric propulsion machine rated at 4000 kW to propel the vessel. The electric power required by the electric machine and auxiliary components is supported by four GenSets, of which three are rated at 1300 kW and one is a smaller GenSet rated at 600 kW.

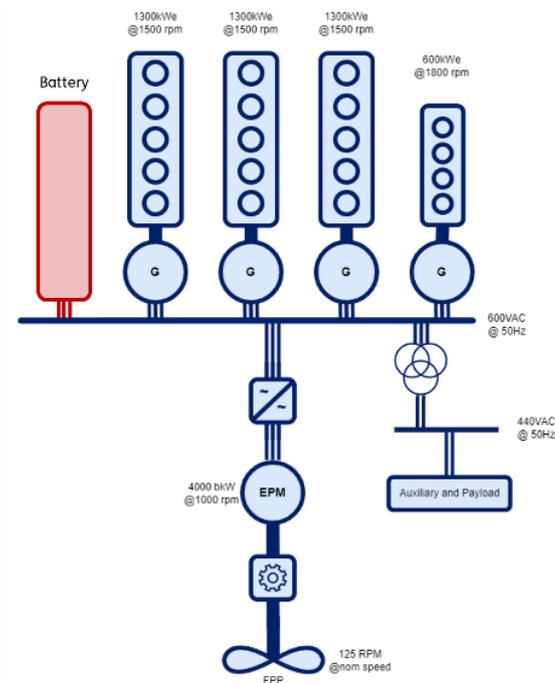


Figure 5-2: ICE-electric architecture with added battery coloured red.

The base ICE-Electric architecture is modified through the addition of a battery pack as highlighted in red in Figure 5-2. For the purpose of the simulation study, certain tuneable parameters are defined, namely, battery pack capacity, maximum charge and discharge C-rate, and the State-of-Charge (SoC) range. These, along with other battery parameters, are listed in Table 5-1. The initial sizing of the battery is defined by the C-rate and the target of replacing the smallest genset with a margin on the capacity to prevent using the battery pack below 20% SoC (thereby minimizing cycling effects to reduce degradation). The battery pack is based on NMC cells with a nominal voltage of 3.6V. NMC batteries offer the advantage of high energy density thereby limiting impact on vessel design in terms of cargo volume loss. Alternate chemistries such as LFP are cheaper but have lower energy density, thereby requiring more floor space for the same energy as an NMC battery.

Table 5-1: Battery parameter values.

Parameter	Value	Units
Battery Capacity	1.61	MWh
Maximum discharge C-rate (continuous)	0.5	-
Maximum charge C-rate	1	
Nominal Voltage	805	V
Initial State of Charge (SoC)	80	%
SoC upper limit	95	%
SoC lower limit	20	%

The supervisory control algorithm for the ICE-electric architecture follows a specific order. The GenSets are switched on one after the other, with the smallest GenSet reserved for last. As explained in the component models, the GenSets are always operated along their optimum operation lines, which is a common approach for GenSet control. This strategy ensures that the GenSets operate efficiently, reducing fuel consumption and maintenance costs.

5.1.2 Results

The results of the additional simulations are discussed in this section.

5.1.2.1 Use case 1: Battery only sailing

Firstly, we analyse the last mile emission-free sailing case. The primary goal of conducting simulations for this use case is to evaluate the advantages of sailing completely emission-free. Studies on the potential contamination caused by ships near the shore have shown that a ship deposits contaminants on the shore through air or water currents even when they are 25 km away from the shore [18]. This leads to pollution, loss of biodiversity, and other environmental issues. To mitigate these effects, sailing emission-free could be a viable solution. This approach ensures that the ship operates in an environmentally friendly manner when close to sensitive coastal areas, thereby reducing its ecological footprint and contributing to the preservation of marine and coastal ecosystems.

In this use case, we have considered that the ship needs to sail entirely on battery power without the use of GenSets when it is within a radius of 12 nautical miles from the port (in territorial seas). Figure 5-3 illustrates these sailing conditions for the chosen sailing cycle. The top subplot shows the total distance travelled by the ship as a function of time. The periods when the distance does not change indicate that the ship is docked in the port. Based on the definition of zero emission zones, the battery pack supplies the auxiliary power demand when docked (provisions are not made to consider on-shore charging). By identifying the times when the ship is exactly 12 nm away from the port, both when entering and exiting, we can delineate the zero-emission zones where the battery pack supplies the required energy for both propulsion and auxiliaries.

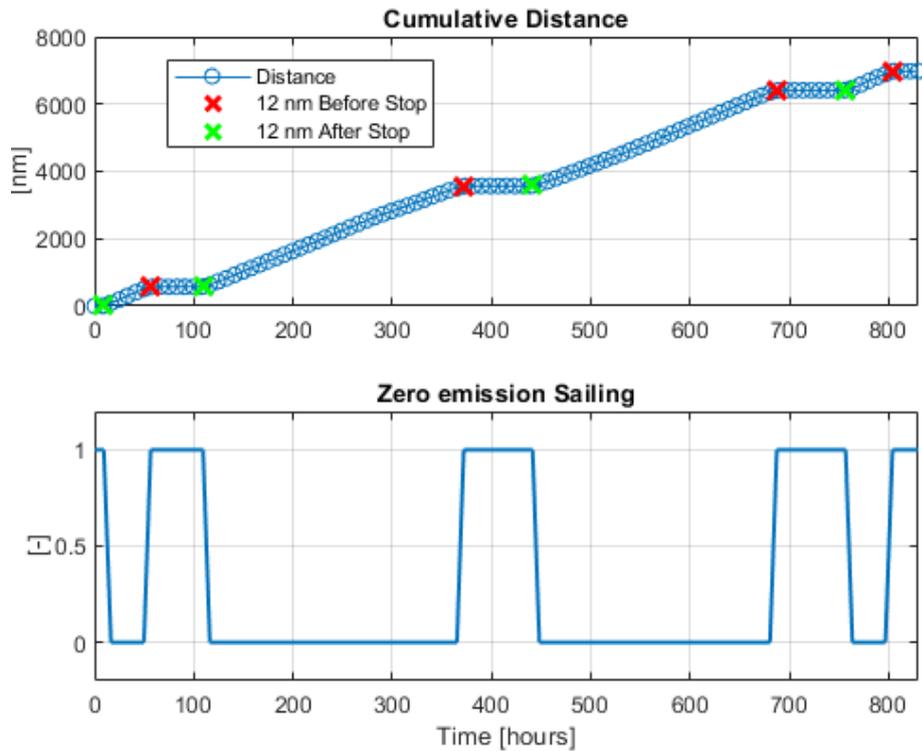


Figure 5-3: Potential zero emission sailing zones in territorial seas for the short sea transport vessel.

Figure 5-4 shows the simulation results for this use case. The blue lines represent the results from the ICE-electric simulations, whereas the magenta lines represent the simulations with zero-emission sailing.

To operate the battery within its SoC window, the gensets are used to charge the battery pack during open sea sailing, this leads to the gensets operating closer to maximum load, i.e., closer to its best BSFC area. This results in a higher instantaneous fuel consumption during sailing but in a reduction in overall fuel consumption by avoiding operating the gensets in lower loads where it is inefficient. A further reduction in fuel consumption can be achieved in cases where onshore charging infrastructure exists, thereby charging the battery through the grid rather than with gensets while sailing.

Key Observations

- **Fuel Consumption:** As observed in the fourth subplot, the fuel consumption is zero when the vessel is close to the shore during zero-emission sailing. This indicates that the vessel is operating entirely on battery power in these zones, effectively eliminating emissions in sensitive coastal areas.
- **Overall Efficiency:** The third subplot shows the overall efficiency of the vessel. It can be noted that the efficiency is lower in the zero-emission sailing case compared to the ICE-electric case. This is expected due to the additional energy conversion losses associated with battery usage.
- **Cumulative Fuel Consumption:** A reduction of approximately 4 percent in fuel consumption (397 tonne vs 413 tonne), highlighting the potential benefits of incorporating battery power for specific operational scenarios.
- The inclusion of a battery pack in the hybrid architectures for the Short Sea Transport Vessel opens up some new operational possibilities, such as zero-emission sailing near shores, and technical possibilities such as downsizing GenSets. The simulations demonstrate that zero-emission zones are feasible.

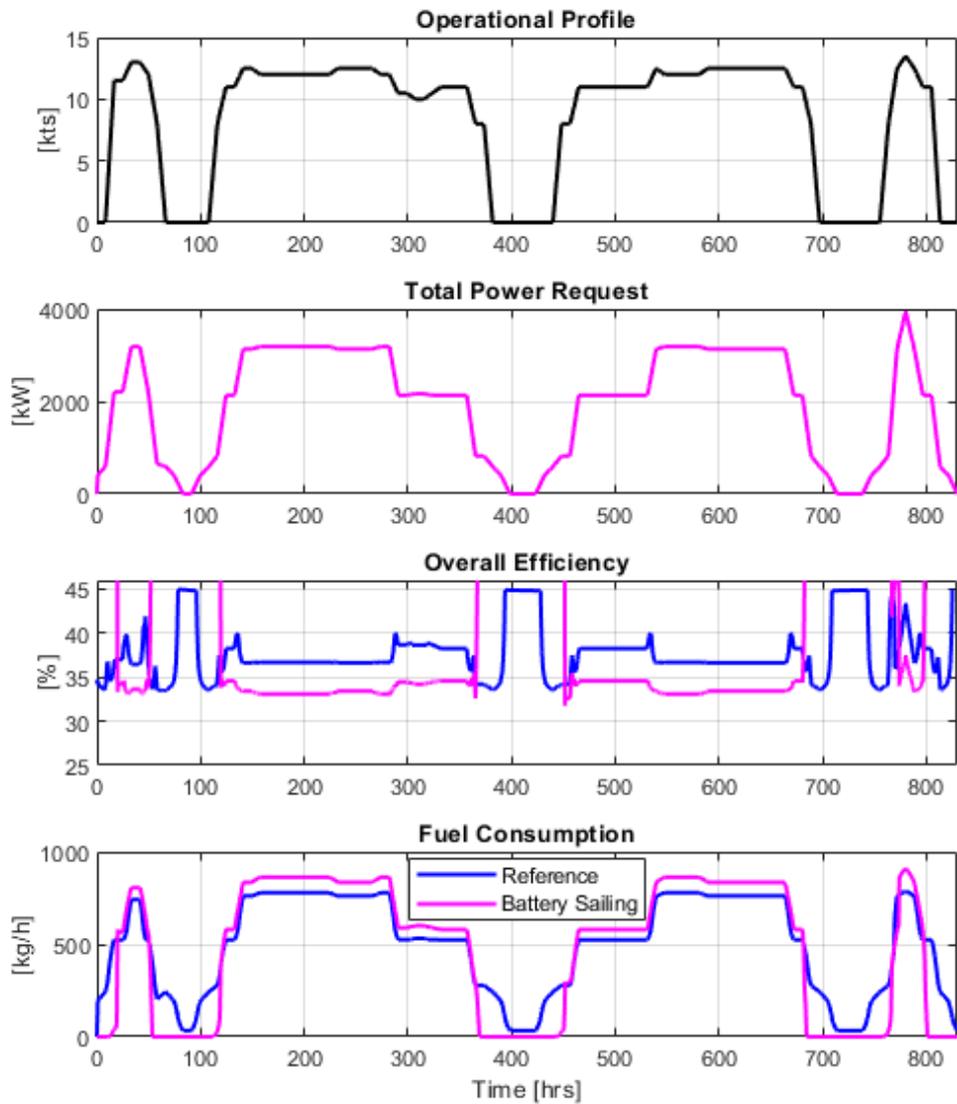


Figure 5-4: Efficiency and Fuel consumption for Short Sea Transport Vessel while using the battery

Figure 5-5 shows the SoC of the onboard battery on the left axis and the operational zone of the ship on the right axis. The battery SoC decreases when the vessel is in the zero-emission zone and when the vessel exits the zero-emission zone, the battery is recharged by the GenSets.

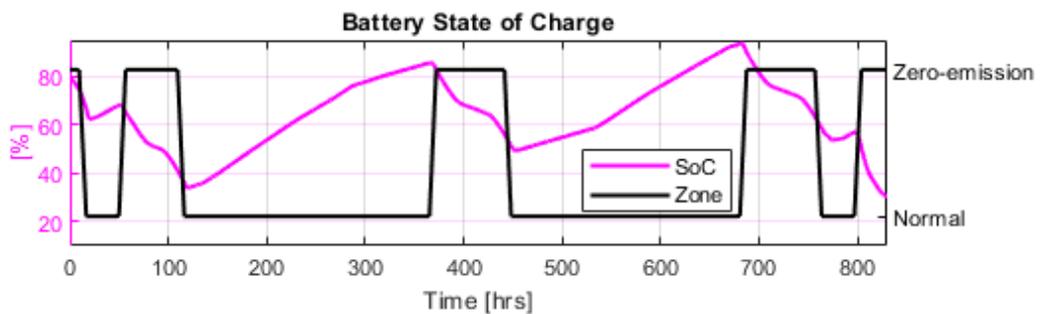


Figure 5-5: SoC of the Short Sea Transport Vessel during sailing.

Figure 5-6 shows the simulated NO_x emissions of the reference vessel (mechanical architecture) and the electrical vessel incorporating batteries. The trends are similar to the fuel consumption figure with a slight increase in NO_x emission during sailing since the gensets are operated at higher loads with zero emission within 12 nautical miles from coast. In overall terms, the electrical vessel achieves a improvement in NO_x emissions of 3% (2.62 ton vs 2.7 tonne) with the main benefit of zero NO_x emissions in the highest sensitive areas such as the port and close to coast.

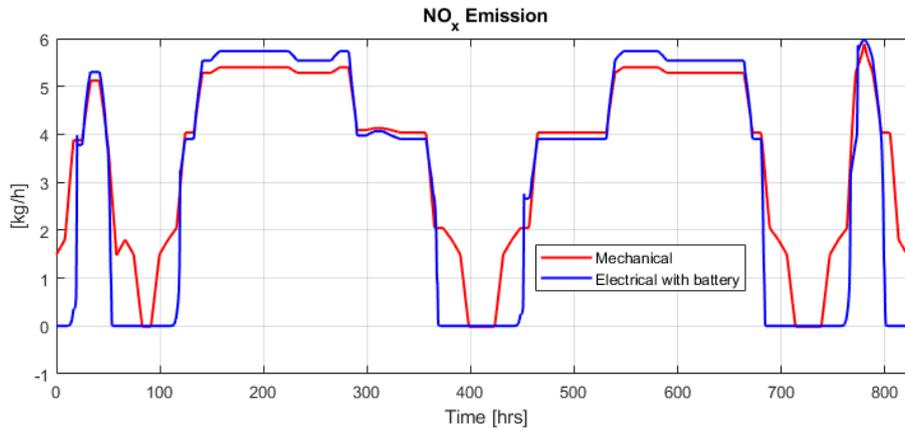


Figure 5-6: NO_x emissions of the Short Sea Transport Vessel during sailing.

These simulations shows that incorporation of a battery pack can enable zero-emission sailing close to coast thereby decreasing local emissions (NO_x, PM and CO₂). Battery technology improvements will play a key role in improving the economic and technical feasibility of such solutions. The battery pack currently implemented would weigh approximately 8 tonnes representing 0.2% of the total cargo volume with an expected cost of between 1-1.5 million. The possibility of on-shore charging is not investigated but is seen to be a crucial technology to enable the wide-spread adoption of battery powered vessels.

5.1.2.2 Use case 2: Downsizing

In this use case, one of the four GenSets from the ICE-electric architecture (as shown in Figure 5-2), specifically the smallest GenSet rated at 600 kW, is removed from the architecture. Additionally, the control algorithm is slightly modified to incorporate a horizon-looking capability. This means that the supervisory controller can recharge the battery more efficiently and to higher states of charge (SoC) when additional power is available from the GenSets and not required for propulsion or auxiliary hotel loads.

The results from the simulation are shown in Figure 5-7. The results from the previous use case, battery sailing, are represented in magenta, while the results from this use case are represented in green.

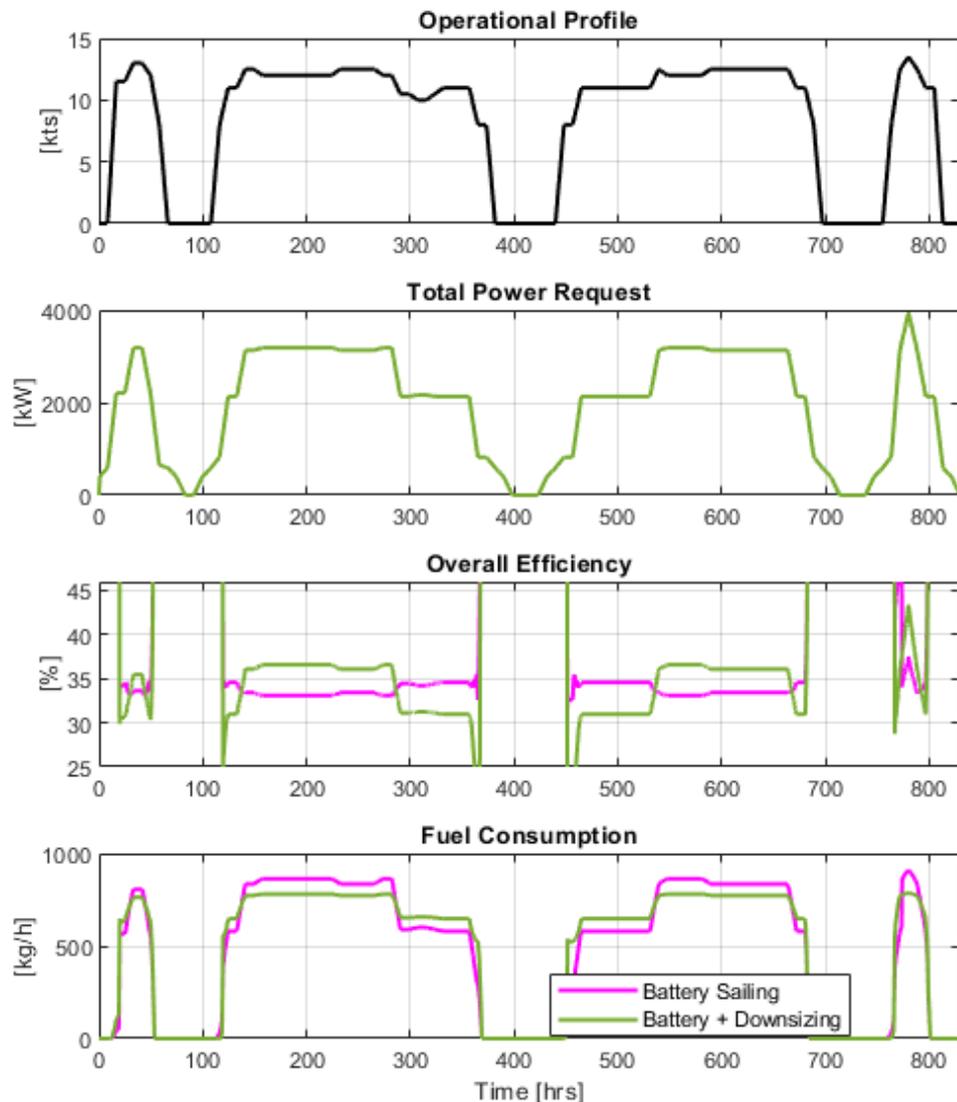


Figure 5-7: Efficiency and SoC of the Short Sea Transport Vessel when downsized.

Overall Efficiency: The third subplot shows that the overall efficiencies for both use cases are similar. The efficiencies hover around comparable values, indicating that the downsized architecture does not compromise performance.

Cumulative Fuel Consumption: The cumulative fuel consumption is reduced by approximately 1% (393 tonne vs 397) for the downsized case. This is mainly achieved through the improved control of battery SoC with the predictive horizon. The overall fuel consumption benefit is in the order of 5% compared to the baseline ICE-Mechanical vessel.

Figure 5-8 shows the battery SoC and results related to the GenSets. The battery SoC starts at 80% and ends around 20% for both use cases, making them comparable. The battery behaviour remains the same for both the cases which indicates that a change in battery size is not required to accommodate the reduced number of GenSets onboard. It is possible that the battery size could be optimized further in the, to achieve more cost savings.

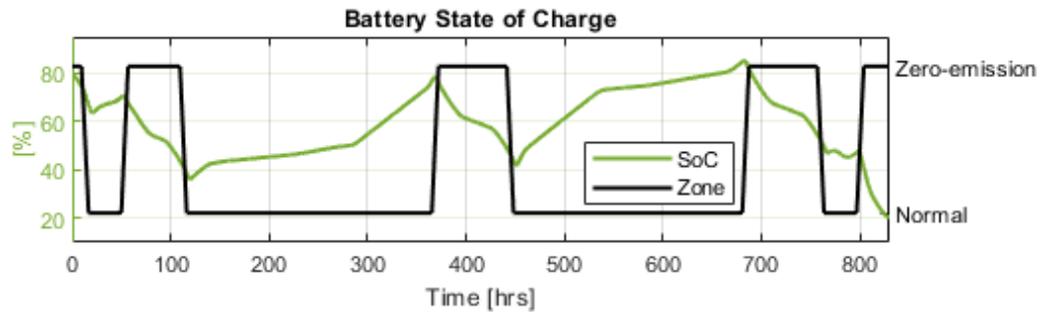


Figure 5-8: SoC of the Short Sea Transport Vessel when downsized.

The design of the vessels considers multiple gensets for emergency and redundancy while incorporating a battery pack could provide similar functions while enabling emission and fuel consumption reduction. The option of removing or downsizing gensets to add the battery pack would also reduce the economic impact in the design.

Discussion

As discussed earlier, the overall efficiency improvements by switching to electrified powertrains in the case of general cargo vessels are minimal. This is primarily due to the relatively long and static journeys that these ships undertake. However, electrification still provides an important pathway for improving emissions and enabling silent operation close to ports and shores.

Benefits of Electrification

- **Emission Reduction:** Electrified powertrains can significantly reduce emissions, particularly in environmentally sensitive areas such as ports and coastal regions. This contributes to cleaner air and water, benefiting both the environment and public health.
- **Silent Operation:** Electric powertrains enable vessels to operate silently, which is advantageous when navigating close to populated areas or marine habitats where noise pollution can be a concern.

Shore-Based Charging

The ability to charge the batteries at the shore could also be explored. Shore-based charging infrastructure would allow vessels to recharge their batteries while docked, reducing the need for large onboard battery capacities.

This approach has several advantages:

- **Reduced Battery Size:** By charging at the shore, the size of the onboard battery can be reduced, leading to lower capital expenditure and weight savings.
- **Operational Flexibility:** Shore-based charging provides flexibility in operations, allowing vessels to maintain optimal battery levels without relying solely on onboard generation.
- **Cost Savings:** Smaller batteries and reduced fuel consumption can lead to significant cost savings over the vessel's operational life.

In conclusion, the direct efficiency improvements from electrification are minimal for the investigated Short Sea Transport Vessel. The potential for emission reduction, silent operation, and shore-based charging make it a viable option for enhancing environmental performance and operational flexibility.

5.2 Results dynamic fuel efficiency calculations

As stated by market parties, the control of electrified vessels could be beneficial over classic ICE-mechanic vessels. Hence the research question “*Can the electrification of the propulsion line benefit from total average system efficiency in dynamic operation conditions by improved control strategies?*” is posed.

This section tries to answer this question. As mentioned, the Short Sea Transport Vessel use case is taken to perform detailed system modelling in order to predict the fuel consumption in several seaway conditions. In this way, the realistic operational loads as experienced by the PPE system are assembled from the hydrodynamic effects on hull and propeller and taken into account. Also the behaviour of the PPE system components as well as the energy optimization logic in an energy or power management system are taken into account in the time domain simulation.

In order to assess the hydrodynamic effects, a generic hull shape was created and propeller designs made for the ICE mechanical and ICE-electric architectures.

The ICE-mechanical and ICE-electric PPE architectures are worked out further to study the effects on fuel consumption. The fuel consumption is then calculated by operating the vessel in seaway in a time domain simulation, where movements of the vessel, varying ship resistance, inflow variations on the propeller and resulting torque and power variations in the propulsion shaft are compensated by the PPE systems. The test scenarios for these simulations are no longer the total operational profile, but fixed sea state conditions. The vessel is operated such that a continues vessel speed and course are achieved.

5.2.1 Architecture assumptions

As the dynamical modelling makes use of more detailed component models, also new assumptions needed to be made. A short list of the most important assumptions is given in this sub section.

Propeller type

For each architecture, a different propeller type is taken into account. The propeller type is matched against the characteristics available or limiting from the PPE systems.

The original reference ship had a 4.5m propeller diameter. For the ICE-mechanical architecture features a ducted CPP. The diameter of the ducted propeller was selected such that the outer diameter of the applied 19A duct was marginally larger than 4.5 [m], thus ensuring that duct does not protrude under the base line of the ship. The corresponding propeller diameter is then 3.7m.

The electric architecture features an open Fixed Pitch Propeller (FPP) which has the same diameter as from the reference vessel of 4.5m.

The pitch of the propellers was optimised for maximum efficiency at design speed of the vessel at approx. 70% power output of the propulsion motor/engine resulting in a ship speed of about 12.9kn.

The ICE-mechanical architecture will be operated at constant rotation rate while thrust is varied by changing the pitch angle of the propeller blades. The ICE-electric architecture is operated with varying rotation speed only. Table 5-2 summarizes the main dimensions of the three propellers.

Table 5-2: Main dimensions of the two propellers.

PPE architecture	Electrical PPE	Mechanical PPE
Propeller type	Open FPP	Ducted CPP
Diameter [m]	4.5	3.7
Rotation rate [RPM]	Variable	140

5.2.1.1 ICE-Mechanical Architecture

The simulation model includes the propulsion engine, the gearbox, inertia of the propulsion shaft, the PSG electrical shaft machine and its control. In the free-sailing test scenarios, all electric power is assumed to be provided via the Propulsion Shaft Generator, therefore the auxiliary ICE gensets are not taken into account.

5.2.1.2 ICE-Electrical Propulsion Architecture

Propulsion

The propulsion system includes a Permanent Magnet Synchronous (PMSM) drive motor fed by a DC supplied frequency drive controlled by a speed controller. The choice of a PMSM was made due to its higher efficiency compared to an electric induction motor.

The propulsion motor is operated in speed control mode (i.e. no torque or power control mode).

Electric power generation and distribution

A DC power distribution circuit is assumed. This is due to the potential higher efficiency of DC distribution and conversion. Also, this allows to make use of variable speed generator sets, which are selected in the architecture. These variable speed generators can achieve higher efficiency at lower output power by reducing the rotation speed of the gensets. The rotation speed has been tuned by MARIN to allow sufficient dynamic response of the gensets to load demands.

5.2.2 Dynamic Simulation Test Cases description

The objective of the simulations is to analyse the performance of the Power, Propulsion, and Energy (PPE) system from the perspective of the fuel consumption and efficiency in the realistic operating conditions.

A series of simulations were performed, to analyse the performance of the two architectures – ICE-mechanical and ICE-electric. The operational conditions are described in Table 5-3. These testcases are based on the operational profile that was defined section 4.

Table 5-3: Test cases and conditions.

ID	Test case	Waves			Wind		Ship		
		Hs	Tp	dir	velocity	dir	Auxiliary Power	Payload Power	Ship Speed
		[m]	[s]	[deg]	[m/s]	[deg]	[kW]	[kW]	[kts]
TC01	Calm water	0	-	-	0	-	210	202.5	12.5
TC02	SS3 head waves	0.88	7.5	180	6.9	180	240	202.5	12

TC03	SS6 head waves	5	12.4	180	19.3	180	270	202.5	7
TC04	SS6 bow quartering waves	5	12.4	135	19.3	135	270	202.5	7
TC05	SS6 stern quartering waves	5	12.4	45	19.3	45	270	202.5	7
TC06	Calm water low speed	0	-	-	0	-	270	202.5	7

While the operational profile definition of section 4.2.1 indicated an average vessel speed of 11 knots in sea state 6, it was found that due to the added resistance of the waves and wind in head seas, the vessel could only achieve approximately 7 knots which has been used for the dynamic simulations.

Wind and waves are assumed from the same direction. Both head and stern waves were investigated. Also 2 conditions were added with (true) wind and waves from bow quartering and stern quartering directions in sea state 6, as these conditions can cause for significant load variations as well.

The test are performed by sailing the virtual vessel from stand-still till it covered a sailing distance of 12 nautical miles. The speed and course of the vessel are controlled by an autopilot function, manipulating rudder and throttle levers. For the comparison of fuel consumption and efficiency, the data over the last 10 nautical miles was considered.

5.2.3 Simulation results at fixed conditions

The numerical results of the Test Cases on fuel consumption and maintained average speed are given for both architectures in Table 5-4.

Table 5-4: Dynamic test results summary of fuel consumption.

S. No	Name	Target Speed	ICE-Mechanical		ICE-Electric		Difference
			Average achieved speed over ground	Fuel Consumption for 10 nmi	Average achieved speed over ground	Fuel Consumption for 10 nmi	Fuel ICE-Electric vs ICE-Mechanical
	Unit	[kn]	[kn]	[kg]	[kn]	[kg]	[-]
TC01	Calm water	12.5	12.56	502	12.60	511	+ 1.8%
TC02	SS3 head waves	12.0	12.05	524	12.06	533	+ 1.8%
TC03	SS6 head waves	7.0	7.00	935	7.01	1070	+ 14.5%
TC04	SS6 bow quartering waves	7.0	7.02	854	7.02	940	+ 10.0%
TC05	SS6 stern quartering waves	7.0	6.98	523	6.97	481	- 8.1%
TC06	Calm water low speed	7.0	7.01	416	6.99	306	- 26.3%

A comparison between the two architectures, is shown in Figure 5-9. It can be seen that which concept is more fuel efficient is strongly dependent on the usage profile. From the simulation results, the following conclusions can be drawn:

- Under modest circumstances the two concepts are performing comparable.
- Under heavy circumstances the mechanical concept is more fuel efficient. The most severe conditions simulated, sailing in Sea State 6 at 7 knots in head-waves, showed a 14% better fuel consumption.
- Under very mild circumstances the electric concept is more fuel efficient. Slow sailing in calm water showed a reduction in fuel consumption of 26%.

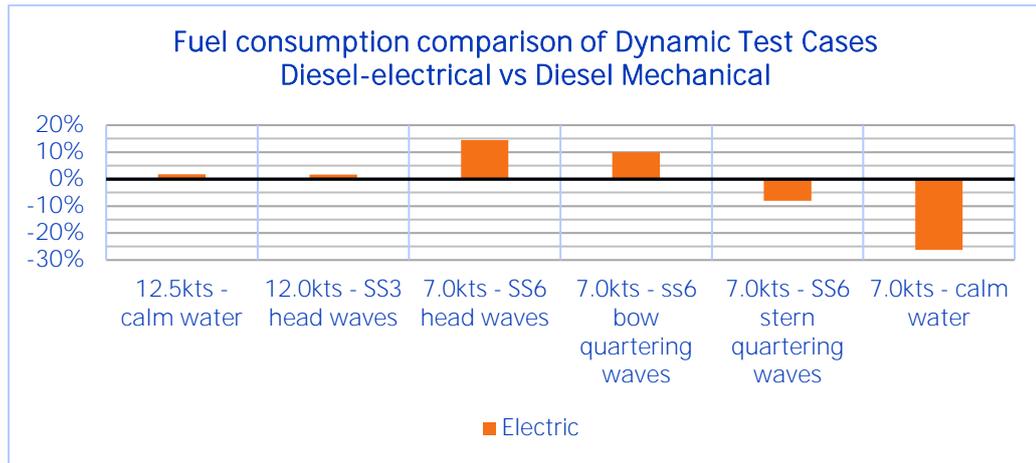


Figure 5-9: Relative fuel consumption of dynamic simulations for the Short Sea Transport Vessel use case over 10 nm in various conditions. A positive number represents the diesel-mechanical architecture having lower fuel consumption.

To analyse the results further and investigate where the differences originate from, the results of each simulation are represented in two ways:

A **Sanky diagram** provides the summed energy over the last mile, starting with the energy of the fuel content, indicating losses of each conversion step and provide the remaining net power for propulsion and auxiliary electric power.

Obtained operational points are represented as red dots in a **contour plot** of the ICE fuel efficiency. The larger the dot, the higher occurrence in the data set is. For the mechanical propulsion the contour plot of the propulsion engine is given, for the electric architecture the ICE of the large generator set is given. The generator sets were loaded equally in the simulation and the small one was not used.

Example of these plots are provided in Figure 5-13 and Figure 5-14 for test case 5. The plots for all test cases are provided in A.3. The following can be concluded from analysing these plots:

The effective propulsion power is different for the two architecture types for each comparable test case. This is due to the variation in the propeller type and operation mode (constant rpm vs varying rpm). This effect for the test cases is represented in Figure 5-10. It can be seen that for nearly all conditions, the ICE-mechanical architecture requires more propulsion energy due to the choice of the propeller type.

The maximum efficiency of the propulsion engine from the ICE-mechanical architecture is higher, due to its type and size, compared to the ICE-electric genset combustion engine.

The ICE-mechanical engine is kept at approx. 750 rpm to keep the propulsion shaft generator at its desired frequency. The variable speed gensets are adjusted in operational speed to provide sufficient power and to seek optimum for fuel efficiency. The achieved operational efficiency of the propulsion engine varies from 37.6% for the lowest power output to 43.1% for the highest power output. The achieved efficiency of the genset engine varies from 39.5% for the lowest power output to 42% for the highest power output.

As the ICE-electric architecture has more energy conversions from the ICE to the propulsion shaft, more loss components are indicated for the ICE-Electric (5 against 3). The losses of the ICE-mechanic architecture sum to 1.3 – 2.0% while the ICE-electric losses sum to 4.2-4.7%.

The total system efficiency is given in Figure 5-11.. It can be seen that the ICE-mechanical architecture benefits from higher total system efficiency for all cases. At lower power demand, the difference in the efficiencies tends to get smaller. Applying the total system efficiency on the required propulsive and auxiliary energy results in the total fuel consumption comparison as provided in Figure 5-12.

Generally can be concluded that for high propulsion load, either caused by high speed sailing or adverse environmental conditions, the ICE-mechanic propulsion architecture benefits from high ICE efficiency and low losses. At low propulsion load, either caused by slow speed sailing or favourable environmental conditions, the ICE-electric propulsion architecture benefits from lower propulsion power requirements and effective genset loading.

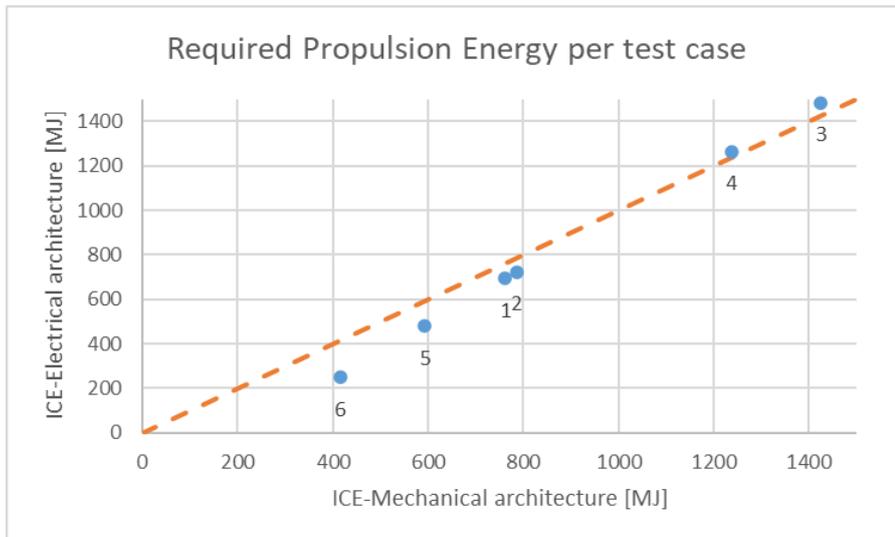


Figure 5-10: Energy requirement for propulsion in [MJ/NautMile] of comparable run with ICE-Mechanc or ICE-Electric architecture for the tested conditions.

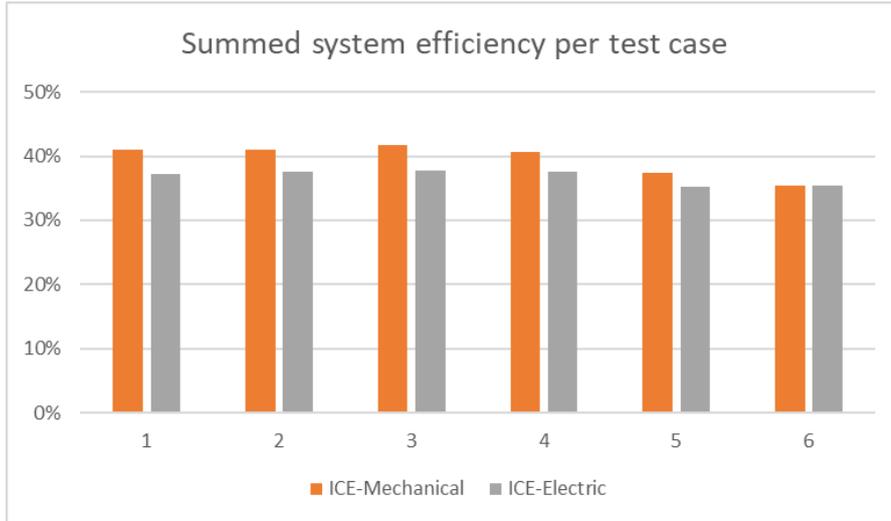


Figure 5-11: The total efficiency of the system from fuel input to the sum of propulsion and electric power supply.

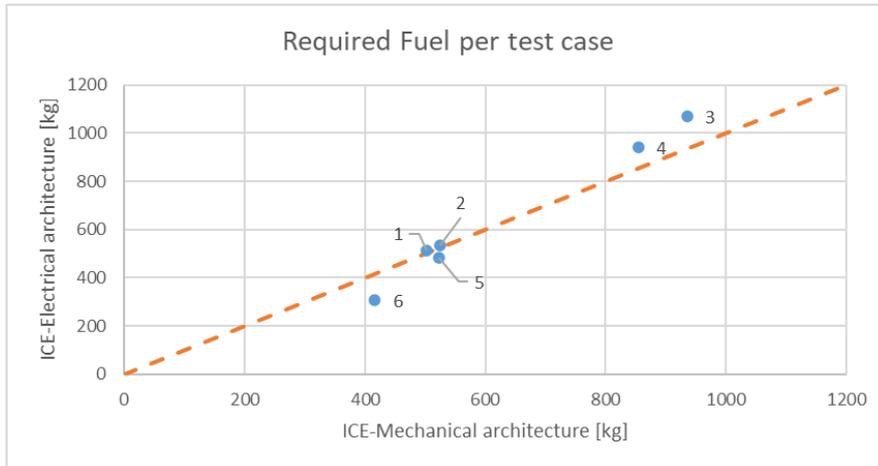


Figure 5-12: Total fuel energy per use case.

Example Sanky diagram and contour plots:

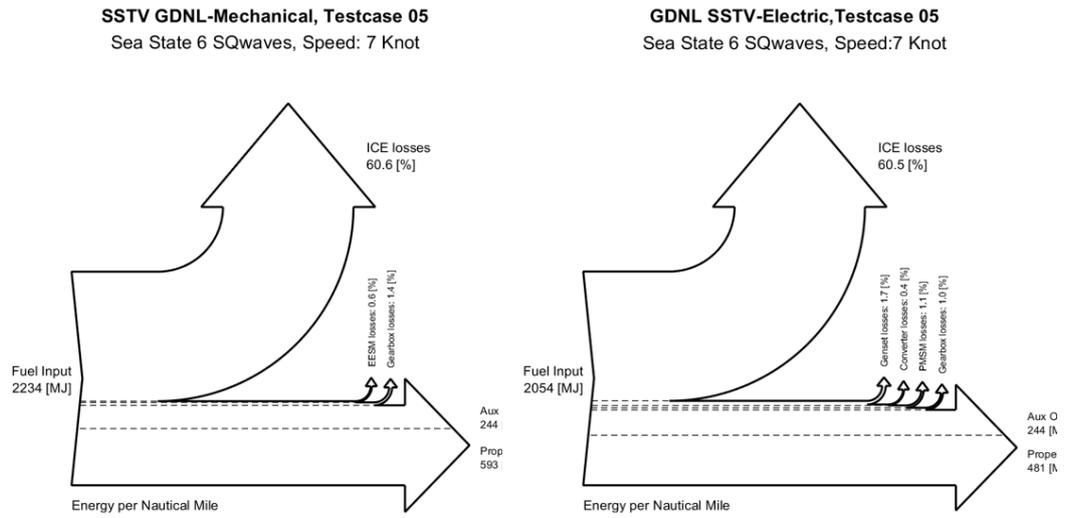


Figure 5-13: Sankey Diagram for the mechanical and electric designs operating in stern quartering waves in Sea-State 6 with an average vessel speed of ~7 knots.

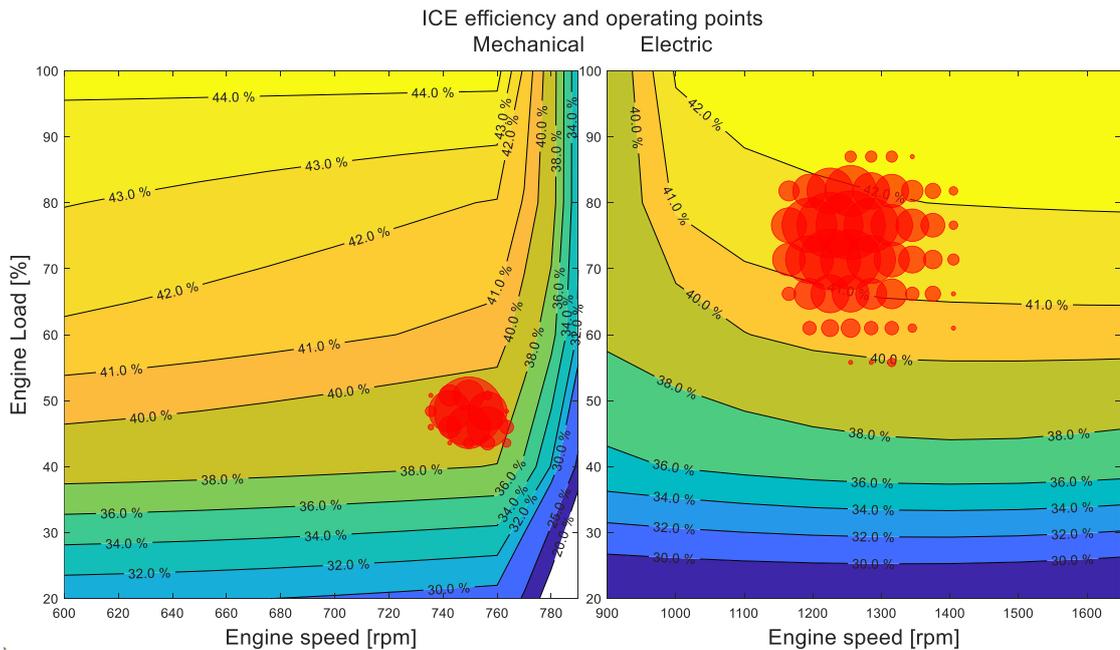


Figure 5-14: Engine efficiency map for the Main engine of the mechanical case, and the ICE of the 1300kW gensets. The red dots represent the distribution of operated points. Testcase 5, Sailing 7 knots in Sea State 6 with stern quartering waves.

5.2.4 Results of routing optimisation

As found in the fixed conditions results of the previous section, the actual most favourable condition architecture depend mostly on the chosen vessel speed and environmental conditions. To further investigate this the realistic operating conditions are being explored via series of routing optimization simulations. These simulations were performed on the Rotterdam-Bergen-Halifax-Rotterdam route from the operational profile of section 4.2.1.

In the simulations, the weather conditions can be included over a year round operation between 2007 and 2012. The routing was performed with a Captain Decision Mimic that can decide to reroute and change speed to meet the comfort and operational limits of the vessel. An example of the successfully completed routes is shown in Figure 5-15. Furthermore the simulations were performed with four target setpoints for the propulsion power, ranging from 50% - 80%. Table 5-5 summarizes the simulation settings and results.



Figure 5-15: Successful voyages for Rotterdam-Bergen-Halifax-Rotterdam.

Table 5-5: Simulation settings for SafeTrans.

Setting	Value
Route	Rotterdam-Bergen-Halifax-Rotterdam
Wave Spectrum	Jonswap
Captain Decision Mimic	Rerouting and changing speed possible
Target propulsion power [%]	50 60 70 80
Target Calm Water Speed [kn]	9.3 10 10.7 11.3
Total Successful Voyages [-]	141 141 156 171

The encountered conditions of the routing simulations could be fed to the ship and PPE system simulations. A selection of conditions (wave height, period and direction with corresponding wind speed) has been made to analyse. The selection was based on a combination of total occurrence and achieved propulsion power.

Simulations were then performed for both the ICE-Mechanical and ICE-Electrical architectures, resulting in total fuel consumption or average fuel consumption rate for all these simulated conditions. They can be compared 1:1 as were the test cases of section 5.2.3. The result is provided in Figure 5-16 and Figure 5.17.

It can be seen that an optimization front is approached, corresponding to required propulsion power, comparable as achieved in Figure 5-10.. At lower fuel flow rates the ICE-electric propulsion concept benefits. At higher fuel flow rates, the ICE-mechanical propulsion concept benefits.

The spread below the limiting line are found to be adverse conditions. This can be seen by the reduced achieved vessel speed in Figure 5-17.

An average for each target propulsion power is made to give a conclusive numerical answer. This is pictured in Figure 5-18 and Figure 5-19. The results show an average benefit of 3.4% for the ICE-electric concept at 50% propulsion power to -2.4% at 80% MCR. These differences are small, but based on various effects and statistically significant over many expected conditions.

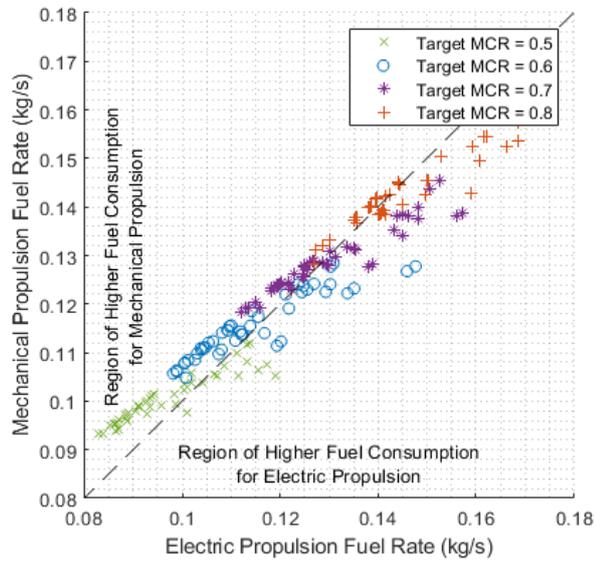


Figure 5-16: Comparison of the Fuel Consumption Rate of the electrical and mechanical concept designs.

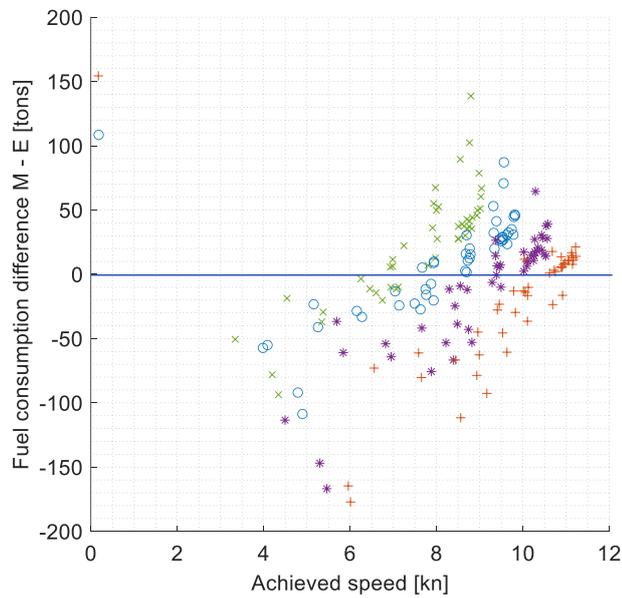


Figure 5-17: Fuel consumption comparison per trip against achieved vessel speed.

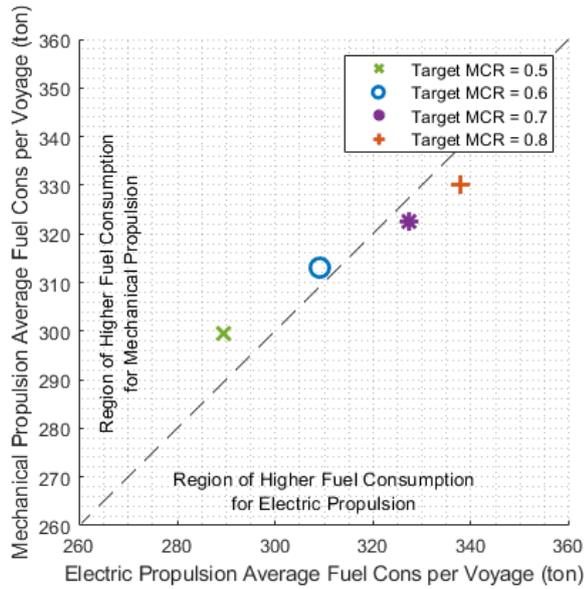


Figure 5-18: Comparison of fuel consumption per voyage for each of the cases.

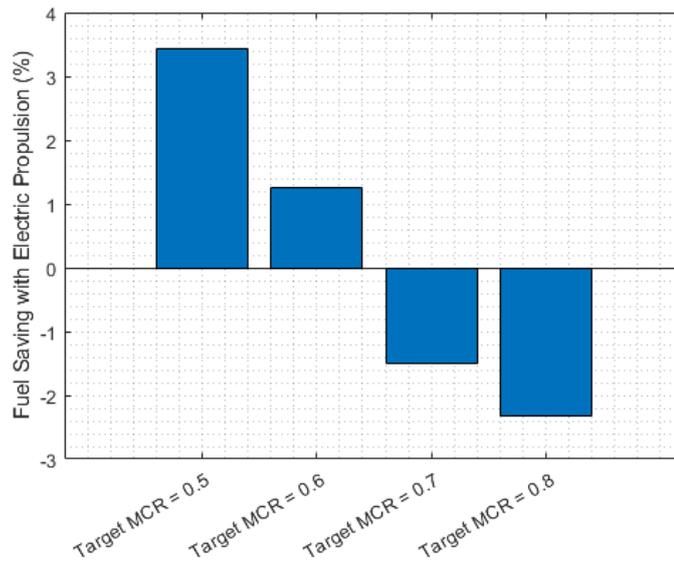


Figure 5-19: Fuel Savings offered by the electrical concept for the four cases.

5.2.5 Summary of the results

The ICE-mechanical and ICE-electrical architectures were simulated in six different testcases for the Short Sea Transport Vessel. The fuel consumption over a steady trip of 10 nautical miles was measured per testcase. A comparison of the fuel consumption for the two concepts is given in Table 5-6.

Table 5-6: Simulation results including the difference in fuel consumption for the electric concept. For positive numbers the diesel-mechanical architecture has lower fuel consumption.

S. No	Name	Diff. in Fuel Cons.
	Unit	
TC01	Calm water	1.8%
TC02	SS3 head waves	1.8%
TC03	SS6 head waves	14.5%
TC04	SS6 bow quartering waves	10.0%
TC05	SS6 stern quartering waves	-8.1%
TC06	Calm water low speed	-26.3%

The conditions have a significant effect on the results. To decouple the results from the choice of specific cases, a routing analysis was added. In order to research which conditions and how often these conditions are encountered, routing simulations have been performed. Here the conditions are concluded from actual routing information, while the only simulation setting is the choice of target propulsion power. The resulting benefits are provided for 4 realistic propulsion power setpoints and summed over a significant set of encountered conditions. The results are provided in Table 5-7.

Table 5-7: Summary comparison between the mechanical and electrical concept.

Target propulsion power [%]	Savings with ICE-Electric concept [%]
50	3.43
60	1.25
70	-1.49
80	-2.33

The following results were observed for the selected use case:

- The applied propulsion power has a significant effect on the achieved benefits of the ICE-electric concept
- In high power demand cases the ICE-mechanical concept has the highest efficiency; its large engine has better peak efficiency, while the ICE-Electrical concept has the disadvantage of additional electrical power conversion losses.
- In low vessel speed and hence low power demand cases the mechanical concept has the lowest efficiency. This is a combined effect of reduced ICE efficiency and reduced propeller efficiency.
- In medium load cases both concepts are comparable with regard to efficiency.
- The medium speed engine in the mechanical concept has a fixed rpm, so engine-power reduction is achieved by reducing engine load while keeping engine speed high. This comes with a reduction in efficiency.
- Slower sailing increases the relative amount of auxiliary system energy demand which becomes significant at very low ship speeds.
- The electrical concept is able to provide power at a relative high efficiency over a wide range of output power. This is because of the variable speed gensets, and the ability to fully switch off gensets.

6 Total Cost of Ownership Analysis

6.1 Introduction

This chapter contains a comparison between total cost of ownership for three variants of the Short Sea Transport Vessel to answer the research question:

How significant is the electrification of the propulsion line on the total cost of ownership for the whole vessel in its operation?

The variants are similar to the results in section 4.2 and are summarised as follows:

- **ICE-mechanical** (traditional) Propulsion is powered by a diesel combustion engine, and onboard power is generated by diesel-powered generators.
- **ICE-electric** (diesel genset, electric motor). Propulsion is powered by an electric motor. Power for onboard use and propulsion is generated by diesel-powered generators.
- **Hybrid ICE-electric** (diesel engine, electric engine, twin gearbox) Propulsion can be powered by an electric motor or a combustion engine. Onboard power and power for the electric motor are generated by diesel-powered generator sets.

For a more elaborate description of the propulsion system alternatives, please refer to section 4. The options that are compared for the Short Sea Transport Vessel are described in Figure 6-1 below.

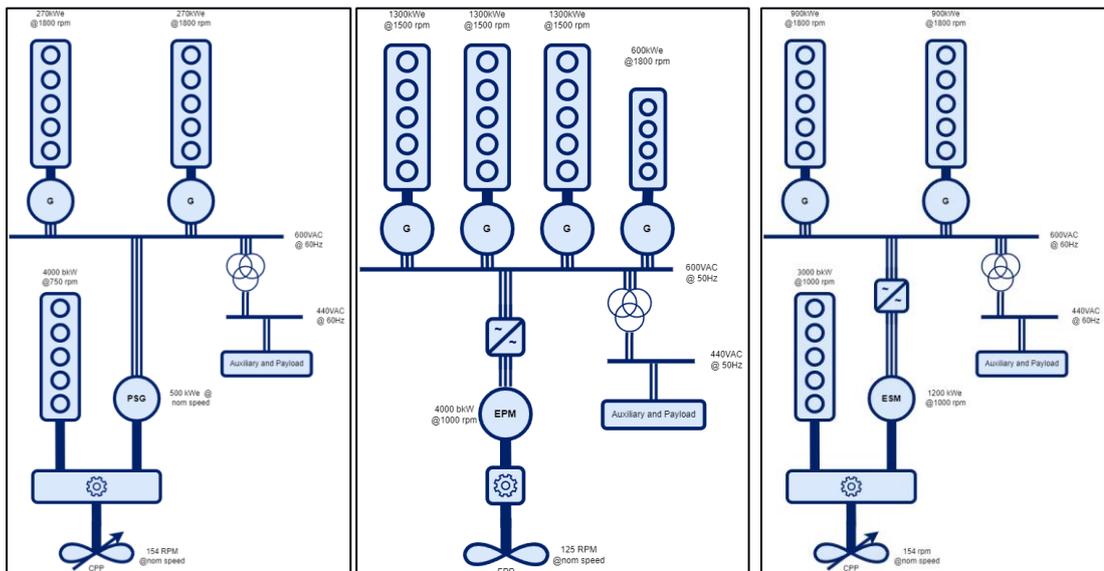


Figure 6-1: Overview of the Short Sea Transport Vessel architectures, from left-right: Mechanically connected Diesel Internal Combustion Engine (ICE), ICE-electrical and Hybrid (using both an electrical motor and a combustion engine).

6.2 Approach

To compute the total cost of ownership for the short sea transport vessel, TNO uses a version of the NavigaTE TCO model, developed by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping [7]. The model is used to calculate total cost of ownership. It includes the cost categories shown in Table 6-1 below. Some simplifications were made by TNO, and values for the model parameters were chosen in collaboration with MARIN to reflect the properties of the General Cargo Vessel archetype.

Table 6-1: Total cost of ownership – cost categories.

TCO		
CAPEX		
Hull + structures + equipment	Base CAPEX	USD/year
Propulsion [1]+[2]+[3]	Total propulsion system CAPEX	USD/year
[1]	<i>Main engine CAPEX</i>	<i>USD/year</i>
[2]	<i>Aux engine / Genset CAPEX</i>	<i>USD/year</i>
[3]	<i>Engine related systems CAPEX</i>	<i>USD/year</i>
Fuel supply and storage [4]+[5]	Fuel supply + storage CAPEX	USD/year
[4]	<i>Tank CAPEX</i>	<i>USD/year</i>
[5]	<i>Fuel supply system CAPEX</i>	<i>USD/year</i>
OPEX		
Fuel cost	Total Fuel OPEX	<i>USD/year</i>
Maintenance	Maintenance OPEX	<i>USD/year</i>
Ancillary OPEX	Ancillary OPEX	<i>USD/year</i>

6.3 Results

The choice of power train influences the total cost of ownership in the following ways:

- Capital expenditure is significantly different for the propulsion system alternatives. A comparison is shown in Figure 6-2.
- Capital expenditure for fuel and energy supply systems are slightly different.
- Maintenance costs are different, as discussed in paragraph 3.2.

However, as we will see, these categories are not the main capital or operational expenses for a general cargo ship. A summary of the Total Cost of Ownership calculation results is shown in Table 6-2 below. A more detailed version of this calculation is attached as Appendix C.

Table 6-2: Total cost of ownership for the Short Sea Transport Vessel use case.

Main category	Subcategories	Cost	Diesel ICE	ICE-electric	Hybrid
Total cost of ownership					
	Total cost of ownership	USD/year	5,655,606	5,698,990	5,670,730
	CAPEX	USD/year	818,530	943,018	914,758
	OPEX	USD/year	4,837,076	4,755,972	4,755,972
CAPEX					
	Total CAPEX	USD/year	818,530	943,018	914,758
Hull	Base CAPEX	USD/year	640,000	640,000	640,000
Propulsion	Total propulsion system CAPEX	USD/year	168,888	293,400	264,960
	Combustion engine CAPEX	USD/year	60,800	*	45,600
	Aux engine / Genset CAPEX	USD/year	8,208	68,400	27,360
	Engine related systems CAPEX	USD/year	99,880	225,000	192,000
Fuel supply and storage	Fuel supply + storage CAPEX	USD/year	9,642	9,618	9,798
	Total tank CAPEX	USD/year	2,918	2,918	2,918
	Total supply system CAPEX	USD/year	6,724	6,700	6,880
OPEX					
	Total OPEX	USD/year	4,837,076	4,755,972	4,755,972
Fuel cost	Total Fuel OPEX	USD/year	2,893,762	2,893,762	2,893,762
Maintenance	Maintenance OPEX	USD/year	243,315	162,210	162,210
Ancillary	Ancillary OPEX	USD/year	1,700,000	1,700,000	1,700,000

**the ICE-electric propulsion system consist only of diesel powered generators, so no internal combustion engine ('main engine') is used.*

6.3.1 Capital expenditure

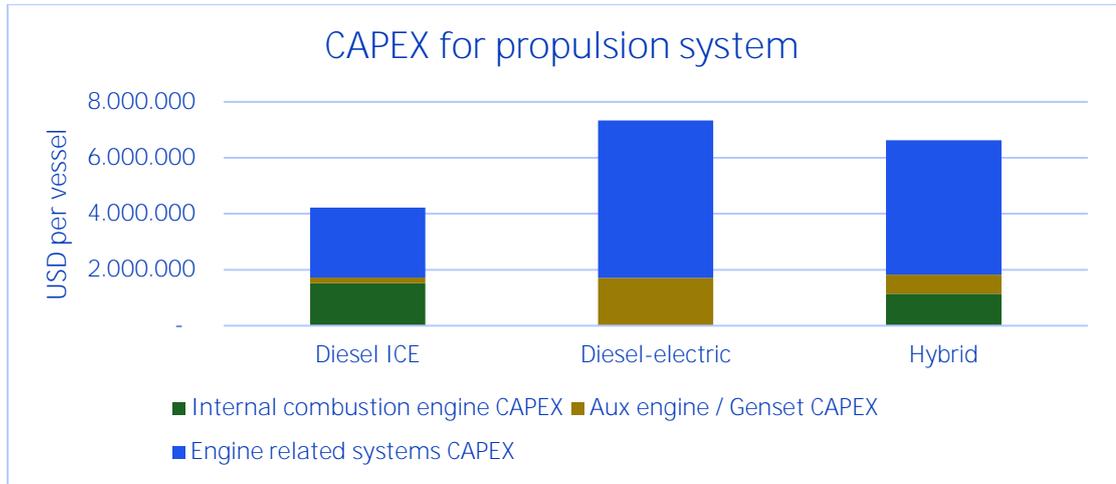


Figure 6-2: Capital expenditure of power generation, distribution and aftertreatment systems.

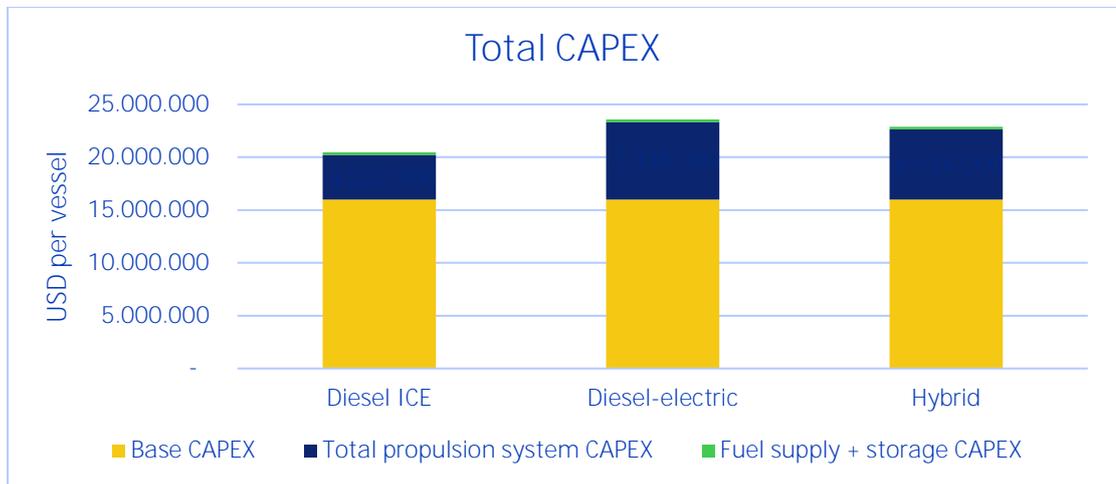


Figure 6-3: CAPEX for the propulsion system is a small part of total CAPEX.

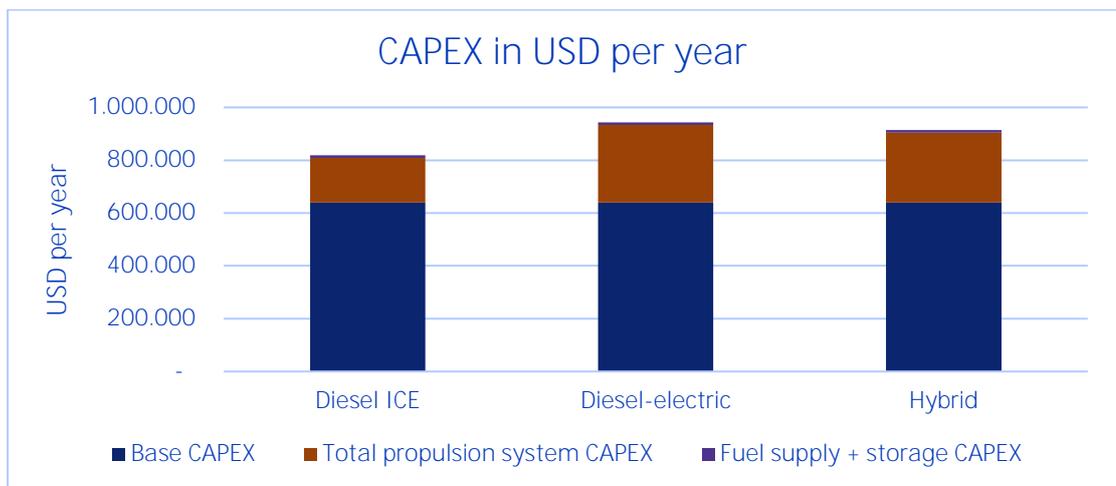


Figure 6-4: CAPEX for the entire vessel, in US Dollars per year.

The capex is lowest for the internal combustion engine, followed by the hybrid system, and finally highest for the ICE-electric propulsion system architecture. This is mainly due to the relatively high cost of power distribution and related systems for the ICE-electric propulsion system. However, as can be seen in Figure 6-3 and Figure 6-4, the choice of power train has only a modest influence on total and annualized CAPEX costs. This is due to the fact that the cost of the ship hull + other powertrain-independent systems make up most of the total CAPEX.

6.3.2 Operational expenditure

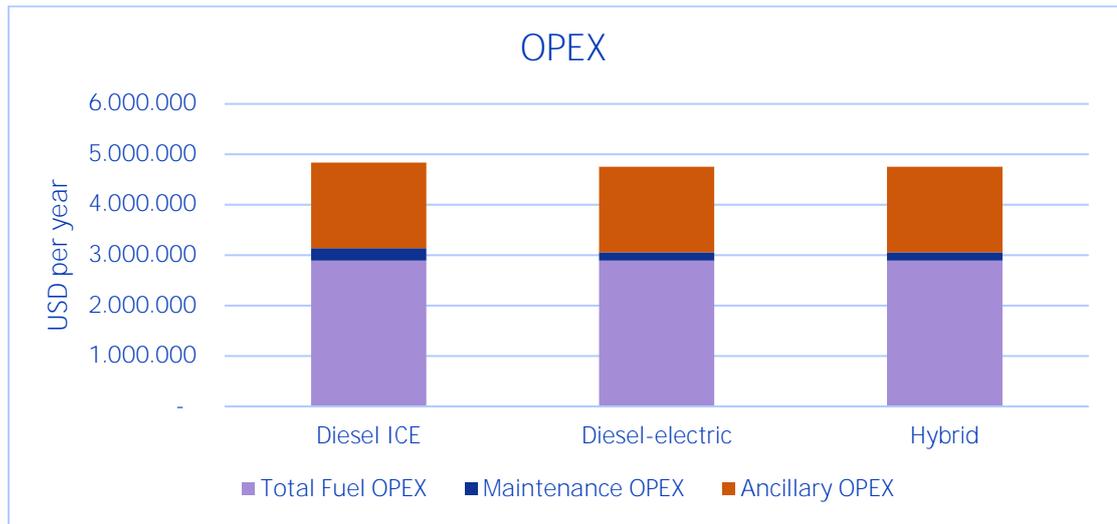


Figure 6-5: OPEX for the short sea transport vessel use case.

The Operational Expenditure consists mainly of Ancillary OPEX and fuel costs. As discussed in paragraph 4.8.1, fuel use is roughly the same regardless of power train type. Crew size and therefore ancillary OPEX are also the same. Maintenance costs are expected to be slightly lower for ICE-electric and hybrid configurations, but this has only a minor influence on total OPEX as shown in Figure 6-5.

6.4 Conclusion

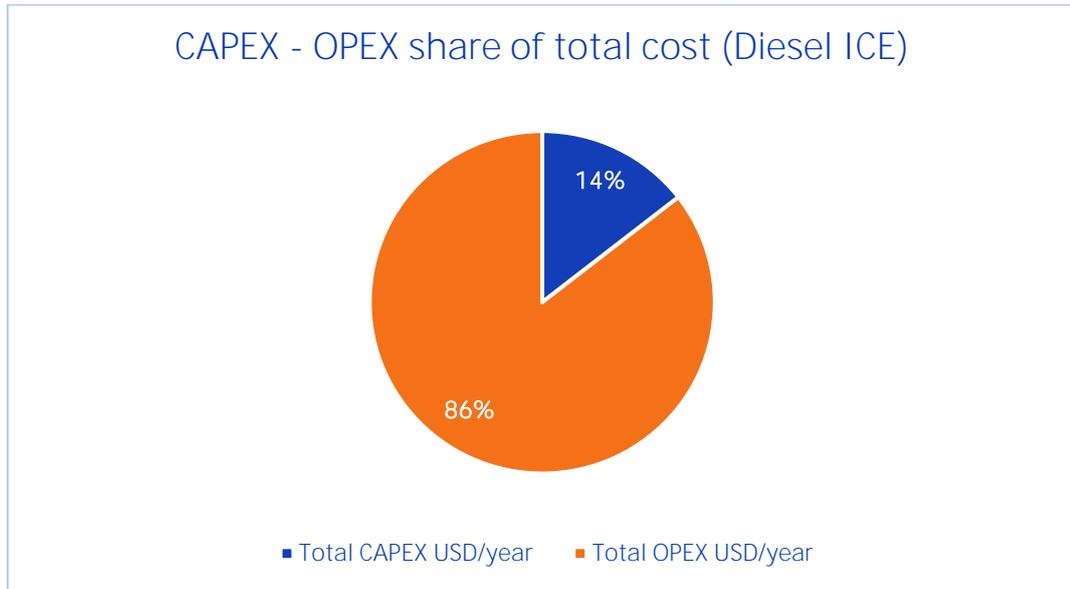


Figure 6-6: CAPEX - OPEX parts of total cost for the Diesel ICE propulsion system. The picture is very similar for the other propulsion system types.

The main costs of ownership for a general cargo vessel are the operating costs. They make up roughly 85% of annual costs. OPEX consists mainly of fuel cost and ancillary OPEX, a broad category of 'other costs' that includes crew cost. These are roughly equal for all three power train configurations. Maintenance costs are only a small fraction of operational expenditure. Therefore the choice of power train has little influence on overall OPEX.

As for CAPEX, the main category is the 'base CAPEX' which represents costs for the ship hull, structures, living quarters et cetera. These are the same for all vessels regardless of which propulsion system architecture is chosen. However, there are significant differences in cost between the different types of propulsion systems. CAPEX is lowest for the internal combustion propulsion system variant, and highest for the ICE-electric variant. However the differences between the alternatives are modest. Overall, total annual cost of ownership are very similar for all variants, with differences of only a few % of the total annual cost between the model results – less than the margin of error of such a general cost estimate.

7 Conclusions

TNO and MARIN have investigated the potential of using ICE-electric and hybrid ship propulsion systems to reduce fuel consumption and therefore emissions of greenhouse gases from maritime fuel use compared to a ICE-mechanical system. Battery assistance on the electric power supply has also been included, as well as control aspects of the electric drive line in real world dynamic load scenarios in seaway. The feasibility of the electrified propulsion concepts are verified against the impact on the ship design and the financial impact by means of a total cost of ownership estimation. Whereas the real impact of propulsion electrification is found to be very case specific, the goal of this study is to provide the sector with an overview of impact while considering electrification options.

Consequences of electrification on ship design and fuel use were studied for six types of reference ships, namely:

- Short Sea Transport Vessel
- Harbour Tugboat
- Offshore Supply Vessel
- Crew Tender Catamaran
- Trailing Suction Hopper Dredger
- Mega Motor Yacht

Battery assisted power optimization and sailing, dynamic performance in real world conditions and total cost of ownership were studied for the Short Sea Transport Vessel use case only.

We found advantages and disadvantages to using electric propulsion systems. They are summarised in Table 7-1 below. The success factor for ships with electric propulsion systems is a combination of all items listed. Optimizing an electric ship concept on a holistic approach can let all aspects contribute and even positively influence each other.

Some key point to mention are:

- Higher investment costs are expected for hybrid and ICE-electric systems
- System weight and volume can be of significant impact for the ICE-electric design, but it gives much more flexibility in the arrangement to counteract a lot of the weight effects.
- Complexity of the system increases with hybrid propulsion, but the impact on the ship design compared to ICE-mechanic system are limited.
- The electric motor for both hybrid and ICE-electric system design has significant benefits on the propulsion dynamics, as they can accelerate fast, can be reversed easily, allow wider operational speed ranges, can allow temporarily over-torque and can be controlled to very low rotation speeds for increased slow vessel speed control
- The ICE-electric platform benefits from high power redundancy and retrofit flexibility for example other alternative energy sources and batteries.

Table 7-1: Advantages and disadvantages of electrification, simplified to a plus or a minus.

	ICE-mechanical propulsion	Hybrid propulsion	ICE-electrical propulsion
Capital expense	+	-	--
Operational Availability	-	+	++
Maintenance	-	+	++
Air pollutants	+/-	+	+
Ship Arrangement	-	-	++
Refit Flexibility	-	+	++
Drive characteristics	+/-	+	++
Noise and vibration	-	+	++
System weight	+	-	--
System volume	+	+/-	-
Fuel saving potential	0	+/-	+/-
Drive line complexity	++	-	++

Electrification shows its impact on the weight and volume requirements of the machinery space. They increase in size requirements compared to the ICE-mechanical propulsion system by around 5-10% for hybrid systems and up to 60% for ICE-electric propulsion systems. Weight increases due to added machinery can be much more significant as electric motors, generators and power electronics are added. For hybrid vessels, an additional system weight up to 30% is estimated compared to ICE-mechanical propulsion. ICE-electric propulsion may even double or triple the system weight. These values are based only on key figures obtained from literature references and not on selected components.

The additional weight and volume is found to be a limiting factor for application of electric propulsion. Feasibility for the harbour tugboat and mega motor yacht is for that reason critical and for the crew tender vessel expected to be an impediment hard to overcome. For the larger vessels studied, short sea transport ship, offshore supply vessel and dredger, the volume and weight impact is not expected to be a critical factor.

Market survey confirms that the application of electric propulsion is suitable for dredgers, offshore supply vessels and tugs. General cargo vessels also show some electrification initiatives.

7.1 Fuel consumption

The electric power train consists of multiple power conversions which come with efficiency losses. However, the power can be smartly distributed over different energy sources, in such way that the equipment is running on better operational conditions, i.e. at higher efficiency. It has been investigated if the optimal loading strategy can counteract the additional conversion losses or even improve the total system efficiency. In order to do so, we have designed specific ICE-mechanical, ICE-electric and hybrid propulsion power and energy system architectures and created operational profiles for specific vessel use cases in order to evaluate the fuel use of these systems with a quasi-static model.

No significant fuel consumption increases were found compared to a mechanical diesel propulsion system, despite the power conversion losses inherent to (hybrid) electric PPE systems.

Significant savings in fuel use were found for the Harbour Tugboat (5%), the Offshore Supply Vessel (7%) and the Dredger Vessel (9%) use cases, at least for the assumed architectures and operational profiles. The other use cases do not show substantial savings or increases in fuel consumption. It must be noted that for the dredger, offshore supply vessel and general cargo vessel part of the improved performance was based on changing the propulsion type, which was allowed because of the electric drive characteristics.

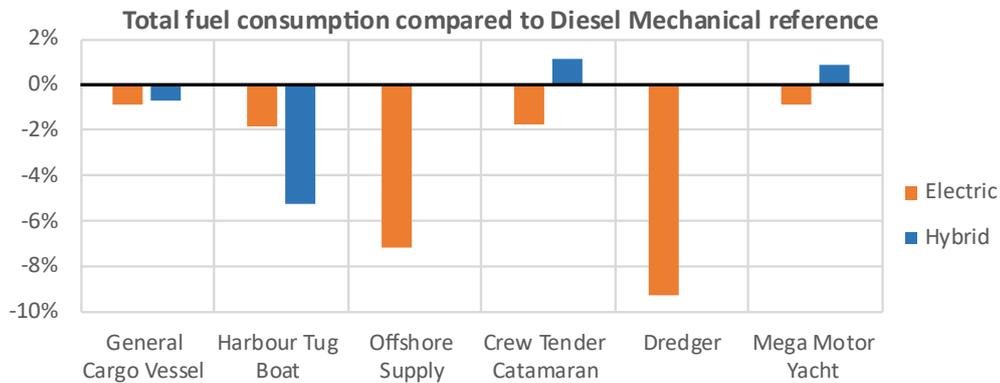


Figure 7-1: Relative comparison of quasi static simulation of fuel consumption for all use cases over their respective operational profile.

As expected, ships with wide operational ranges, or a large spread in operational power distribution, the electrified concepts were found most promising. The harbour tug boat has an operational profile with very low and very high loads and relative low auxiliary power demands. For this particular case, the hybrid solution found an interesting fuel reduction result. The dredger shows a high load profile which is based on both propulsion and payload equipment equally. Hence an ICE-electric system design shows most favourable. The offshore supply vessel case benefits both from low load operation as well as better propulsive efficiency by change of the propeller type. The crew catamaran and mega motor yacht did not show significant benefits regarding fuel use.

The results presented were based on a single use case with a single operational profile for each ship archetype. The study indicates the importance of taking the complete operational profile into account in order to understand the potential of fuel savings for an electric architecture. Actual savings for a specific ship design will depend strongly on the actual operational (part)load distribution and matching architecture design. The study gives a funded numerical argument on the potential of fuel savings for each vessel archetype. However, in order to give generic statements for the whole archetype class, wider investigations on the operational power distribution and variations in architecture design should be performed.

Advanced studies in real world conditions

The previous conclusions were drawn from the generic feasibility study based on key figures and literature as well as from quasi-static analysis of fuel consumption estimations. Other arguments from the market included potential benefits of electrified propulsion systems with regards to absorbing the fluctuating loads during realistic seaway conditions. To investigate this aspect, additional dynamic simulations were performed for multiple operational conditions, comparing the ICE-mechanic architecture with the ICE-electric architecture for the Short Sea Transport Vessel.

From these dynamic simulations the fuel consumption per nautical mile was calculated, for a chosen combination of speed, wind and see state.

Large variations were found between the 2 concepts. To find an improved estimation of realistic operational conditions for the vessel, voyage simulations were studied based on actual hindcast data over the operational profile. These conditions have been used as input for a large set of simulations resulting in the fuel consumption predictions of the two architectures.

From this the following could be concluded:

- Under modest circumstances the two concepts are performing comparable.
- Under heavy circumstances the mechanical concept is more fuel efficient. The most severe conditions simulated, sailing in Sea State 6 at 7 knots in head-waves, showed a 10% better fuel consumption.
- Under very mild circumstances the electric concept is more fuel efficient. Slow sailing in calm water showed a reduction in fuel consumption of up to 26%, which seems an extreme beneficial condition.
- The conditions have a significant impact on the experienced fuel consumption. To investigate this further a large variety of conditions was collected by varying operational routes with statistical weather data and applying a range of target propulsion power settings,. Based on these representative conditions the trends were confirmed as seen from the individual studied conditions. By taking the average of the simulations per group of power settings, the fuel consumption reduction by the ICE-electric architecture is around 3.4% at 50% propulsion power which dropped to -2.3% for 80% propulsion power.

7.2 Batteries

The direct energy efficiency improvements are minimal from battery assisted power supply for an ICE-electric system design of a general cargo vessel.

However, there are other benefits from installing a battery:

- Enabling silent and emission-free operation near ports
- Enabling designs with fewer or smaller GenSets

The downsized architecture, where one GenSet is removed and replaced by a battery, achieves similar performance and efficiency as the full ICE-electric setup. This can pay back some of the battery investment cost. Using shore-based charging could increase operational flexibility, and save cost by enabling the use of a battery with less storage capacity.

7.3 Total cost of ownership

For a general cargo vessel, operating costs make up roughly 85% of total annual costs of ownership. OPEX consists mainly of fuel cost and ancillary OPEX, a broad category of 'other costs' that includes crew cost. The report concludes that the type of power train has little influence on the OPEX for the researched short sea transport vessel case.

As for CAPEX, the largest part of it is the so-called 'base CAPEX' which represents costs for the ship hull, structures, living quarters et cetera. These are the same for all vessels regardless of which propulsion system architecture is chosen. Significant differences exist between the CAPEX for different types of propulsion systems. This figure is lowest for the internal combustion propulsion system variant, and highest for the ICE-electric variant. However, these differences are modest when compared to the total cost of ownership.

Overall, total annual cost of ownership are very similar for all variants, with differences of only a few % of the total annual cost between the model results – less than the margin of error of such a general cost estimate.

7.4 Suggestions for further research

- The simulation done by both MARIN and TNO were performed with simplified Power Management System (PMS) and Genset control approaches. The control strategies should be developed in more detail along with more advanced propulsion control strategies to study if further improvements in efficiency are achievable.
- The dynamic fuel efficiency study should be extended to consider the full operational profile (instead of only specific conditions) and a hybrid propulsion system should be added to the comparison. This will give conclusive evidence on whether it is necessary to perform dynamic simulations to calculate fuel efficiency, or whether quasi-static calculations are sufficient.
- The evaluation of all architectures should be considered in the context of the complete usage envelope of the vessels in order to draw concrete conclusions on the suitability of the architecture for different operating conditions. This also includes a wider selection of different propulsion system architectures per use case.
- Batteries were only studied in combination with the General Cargo Vessel, but may be more attractive for other vessel archetypes, e.g. the dredger and offshore supply archetypes.
- Investigation of shore-based charging infrastructure to support charging of battery packs when the vessel is docked. This would enable down-sizing of battery packs while maintaining a 12 mile travel distance requirement, thereby reducing overall investment costs. Such an investigation should also include the investment impact for such a facility.
- Investigation of total cost of ownership for tug boats and dredgers. The potential fuel savings found for these vessel types in chapter 5 indicate that electrification could possibly lead to significantly lower TCO for these ships.
- Investigate total cost of ownership of propulsion systems combined with batteries. Simulation results from chapter 5 show significant fuel and CAPEX savings are possible.

References

- [1] “Revised GHG reduction strategy for global shipping adopted,” IMO, July 2023. [Online]. Available: <https://www.imo.org/en/MediaCentre/PressBriefings/pages/Revised-GHG-reduction-strategy-for-global-shipping-adopted-.aspx>.
- [2] C. Bekdemir, C. Veldhuis and J. Harmsen, “Vervolgstappen validatie methodieken t.b.v. transitie naar emissieloze scheepvaart,” MARIN; TNO, Wageningen, 2020.
- [3] Clarkson's, “World Fleet register,” 2025. [Online]. Available: <https://www.clarksons.net/wfr/#!/login/?returnPath=fleet>.
- [4] MARIN, “Webinar Ship Power and Energy Concepts,” 2021. [Online]. Available: <https://www.marin.nl/en/events/webinar-ship-power-and-energy-concepts>.
- [5] MARIN, “ESSF-SAPS Sustainable Power portal,” [Online]. Available: <https://sustainablepower.application.marin.nl/>.
- [6] MARIN, “ZERO | MARIN: General Assembly 3 [participants access only],” 26 January 2023. [Online]. Available: <https://www.marin.nl/en/jips/zero#GA-3-January-26-2023>. [Accessed 10 12 2025].
- [7] Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, “NavigaTE to Zero - Modelling of the maritime decarbonization,” 2021.
- [8] H. Moon, W. Park and T. Hendrickson, “Exploring the cost and emissions impacts, feasibility and scalability of battery electric ships,” *Nature Energy*, vol. 10, pp. 41-54, 2025.
- [9] N. R. Ammar and I. S. Seddiek, “Hybrid/dual fuel propulsion systems towards decarbonization: Case study container ship,” *Ocean Engineering*, vol. 281, 2023.
- [10] B. Jeong, H. Jeon, S. Kim, J. Kim and P. Zhou, “Evaluation of the Lifecycle Environmental Benefits of Full Battery Powered Ships: Comparative Analysis of Marine Diesel and Electricity,” *Journal of marine science and engineering*, vol. 8, no. 8, 2020.
- [11] E. Lalonde, “Explained: Environmental impact categories,” Apr 2025. [Online]. Available: <https://helpcenter.ecochain.com/en/articles/9588517-explained-environmental-impact-categories>.
- [12] H. J. Byongug Jeong, Lee, Wookjae, C. Park, S. Ha, D. K. Kim and N.-K. Cho, “Is electric battery propulsion for ships truly the lifecycle energy solution for marine environmental protection as a whole?,” *Journal of Cleaner Production*, vol. 355, 2022.
- [13] P. T. Aakko-Saksa, K. Lehtoranta, N. Kuittinen, A. Järvinen, J.-P. Jalkanen, K. Johnson, H. Jung, L. Ntziachristos, S. Gagné, C. Takahashi, Karjalainen, Panu, T. Rönkkö and H. Timonen, “Reduction in greenhouse gas and other emissions from ship engines: Current trends and future options,” *Progress in Energy and Combustion Science*, vol. 94, 2023.
- [14] A. Ebba, “Challenges and opportunities for decarbonising developing maritime nations’ domestic shipping via green electrification, Indonesia as an exemplary case,” Master’s Thesis, 2022.
- [15] T. Walraven, A. van der Velde and J.-K. de Ronde, “A HYBRID ELECTRIC DC POWER GRID A future-proof solution for dredging vessels,” *SWZ Maritime*, pp. 10-17, November 2023.
- [16] Royal Institute of Naval Architects, Significant Small Ships of 2023, London, 2023.

- [17] European Maritime Safety Agency (EMSA), “Electrical Energy Storage for Ships,” 05 05 2020. [Online]. Available: <https://ktn-csbs-media.s3-eu-west-1.amazonaws.com/62714fed-93be-4ee3-82d4-3195419cc09b/studyelectricalenergystorageforships.pdf>. [Accessed 16 11 2025].
- [18] PBL - Netherlands Environmental Assessment Agency, “Assessment of the Environmental Impacts and Health Benefits of a Nitrogen Emission Control Area in the North Sea,” 2012.
- [19] M. Godjevac, J. Drijver, L. d. Vries and D. Stapersma, “Evaluation of losses in maritime gearboxes,” 2016.
- [20] C. Bajracharya, M. Molinas, J. Suul and T. Undeland, “Understanding of tuning techniques of converter controllers for VSC-HVDC,” 2008.
- [21] L. Harnefors, “Model-based current control of AC machines using the internal model control method,” *IEEE Transactions on Industry Applications*, vol. 34, no. 1, pp. 133-141, 1998.
- [22] H. Polinder, F. van der Pijl, G.-J. de Vilder and P. Tavner, “Comparison of Direct-Drive and Geared Generator Concepts for Wind Turbines,” *IEEE*, vol. 21, no. 3, pp. 725-733, September 2006.
- [23] Z. Jin, L. Meng, J. Guerrero and R. Han, “Hierarchical Control Design for a Shipboard Power System With DC Distribution and Energy Storage Aboard Future More-Electric Ships,” *IEEE transactions on industrial informatics*, vol. 14, no. 2, pp. 703-714, 2018.
- [24] H. Yasukawa and Y. Nakayama, “6-DOF motion simulations of a turning ship in regular waves,” in *MARSIM International Conference on Marine Simulation and Ship Manoeuvrability*, Panama City, 2009.
- [25] J. Moulijn, “Propeller load variations for maneuvering ships in waves,” in *Eighth International Symposium on Marine Propulsors*, Berlin, 2024.
- [26] W. Blendermann, “Wind Loading of Ships – Collected Data From Wind Tunnel Tests in Uniform Flow,” Institut für Schiffbau der Universität Hamburg, 1996.
- [27] S. Qazi, P. Venugopal, G. Rietveld, T. B. Soeiro, U. Shipurkar, A. Grasman, A. J. Watson and P. Wheeler, “Powering Maritime: Challenges and prospects in ship electrification,” *IEEE Explore*, 2023.
- [28] H. Mahdi, T. Østrem and B. Hoff, “A Review of Power Converters for Ships Electrification,” *IEEE Transactions on Power Electronics*, vol. 38, no. 4, 2023.

Signature

TNO) Mobility & Built Environment) The Hague, 18 December 2025

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Author

Appendix A

Description of models

A.1 General Cargo Vessel – Electrical Propulsion model

A.1.1 Architecture

The General Cargo Vessel with electrical propulsion uses a Permanent Magnet Synchronous Machine (PMSM), with a fixed coupling with the propeller through a gearbox. After the quasi-static approach the design for the ICE-electric architecture is further improved for efficiency by implementing a DC distribution with variable speed generator sets. The propeller is of the fixed pitch type. The system is powered by four medium-speed Diesel Gensets, three of which are rated at 1300 kW and one at 600 kW. The layout is depicted in Figure A-1.

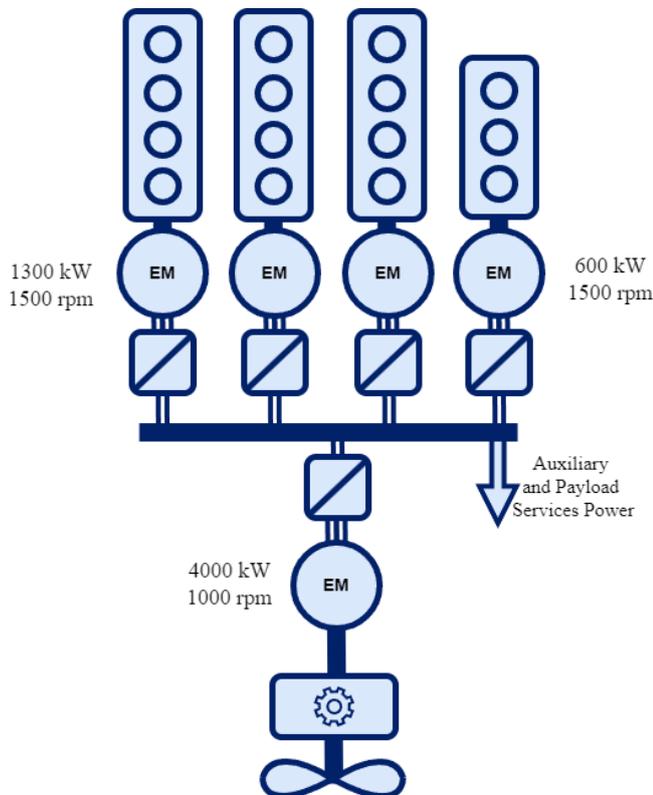


Figure A-1: Architecture of the PPE system of the General Cargo Vessel with electrical propulsion.

A.1.2 Control Structure

The central control and automation system, shown in Figure A-2 consists of two parts:

1. 4110 Propulsion Management System (PropMS) – Assures the availability of the propulsion system.

The PropMS is responsible for defining the propulsion configuration and mode (in this case this is not used because the propulsion system only has an electric drive). Furthermore, the PropMS limits the propulsion power to the available power of the system.

2. 4120 Power Management System (PMS) - Assures the availability of demanded electrical power within the power plant limitations. The PMS is responsible for executing the load sharing between sources by defining the appropriate control parameters for the lower control layers.

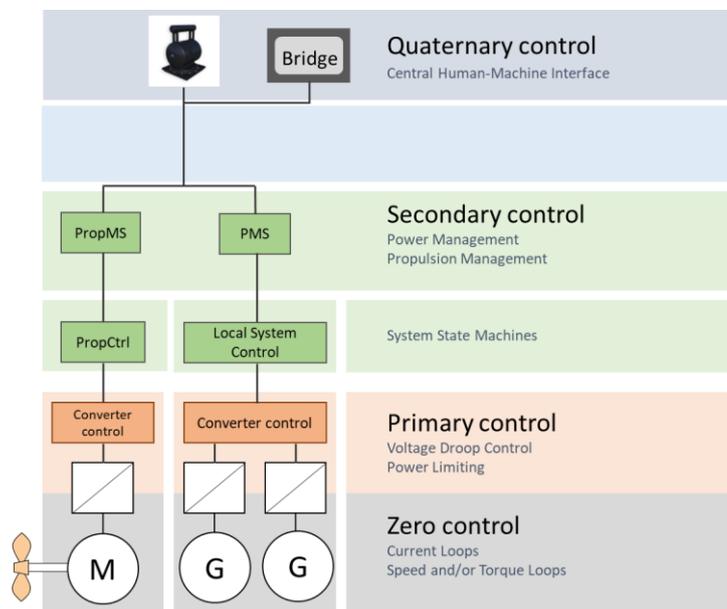


Figure A-2: Structure of the Control and Automation System

In the control hierarchy, the PMS and PropMS deliver setpoints to the local Secondary Controllers that are distributed across the different systems. These modules are included in the system models of the power producing systems. The Local Secondary Controllers interface the Primary Control with the Central Secondary Control and also implement the System State Machines. For all systems a common state machine is implemented as shown in Figure A-3.

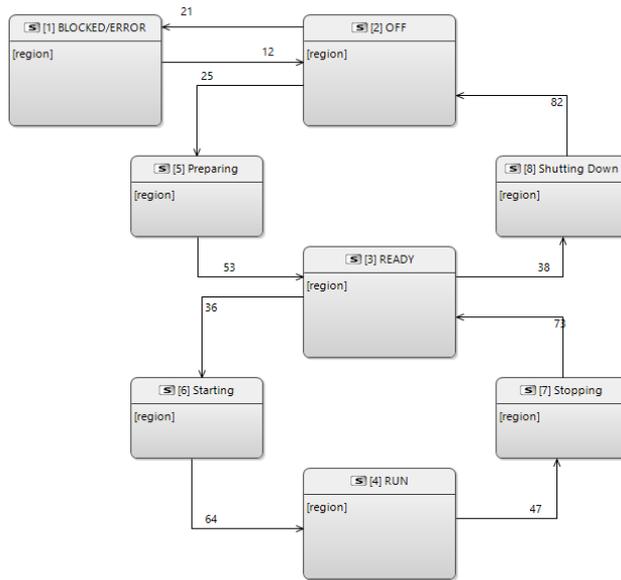


Figure A-3: Generic State Machine for Local System Controllers for all systems

The Primary Control is responsible for the actual control of the system. Here, voltage droop control is used as the control approach in order to balance the load between producers. A description of this approach can be found in 0. The droop control acts on the parameters defined by the PMS.

A.1.2.1 4120 Power and 4110 Propulsion Management System (PMS and PropMS)

There are two functions being performed in the PMS:

1. Calculating the individual system states – Depending on the required power, the PMS sets the required States for each of the systems in the PPE System.
2. Set Droop Parameters – the PMS sets the droop parameters for the Power Control of each of the systems of the PPE system.

The Propulsion Management System manages the propulsion load to ensure that the requested power does not exceed the available power. It also relays the speed setpoint from the user to the propulsion system. The schematic of the PMS is shown in Figure A-4. The Control Action is calculated on the basis of a state machine that is shown in Figure A-5.

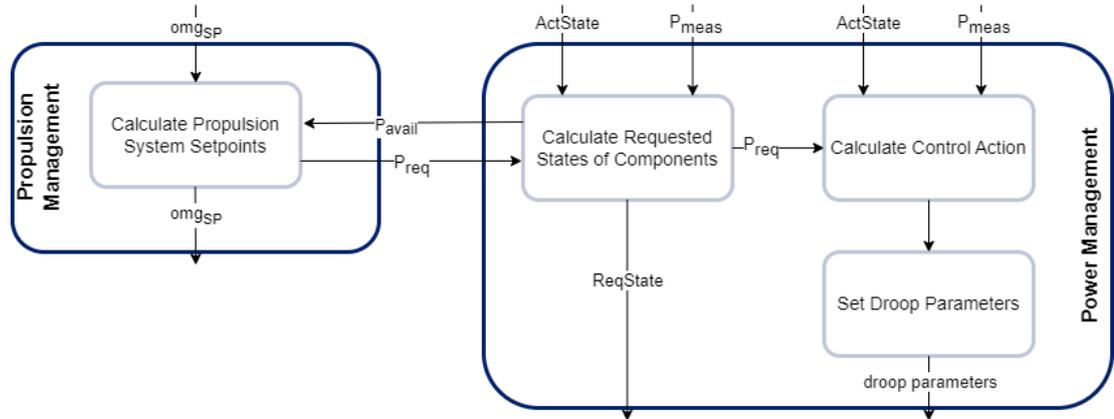


Figure A-4: Schematic of the Power and Propulsion Management System.

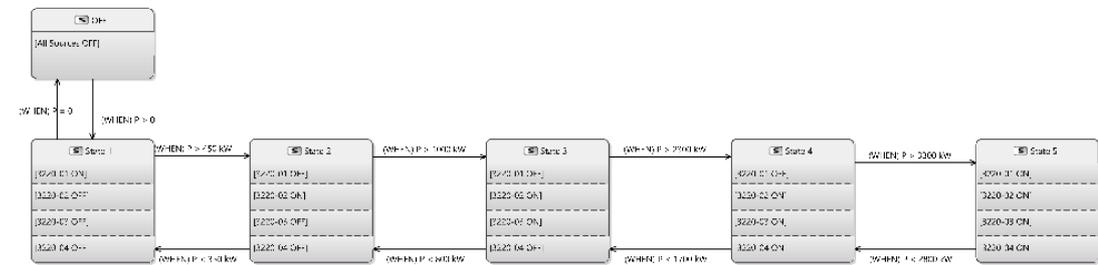


Figure A-5: State Machine used in the PMS.

The droop parameters used for the system is shown in Table A-1.

Table A-1: Droop Parameters for the individual systems for General Cargo Vessel.

Parameter	Description	unit	3220-01 Genset	3220-02/03/04 Genset
U_ref	Reference voltage for the calculation of the droop resistance	V	1000	1000
U_droop	Nominal voltage droop	V	80	80
P_nom	Nominal system power	kW	600	1300
P_BUS_max	Maximum power output to the DC Bus	kW	600	1300
P_BUS_min	Minimum power output to the DC Bus	kW	0	0
I_BUS_max	Maximum current to the DC Bus	A	650	1450
I_BUS_min	Minimum current to the DC Bus	A	0	0
P_ramp_pos	Maximum allowed power positive ramp	kW/s	120	260
P_ramp_neg	Maximum allowed power negative ramp	kW/s	-120	-260

A.1.2.2 Propulsion System

The propulsion system includes a Permanent Magnet Synchronous (PMSM) drive motor fed by a DC supplied frequency drive controlled by a speed controller. The choice of a PMSM was made due to its higher efficiency. Mechanical power from the electric motor is transferred through a reduction gearbox to the shaft line. Table A-2 contains the main design parameters for the Propulsion System.

Table A-2: Main parameters for the Propulsion System.

Parameter	Description	unit	2300 EM Drive Systems
	Type of Electric Machine		PMSM
P_nom	Nominal Machine Power	kW	4000
n_nom	Nominal Rotational Speed	rpm	1000
I_GB	Gearbox ratio		8.475

The rotational dynamics of the rigidly coupled inertia's (propeller, shaftline, gearbox, electric motor) and the losses in the shaftline and gearbox are captured in the Mechanical Power Transmission model. The losses are modelled using the torque loss model further elaborated on in [19]. Using the parameters in Table A-3 the resulting efficiency map can be viewed in Figure A-6.

Table A-3: Model Design Parameters for the Mechanical Power Transmission.

Parameter	Description	unit	2200 Mechanical Transmission
J_sl	Shaft Line Inertia	Kg.m ²	30
J_gb	Gearbox Inertia (propeller side)	Kg.m ²	900
M_nom	Nominal Torque rating	kNm	375
n_nom	Nominal Shaft line Rotational Speed	rpm	120
M_loss_nom	Torque loss in the nominal operating point	kNm	11.25
a	Torque dependent loss factor		0.5
b	Speed dependent loss factor		0.4
b	Constant loss factor		0.1

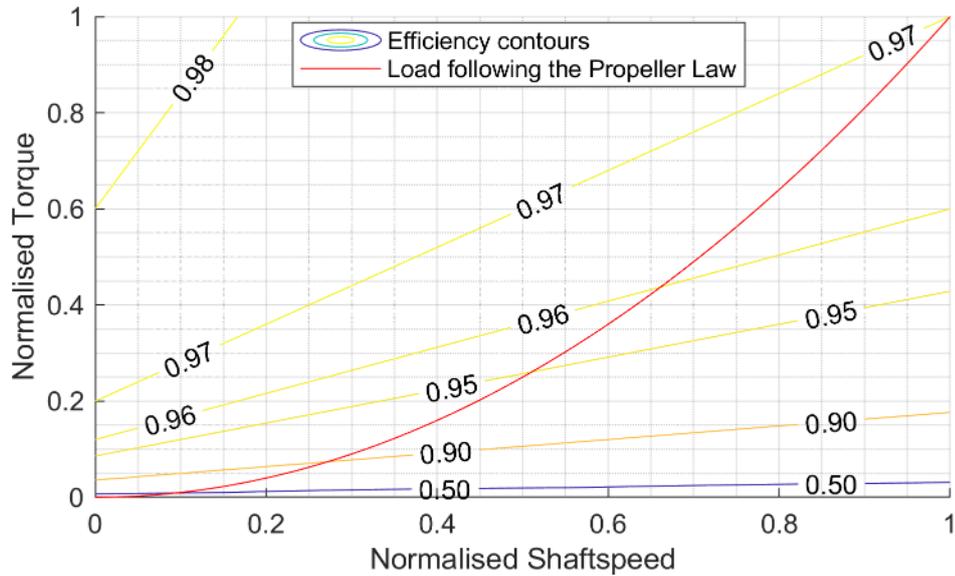


Figure A-6: Efficiency contours of the torque loss model with indicated in red the load following a cubic propeller law.

The model used for the PMSM in this study is widely reported in literature [19]. The parameters used in the model are detailed in Table A-4.

Table A-4: Model Parameters for the PMSM.

Parameter	Description	unit	2300 EM Drive Systems
M_nom	Nominal Machine Torque	kNm	38
n_nom	Nominal Rotational Speed	rpm	1000
V_nom	Nominal Voltage (3-phase rms)	V	690
p	Pole Pairs		6
J	Rotor Inertia	kg.m ²	1128
Rs	Stator Resistance	mΩ	6.54
Ld	D- axis Inductance	mH	0.165
Lq	Q - axis Inductance	mH	0.165

The machine is operated in speed control mode, the Propulsion Management System converts the User Telegraph to a required propeller speed setpoint. A cascaded speed-torque controller is used to control the speed of the PMSM. The outer speed control loop is tuned using the symmetric optimum method [20], while the inner torque controller is tuned using the Internal Model Control method [21].

The resulting controller performance with a selected rise time of 10 s is shown in Figure A-7 and it can be observed that the response matches the required rise time (10% to 90% of setpoint). This simulation is performed with a torque load that varies quadratically with rotational speed.

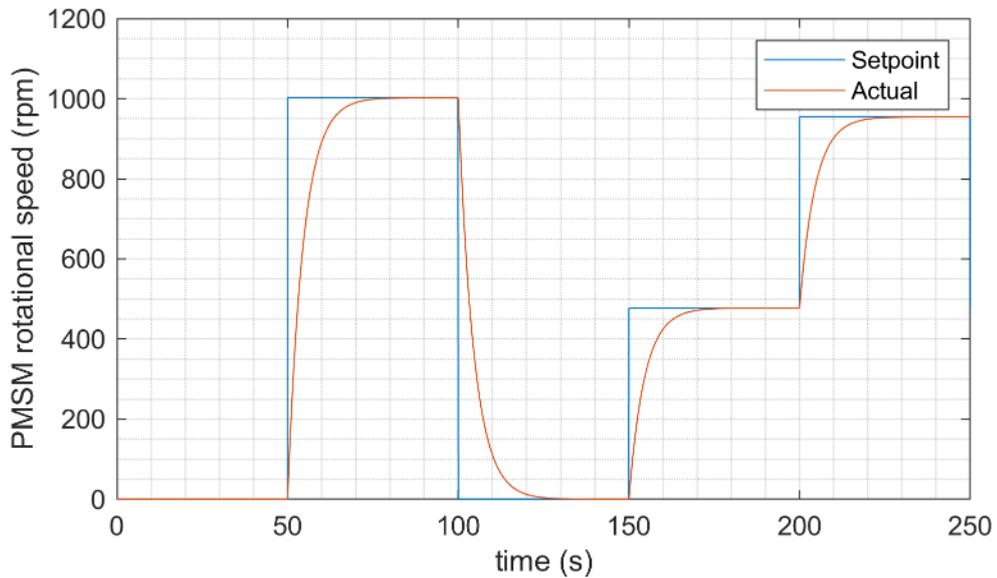


Figure A-7: Response of the Electric Machine to a step in the reference torque. The rise time with matches the design point of 10 s.

For the converter losses, a simplified converter loss model is used as described in [22] The nominal efficiency of the converter is assumed to be 98%. Table A-5 gives an overview of the nominal efficiencies of the components of the Electric Propulsion Drive System.

Table A-5: Estimated Efficiencies of the components of the Electric Propulsion Drive System

Parameter	Description	unit	Electric Propulsion Drive Systems
η_{PMSM}	Nominal Electric Machine Efficiency	%	97
η_{conv}	Nominal Converter Efficiency	%	98
η_{mech}	Nominal Mechanical Power Transmission Efficiency	%	97

The efficiency map of the complete Electric Propulsion Drive system is shown in Figure A-8.

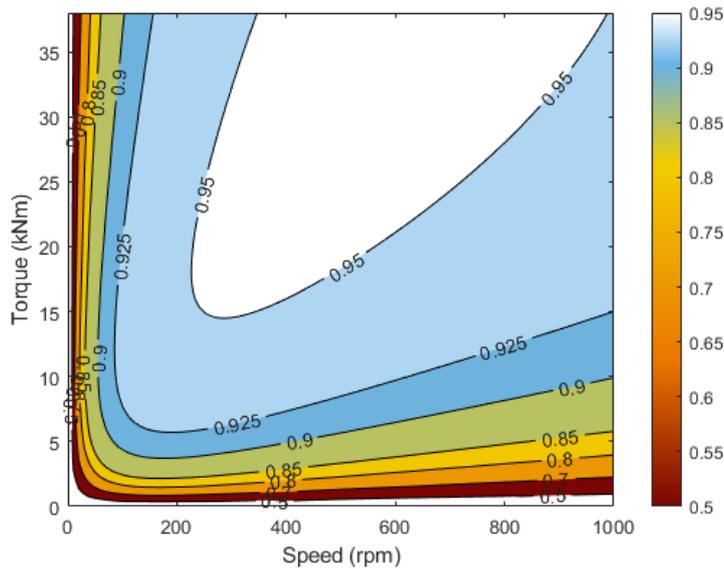


Figure A-8: Efficiency map of the Electric Propulsion Drive System including losses in the PMSM and Converter

A.1.2.3 Variable speed generator models

The ship contains two types of variable speed generator sets. They differ in power and according component sizing, but have the same principal layout.

Each ICE Generator system model includes an ICE, an Electric Machine that in this case is a PM Synchronous Machine, a Converter that in this case is an AC-DC Converter and a Local System Controller as shown in Figure A-9.

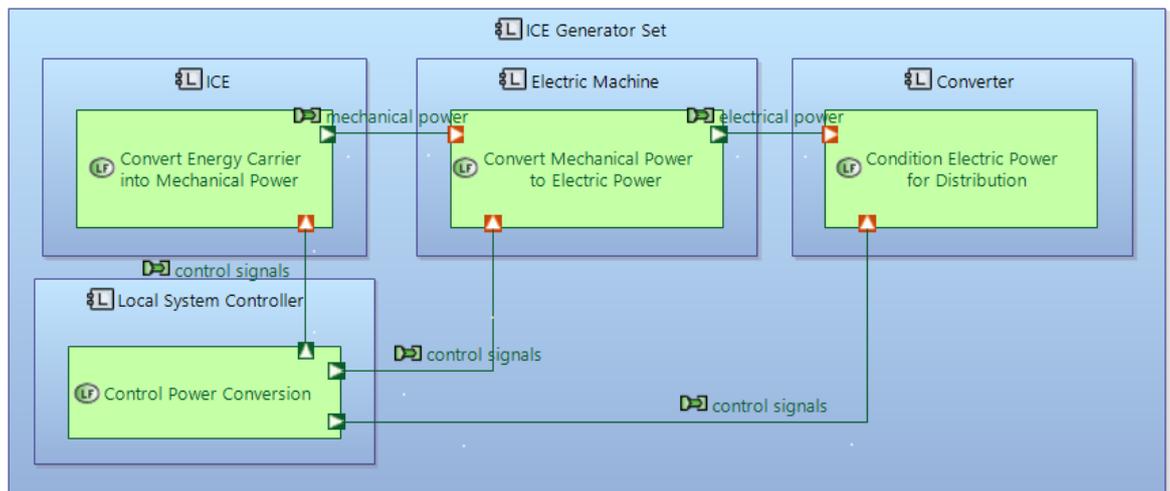


Figure A-9: Logical Architecture of the ICE Genset including the principal components and principal functions.

The ICE model can simulate the behaviour of the internal combustion engine produces by calculating the torque based on load input, for which it calculates the required fuel amount. Through combustion represented by a Wiebe model, this fuel is converted to useful work. The electric machine uses a Simplified Permanent Magnet Electrical Machine model. The model uses the steady-state phasor approach. The rotational dynamics are calculated in a separate shaft block. The converter uses an averaged model of an AC-DC Converter.

This is modelled for direct connection to a DC Bus. The capacitance of the converter is accumulated at the DC-Bus and the resultant voltage on the Bus is the output voltage of the converter. The Local System Controller handles the state machine of the ICE Genset system. The state machine is identical to the Generic State Machine described in A.3. Further, the Local System Controller includes the Droop Controller that is responsible for generating the control setpoints for the system, and the ICE control.

The Physical Architecture developed for the PPE system indicates one ICE Genset of type 3220-01 (600kWe output) and three gensets of type 3220-02 (1300kWe output). The parameters for these models are collected in Table A-6 and Table A-7.

Table A-6: Model Parameters for 3220-01.

DESIGNATION	SYMBOL	MAGNITUDE	UNIT
ICE			
Nominal Output Power	p_{ICE}^{nom}	632	kW
Nominal Speed	n_{ICE}^{nom}	1800	rpm
Moment of Inertia	J_{ICE}	14	kg.m2
Electric Machine			
Nominal Output Power	p_{EM}^{nom}	600	kW
Nominal Stator Voltage (line)	U_{line}^{nom}	990	V
Nominal Speed	n_{EM}^{nom}	1600	rpm
Moment of Inertia	J_{EM}	22	kg.m2
Pole-Pairs	p	1	-
AC-DC Converter			
Output Capacitance	C	10	mF

Table A-7: Model Parameters for 3220-02.

DESIGNATION	SYMBOL	MAGNITUDE	UNIT
ICE			
Nominal Output Power	p_{ICE}^{nom}	1368	kW
Nominal Speed	n_{ICE}^{nom}	1600	rpm
Moment of Inertia	J_{ICE}	19.95	kg.m2
Electric Machine			
Nominal Output Power	p_{EM}^{nom}	1300	kW
Nominal Stator Voltage (line)	U_{line}^{nom}	990	V
Nominal Speed	n_{EM}^{nom}	1600	rpm
Moment of Inertia	J_{EM}	36	kg.m2
Pole-Pairs	p	1	-
AC-DC Converter			
Output Capacitance	C	10	mF

When the ICE Genset system is in the FIRING state, the control approach applied is shown in Figure A-10. The PMS set the power setpoint for optimal PPE system operation via the droop parameters. The power to be fed to the DC Grid is set by the Electric Machine and Converter. This is translated into a current setpoint for the AC-DC converter and the Electric Machine, and a speed setpoint for the ICE. The current setpoint results in a torque at the input shaft of the electrical machine which has to be supplied by the ICE. The speed-controller of the ICE makes sure, through the load input of the ECU, that the required amount of fuel is supplied to deliver this torque at set speed.

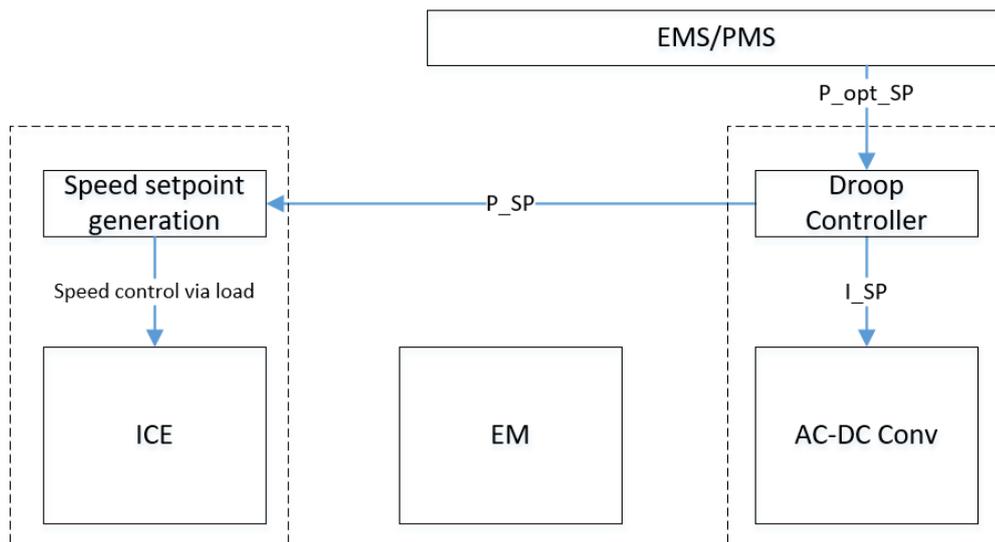


Figure A-10: Schematic for the control approach followed in the Local System Controller of the ICE Gensets.

For a variable speed generator the calculation of a speed setpoint has to ensure that the requested power is delivered at with a good response, at high efficiency, and for durability and noise and vibration reasons, with a limited variation in speed. For this an algorithm was developed which chooses an rpm setpoint at which the requested power can be delivered at around 70% load. This value is a trade-off between engine efficiency and response. At the chosen value most engines are close to their highest efficiency, while there is still margin to deliver more power without the need of a speed increase. As long as the requested power is not strongly varying, the speed setpoint is only slowly updated to keep engine load at the target value. In this situation the occurring faster variations can be handled by changing the engine load. In case of a severe change in requested power, the speed setpoint will be updated much faster. This ensures the requested power can be delivered within a reasonable response time.

The performance of the ICE Genset with this control approach is shown by setting a 0-100% load step on the system.

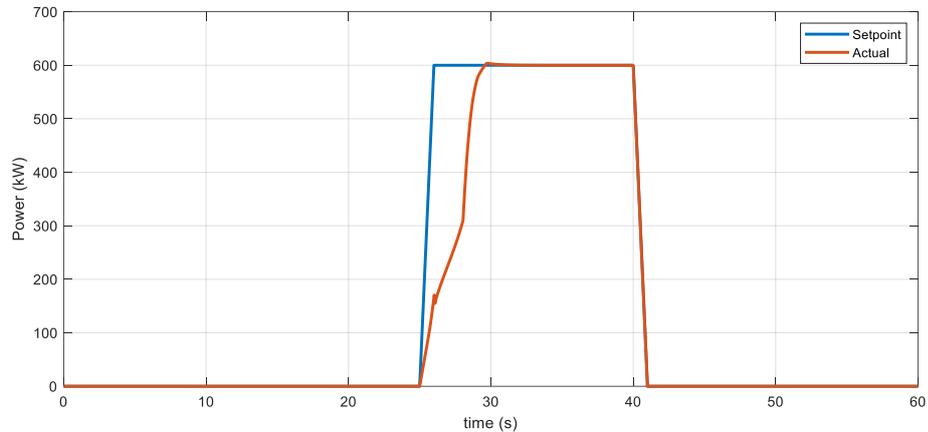


Figure A-11: Genset response for a step in Power Request at $t = 25$ s. The control limits the power output while the ICE accelerates to the new speed setpoint. Then the power output is also increased to meet the demand.

A.2 General Cargo Vessel – Mechanical Propulsion model

The following part describes the model for the ICE-Electric architecture of the General Cargo Vessel.

A.2.1 Architecture description

The General Cargo Vessel with mechanical propulsion is powered by a medium speed engine, with a fixed coupling with the propeller through a gearbox. The propeller is of the controllable pitch type and ducted. To achieve the desired speed of the vessel, the propeller pitch is adjusted while the speed of the propulsion engine remains constant. The layout is depicted in Figure A-12. Through a Propulsion Shaft Generator connected to the gearbox, a generator is powered. This delivers electric power for auxiliaries and payload. In situation where the propulsion engine is not running (i.e. mooring) electric power can be delivered by two identical high-speed diesel gensets. These gensets are not included in the current dynamic modelling.

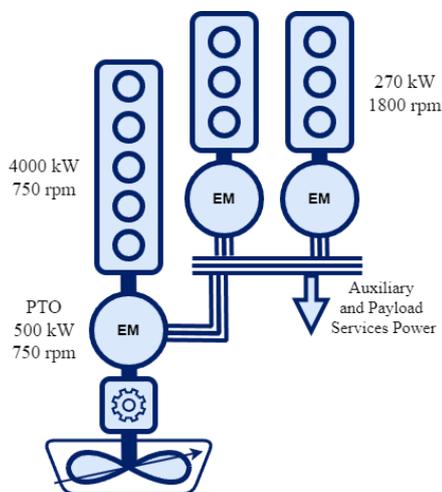


Figure A-12: Architecture of the PPE system of the General Cargo Vessel with mechanical propulsion

The simulation model includes the propulsion engine, the gearbox, inertia of the propulsion shaft, the PSG electrical shaft machine and its control.

A.2.2 Control Structure

The central control and automation system for this architecture is identical in structure to that defined in §A.1.2. The Propulsion Management System delivers the speed setpoint to the Propulsion ICE. For the test cases performed in this study, the electric power is delivered by the shaft machine alone acting as a stand-alone generator. Therefore, no additional Power Management system has currently been modelled.

A.2.3 Propulsion engine model

The propulsion power is provided by a medium speed Diesel engine operating at constant speed. This engine is modelled using a dynamic engine model, providing mean value output torque, based on a Wiebe combustion representation.

Table A-8: Main properties of the propulsion engine for General Cargo Vessel-Mechanical.

DESIGNATION	SYMBOL	MAGNITUDE	UNIT
ICE			
Nominal Output Power	P_{ICE}^{nom}	4000	kW
Nominal Speed	n_{ICE}^{nom}	750	rpm
Moment of Inertia	J_{ICE}	485	kg.m ²
Nr of cylinders	$Engine_I$	8	-
Swept volume / cylinder	$Engine_V$	32.2	[l]
Combustion type		Compression ignited, single fuel	-
Fuel		LFO	-

The output power and efficiency of the model are shown in Figure A-13. They are only plotted for the small range around 750 rpm, which is the designed operating speed of this engine. It can be recognised that output power is linearly scaled over engine-load. It is made clear that efficiency is best at maximum engine load, while it strongly decreases at a load below 50%. A more detailed overview of the efficiency map is used in the results shown in chapter 5.2.2.

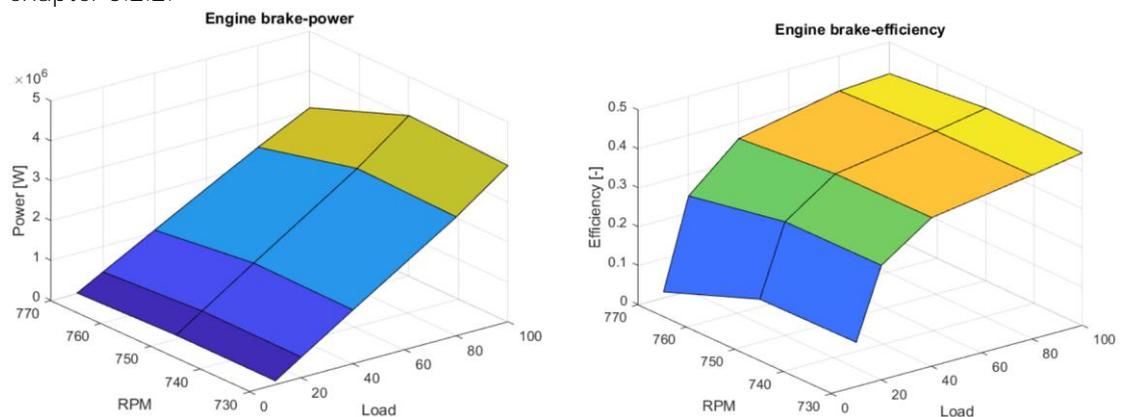
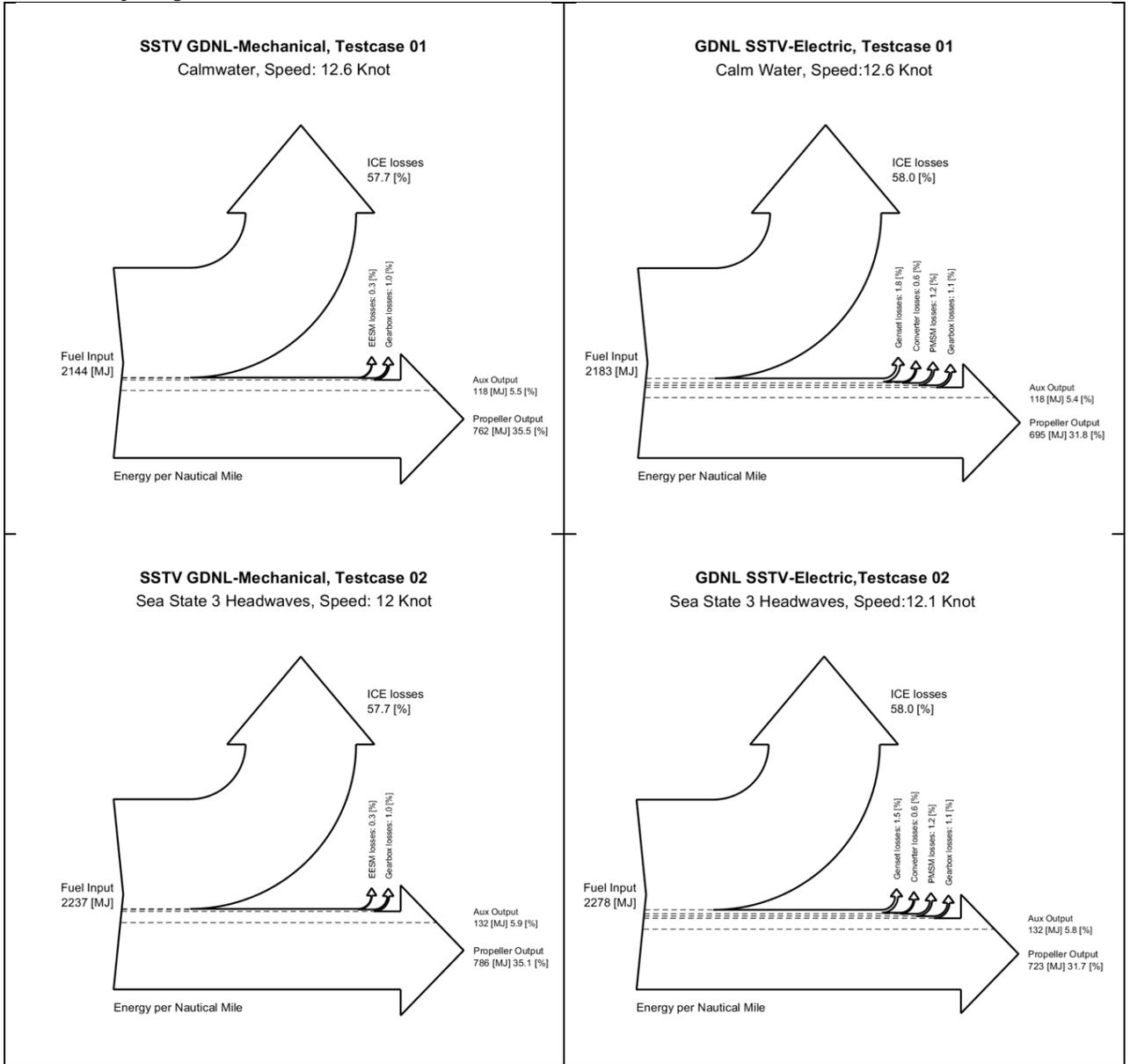
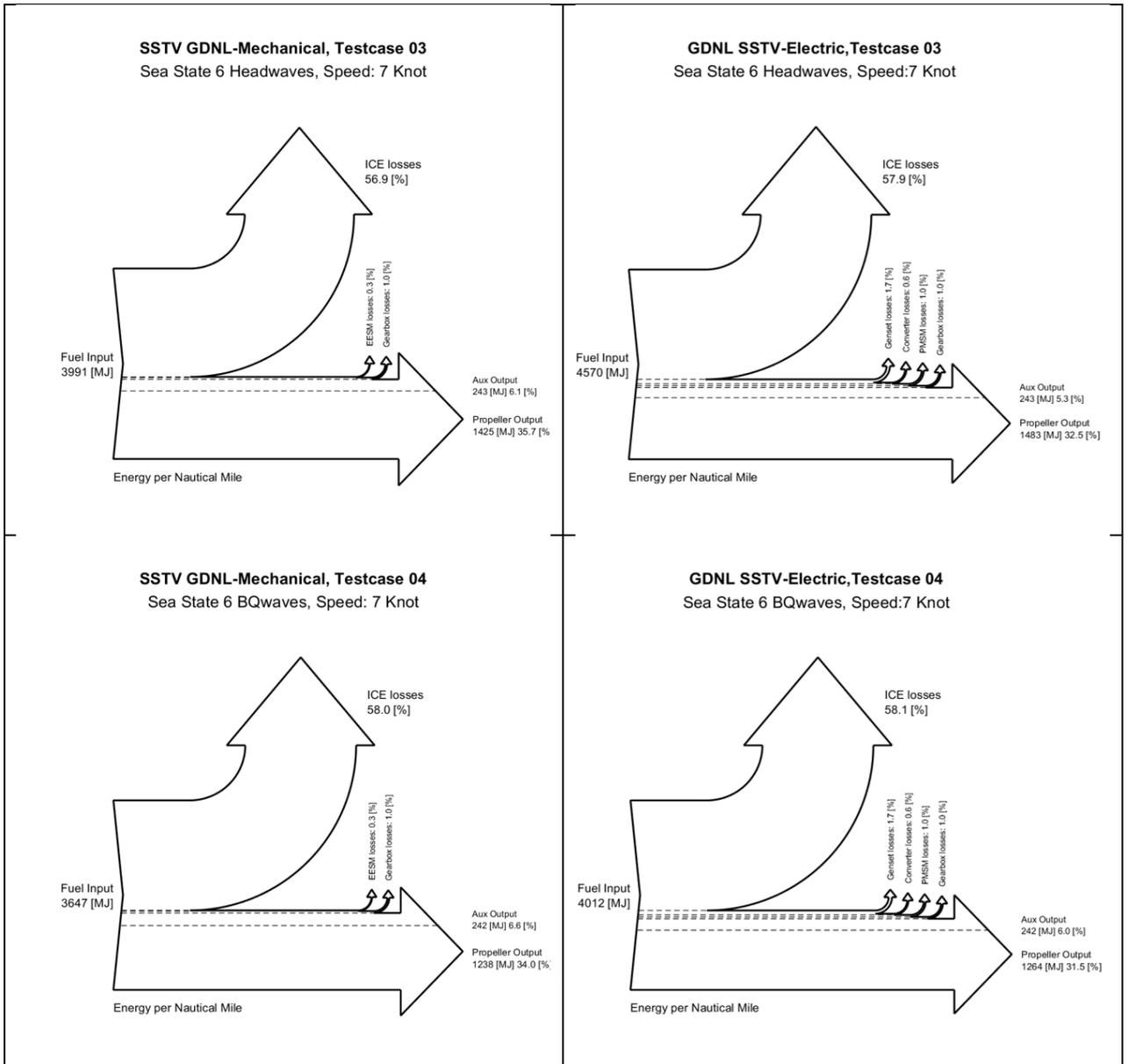


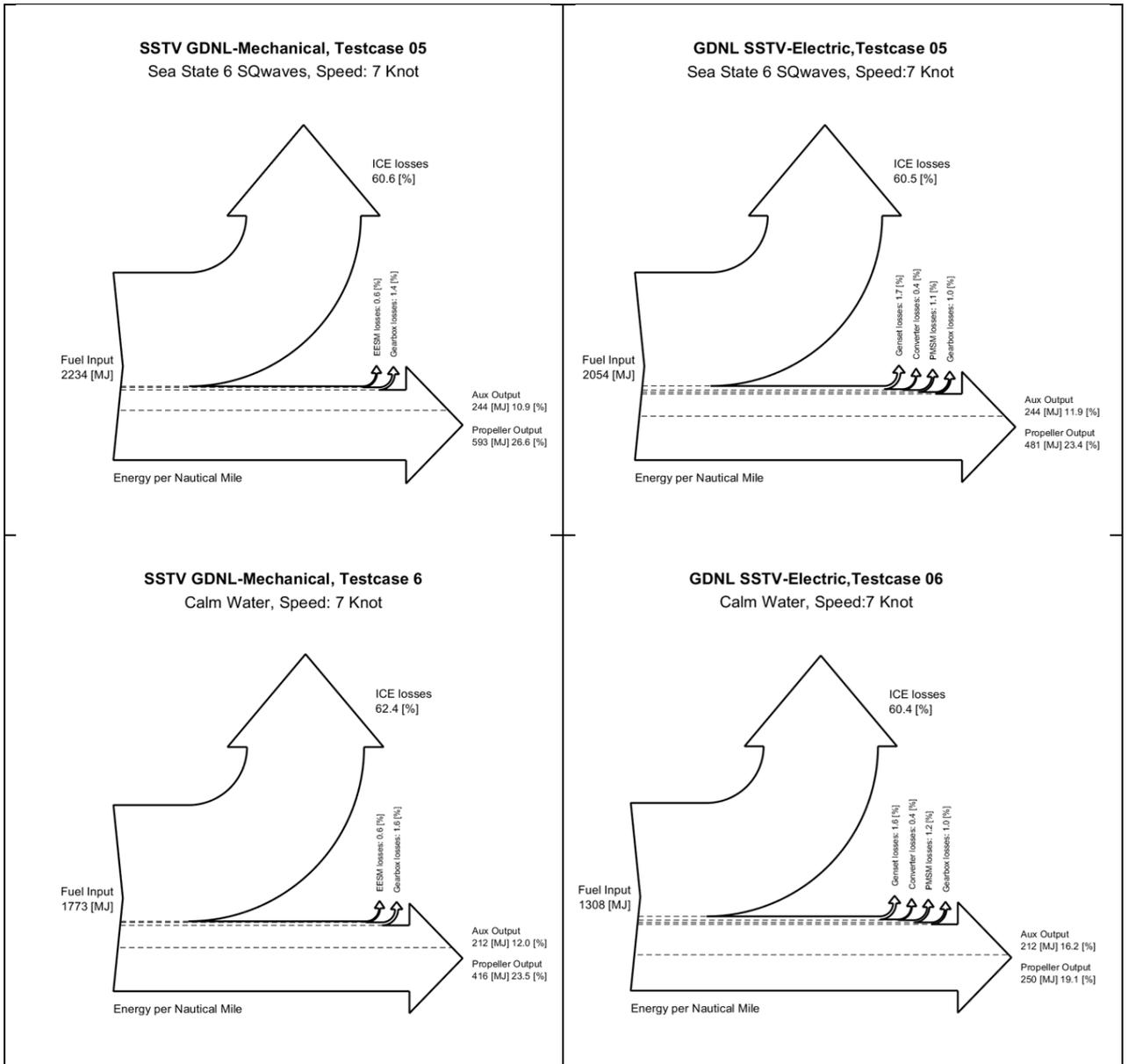
Figure A-13: Output power and efficiency of the modelled propulsion engine

A.3 Results of dynamic models

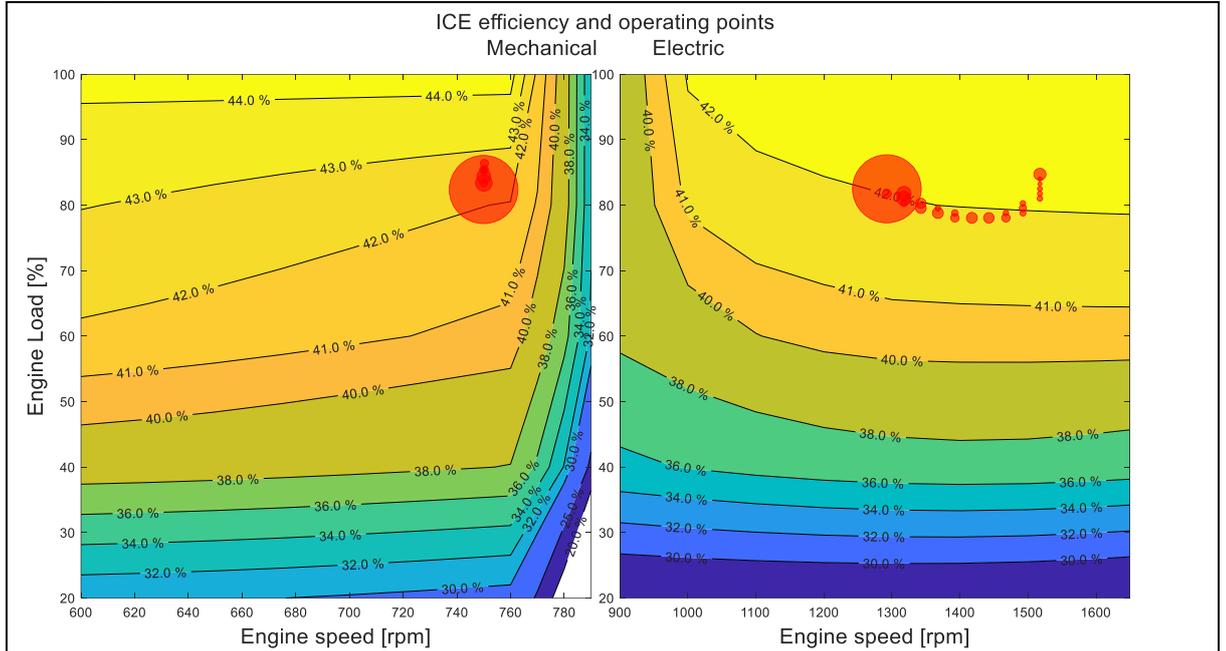
Sanky diagrams of all test cases as described in section 5.2.2.



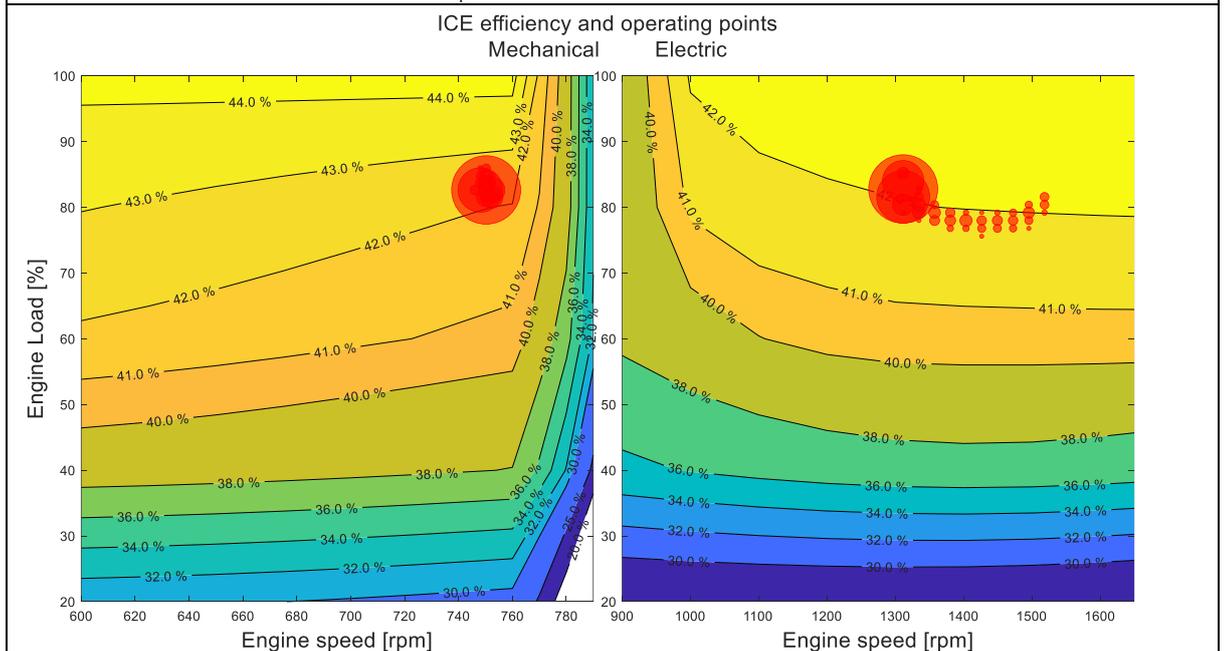




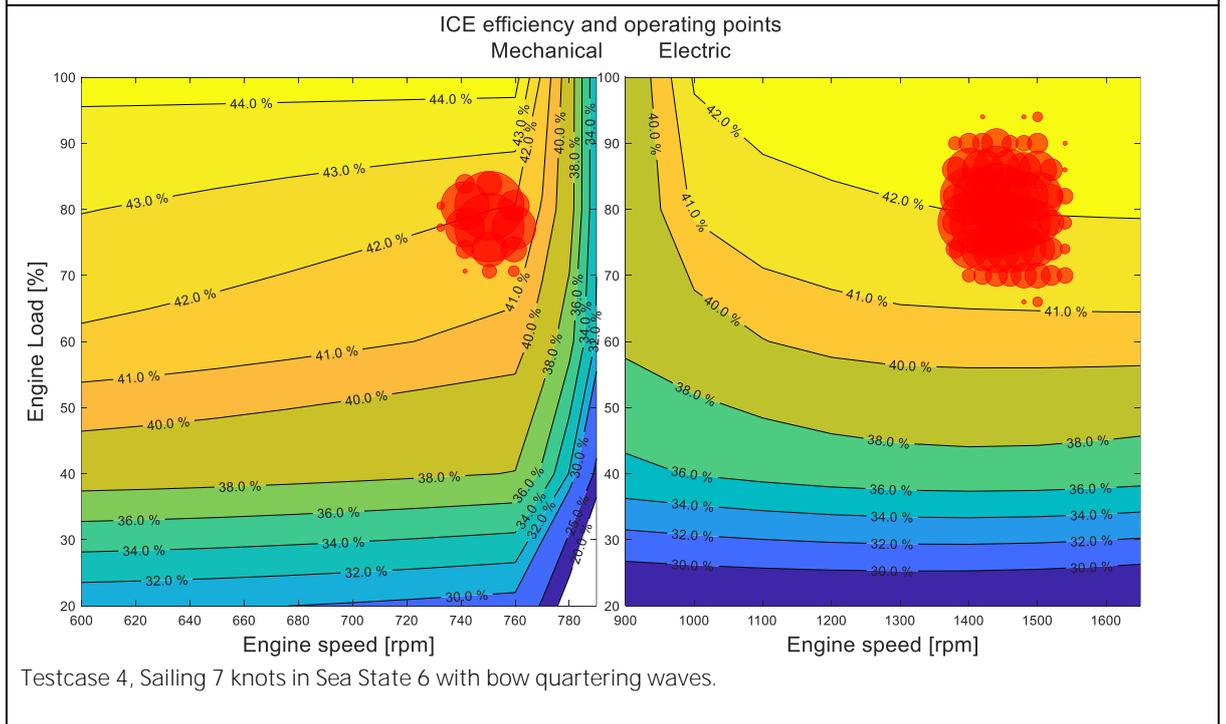
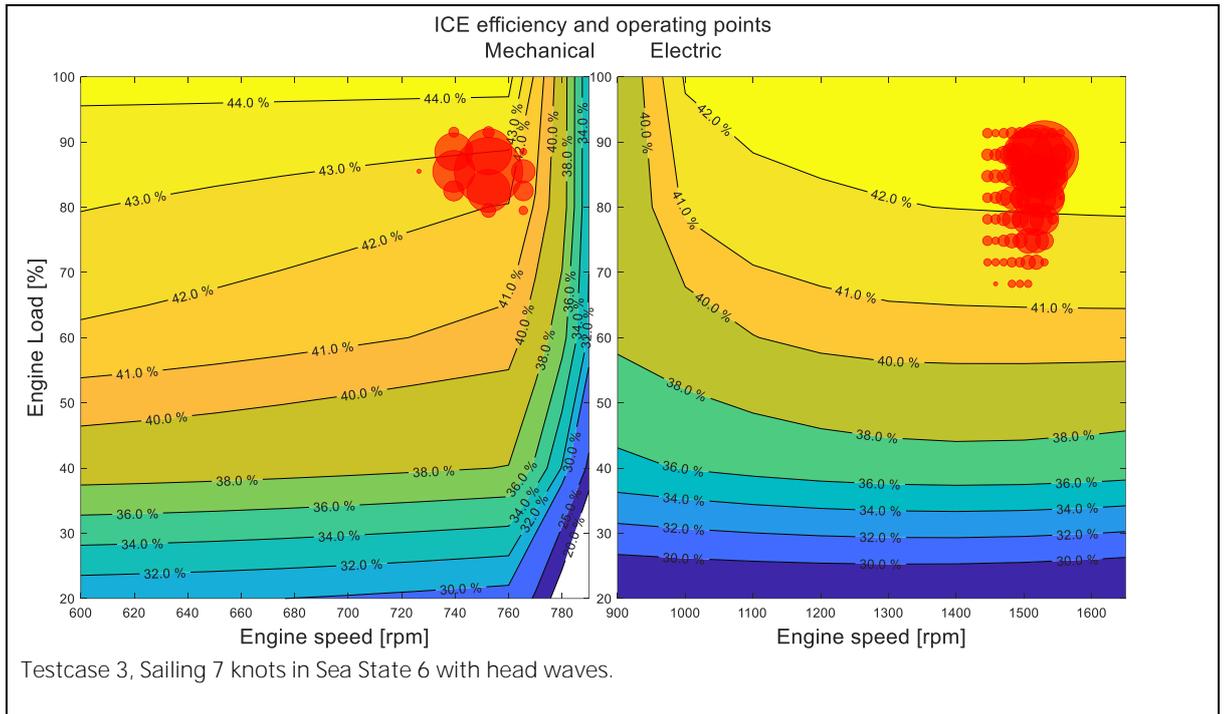
Contour plots of the testcases as described in section section 5.2.2.

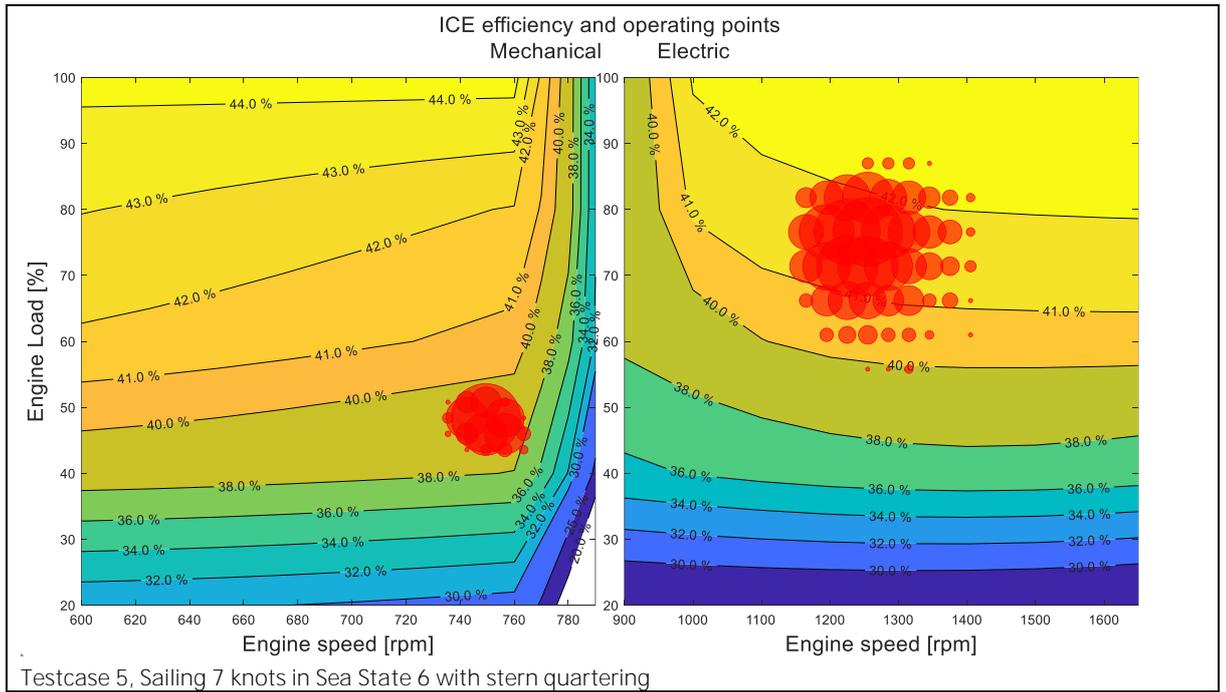


Test case 1 – Calm water, achieved speed 12.6kn

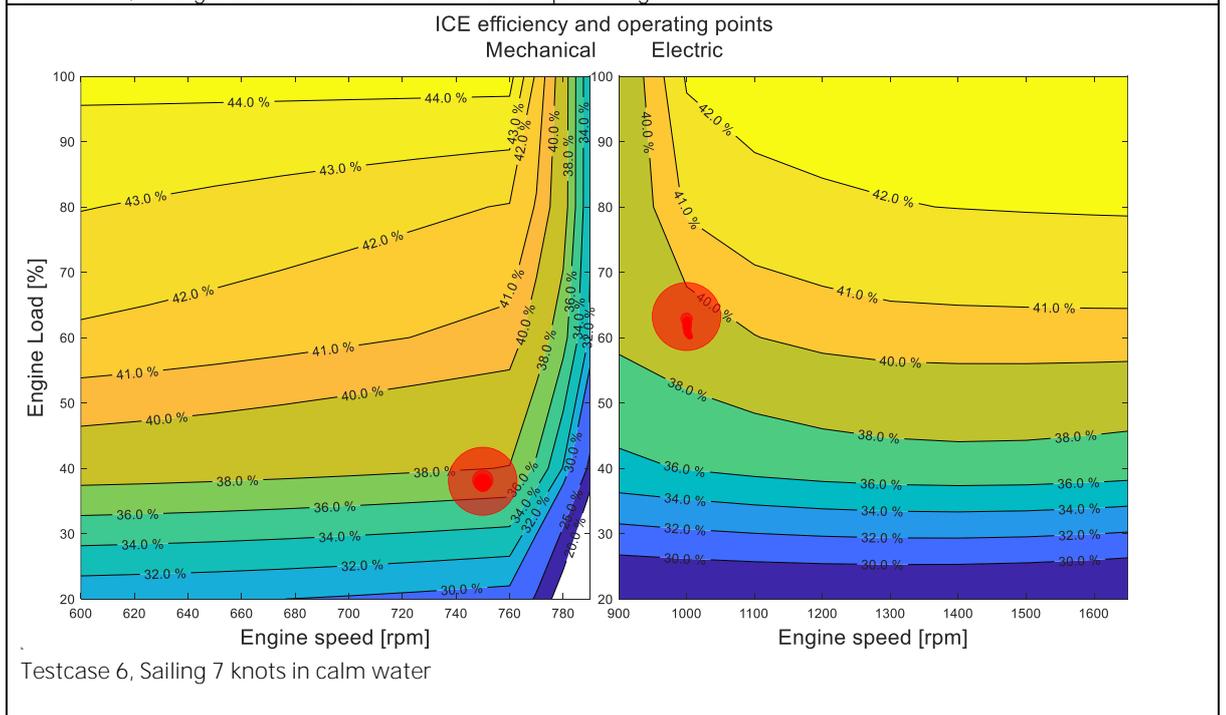


Testcase 2, Sailing 12 knots in Sea State 3 with head waves





Testcase 5, Sailing 7 knots in Sea State 6 with stern quartering



Testcase 6, Sailing 7 knots in calm water

Appendix B

Details of the ship and propeller simulation model

B.1 Sub-models in the ship and propeller model

This appendix describes the details of the aNySIM XMF model, including the various sub-models in the XMF ship and propeller time simulation model.

The time simulation model for the Green Deal NL Electrification Use Case Nr. 1 General Cargo Vessel (SSTV.GDNL.1) is based on a separation of time scales approach. This method was first introduced by Yasukawa & Nakayama [24]. The present implementation includes the effect on propeller load variations. It has been validated and published by Moulijn et al. [25]. Separation of time scales implies that low frequent motions such as manoeuvring and motions due to wave drift force variations are solved in the time domain in MARIN's aNySIM simulation framework. The wave frequent motions, and also the wave frequent propeller inflow variations, are solved in the frequency domain by means of the seakeeping code SEACAL.

The manoeuvring motions are the motions that are initiated by the helmsman (or the autopilot) in the form of rudder actions and/or changes in telegraph setting. This can result in a change in speed or heading, or the performance of a specific manoeuvre like a turning circle or a zigzag manoeuvre. Heading keeping or track keeping is also considered as manoeuvring. In that case the rudder actions have the purpose to counteract disturbances that are caused by waves or a sudden wind gust.

Manoeuvring causes speed variations of the ship. It also may cause the ship to sail under a drift angle and/or make the ship turn. Therefore, manoeuvring has a strong effect on the propeller inflow velocity field, which has a strong impact on the propeller loading (i.e. the propeller thrust and torque).

The forces that the ocean waves exert on a ship are split in two components: first order wave frequent forces and second order drift forces.

The first order forces make the ship move at the frequency at which the ship encounters the waves. They have a zero mean value and their magnitude is proportional to the wave height (hence first order).

The second order (drift) forces have a non-zero mean value, and they are proportional to the wave height squared (hence second order). The term drift forces originates from the offshore world. These are the forces that make a (free floating) floating object drift. In the case of ships, the best known manifestation of the second order forces is the added resistance due to waves. The added resistance due to waves is minus the second order force component in sailing (surge) direction. (The minus signs applies because the second order force is defined positive in forward direction.)

Next to the added resistance, there are also second order wave force components in sway direction and a yawing moment.

When the ship sails in irregular waves the second order wave forces are not constant. At some point in time the ship encounters a group of high waves and the ship experiences a large drift force. A little later (order of magnitude one or a few minutes) the sea is more quiet, and the drift forces are much smaller.

The frequency of the second order wave forces variations is much lower than the wave encounter frequency. Often, the added resistance due to waves refers to the mean value of the second order wave force in sailing direction.

In the time simulation, only the second order wave drift forces are considered (the mean value as well as the low frequent variations). The wave frequent first order wave forces are not included. They are used in the frequency domain sea keeping code SEACAL. SEACAL solves the wave frequent ship motions and also the wave frequent propeller inflow variations. The wave frequent motions and propeller inflow variations are simply superimposed on the low frequent motion and propeller inflow variations that follow from the time simulation. As a matter of fact, the low frequent drift forces are also computed by SEACAL, but these are not used by SEACAL to calculate any motions.

B.2 The XMF Model Structure

The XMF model structure (Figure B-1) shows a schematic representation of the XMF model structure. The blue blocks are true XMF functionality, the green blocks are Python scripts that are included in the XMF model.

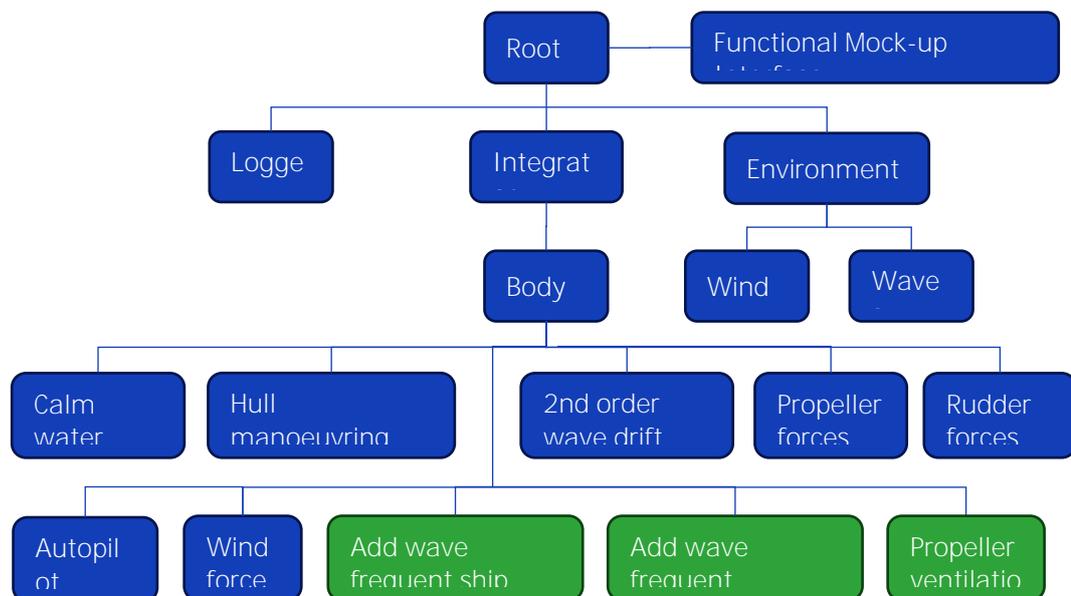


Figure B-1: XMF model structure

The representation in Figure B-1 is not complete. For instance, the Hull manoeuvring forces block actually contains two sub-blocks that represent Slender body and the Cross-flow drag models to predict the manoeuvring forces. There are also two sensors that measure the instantaneous wave height and wind velocity at the ship's centre of gravity.

The root is the starting point of the simulation model. It contains the Functional Mock-up Interface (FMI) that provides for the communication with the calling application of the Functional Mock-up Unit (FMU). The FMI is described in Section B.2.3. Furthermore the root has the following childs: a logger node that exports time traces of relevant simulation results (positions, velocities, forces, etc) to a CSV-file, the integrator node that performs the integration of all differential equations included in its children, and the environment node that models the environment in which the ship is sailing. The children of the Integrator and Environment nodes are described in the next section.

B.2.1 Auto pilot

The configured autopilot is the one that is used in the `xship::man::AccelerationTest` node. This node controls the telegraph and the rudder. It will accelerate the ship up to the required ship speed while keeping the desired heading and then stop the simulation. Table B-1 presents the properties of the node. The properties in grey font are actually default parameters, but they are reported here for completeness.

Table B-1: Properties for the `xship::man::AccelerationTest` node

Property name	Unit	Value	Description
approachSpeed	m/s	20	Initial value for the approach speed
minimumStartTime	s	365 * 24 * 60 * 60	The manoeuvre will be stopped after 1 year
I	rad/(rad/s)	0.01	I gain for the rudder PID controller
P	rad/rad	5	P gain for the rudder PID controller
D	rad/(rad/s)	20	D gain for the rudder PID controller
I_speed	1/(m/s ²)	0.0005	I gain for the telegraph PI controller
P_speed	1/(m/s)	0.01	P gain for the telegraph PI controller

The approach speed is initialized by a high value, a much higher value than the ship can actually attain. This was done on purpose. One may decide to ignore the telegraph in the calling simulation program and just set the propeller RPM (and pitch) to a desired value, while still using the autopilot to control the rudder. When it happens that the ship sails faster than the desired approach speed, the I term of the speed PI controller reduces and the telegraph position eventually gets negative. From that point the desired rudder angle will be multiplied by -1.0, as the autopilot expects that the propeller will be producing negative thrust.

B.2.2 SEACAL calculations

This section presents the SEACAL calculations. The results of the SEACAL calculations are an import data source to the FMU.

SEACAL is a linear seakeeping code that solves the motions of a ship that is sailing at a forward speed in waves. The method uses potential flow theory to solve the linearized waves due to ship motions and diffraction of the incident waves in the frequency domain.

This results in the wave exciting forces on the hull as well as the hydrodynamic reaction forces on the hull due to the harmonic motions of the ship. Subsequently, the equations of motion are solved. Next to the ship motions, SEACAL also calculates the relative water velocity for a number of reference points at the propellers. These velocities are used to predict the load variations on the propellers.

SEACAL also calculates the second order wave drift forces. These drift forces are proportional with the wave height squared (hence second order) and have a non zero mean value. When the ship sails in irregular waves, the second order wave drift forces also have a low frequent varying component that is related to the occurrence of wave groups at sea.

SECAL requires a panel mesh on the wetted part of the ship hull. First step is to generate a CAD model of a representative hull geometry. A CAD model of a reasonably similar ship from MARIN's database was transformed to match the specifications of the General Cargo Vessel of the Green Deal NL Electrification project.

Subsequently, three different meshes were generated on the wetted part of the hull: a course mesh, a medium mesh and a fine mesh. These meshes were used in SEACAL calculations for a limited number of conditions, namely head waves, a ship speed of 12 knots and a wave frequency range from 0.3 to 1.5 [rad/s] in steps of 0.1 [rad/s]. The results are compared to investigate the effect of the mesh on the results.

Figure B-2 shows a comparison of the results of the various meshes for the surge, heave and pitch motions and for the second order surge drift force (i.e. added resistance due to waves). The motions are presented as a Response Amplitude operator (RAO) which is the motion amplitude divided by the wave height in [m/m]. The drift force is presented as a Quadratic Transfer Function (QTF) which is the force divided by wave height squared in [kN/m²]. The effect of the mesh on the motions is small, but there is a strong effect on the drift force. This behaviour is caused by a poor convergence of second derivatives of the potential for the steady flow, which cause very high unrealistic pressures on certain panels at the bulbous bow and the stern gondola.

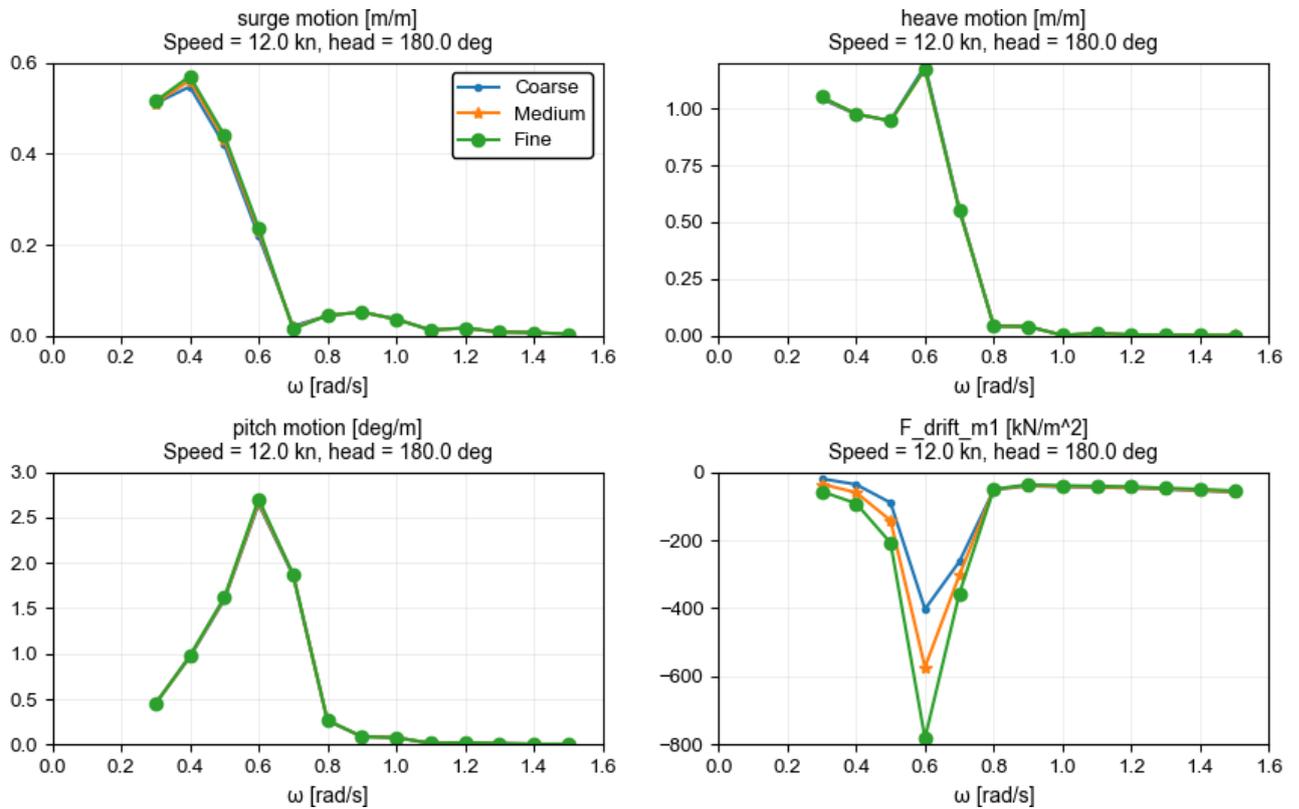


Figure B-2: Effect of the computational mesh on the surge heave and pitch motions and the surge drift force.

In order to mitigate the consequences of this behaviour, the second derivatives can be truncated at a maximum that can be specified by the user. Figure B-3 shows the same comparisons as Figure B-2 when the second derivatives of the potential are limited to 20 ($maxGradVelocity = 20$). Now the effect of mesh on the second order surge drift force is much smaller.

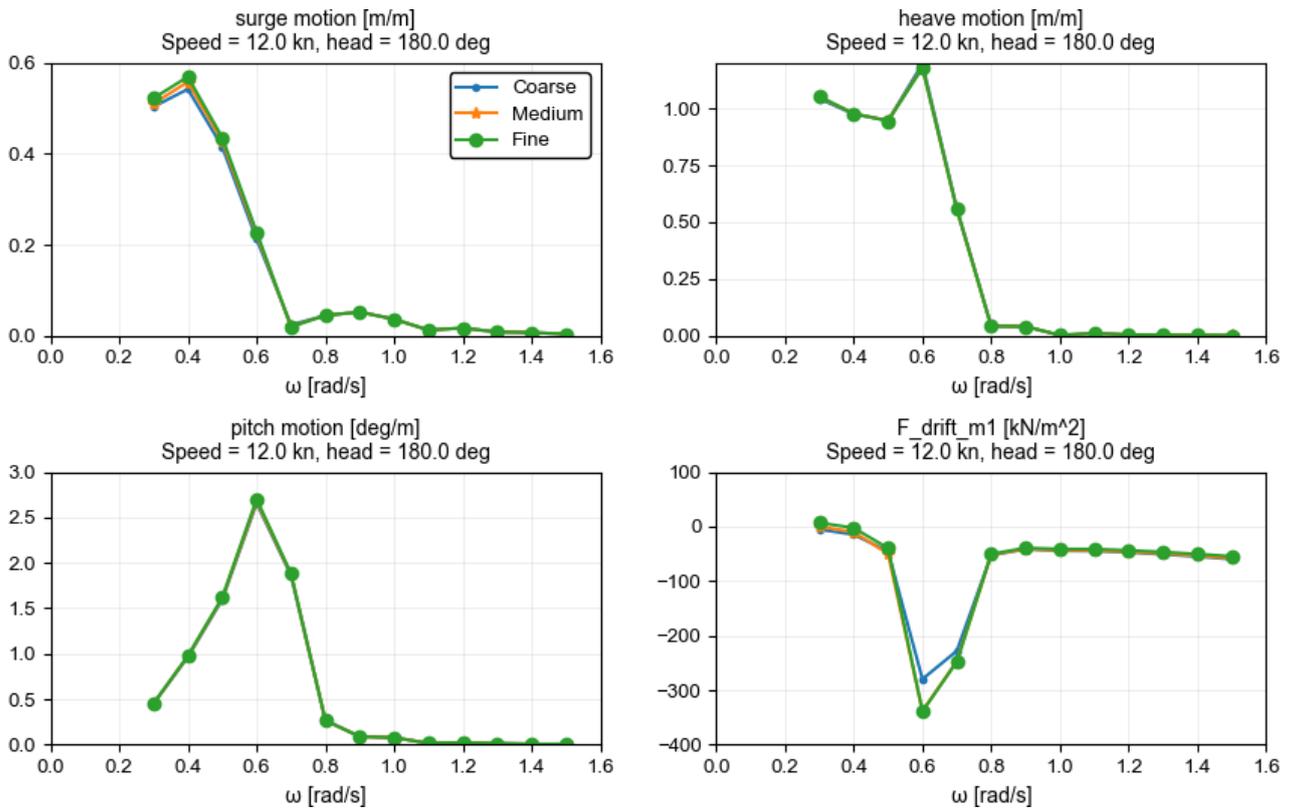


Figure B-3: Effect of the computational mesh on the surge heave and pitch motions and the surge drift force when maxGradVelocity is set to 20.

Figure B-4 presents the medium mesh. It also shows the reference points at the propeller disk at 0.0R, 0.4R, 0.7R and 1.0R radius and at an angular spacing of 45°. Figure B-5 shows the effect of the computational mesh on the relative axial velocity at selected reference points. The convergence is generally good. Only for low frequencies small differences occur.

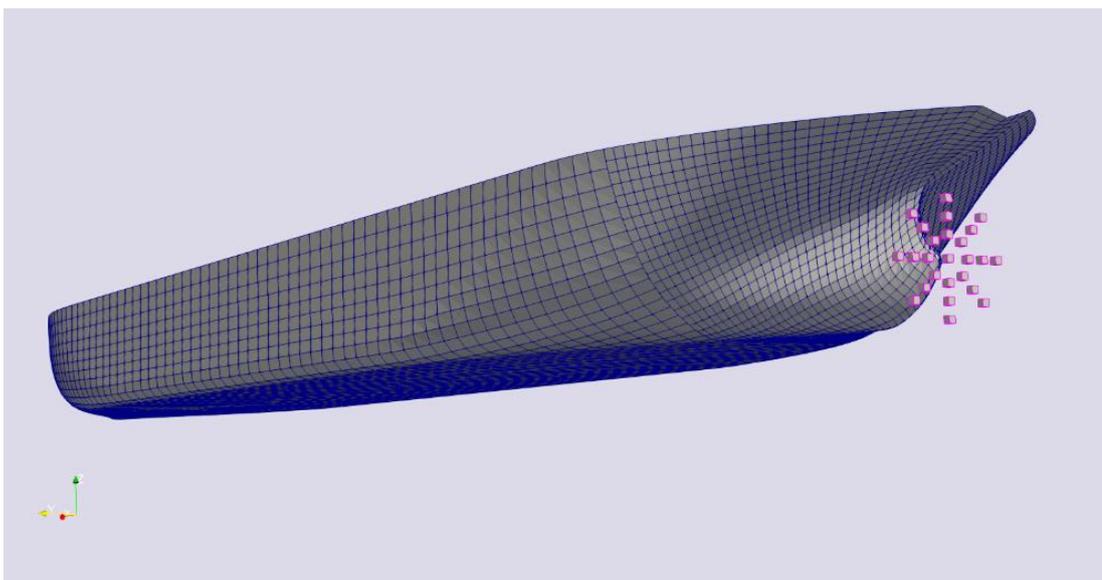


Figure B-4: Medium computational mesh on the hull and reference points at the propeller disk

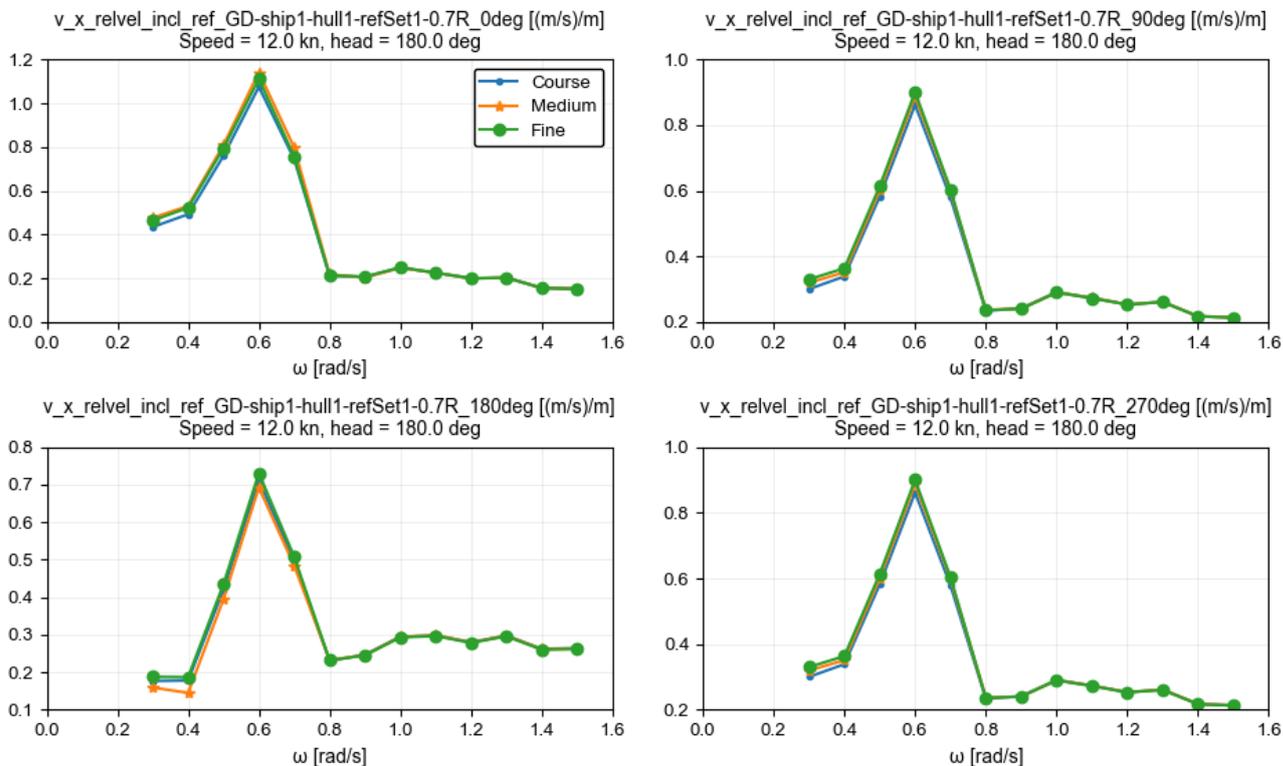


Figure B-5: Effect of the computational mesh on the relative axial velocity for reference points at 0.7R radius and various angular positions.

Figure B-6 also shows relative water velocities at four reference points at 0.7R radius. The top left chart show the axial velocity, the top right chart shows the horizontal transverse velocity and the bottom left chart shows the vertical transverse velocity. Furthermore, the bottom right chart shows the relative wave height at the propeller centre. This latter chart shows a result without the effects of the radiated and diffracted waves and a result that includes the radiated and diffracted waves. Basically, the latter result should be more complete, but it is not clear how the method can predict the wave height for a point that is under the ship hull. Therefore, the result without radiated and diffracted waves is used until the relevance of the result including these waves is clarified.

The results in Figure B-6 all apply to a ship speed of 10.5 knots while sailing in bow quartering waves (135°). It is interesting to see that the amplitude of the axial velocity variations for the reference point at 270° angular position is much larger than that of the point at 90° angular position. The point at 270° is on the windward side of the ship, while the point at 90° is on the leeward side. The leeward side is shielded by the ship's hull. For the transverse velocities, there is not such a strong shielding effect of the ship hull.

The SEACAL final database that is used in the XMF simulation model contains a full matrix for the following conditions:

- Ship speeds: 0.0, 3.5, 7.0, 10.5 and 14.0 [Kn]
- Wave headings: 0, 15, 30, ..., 180 [deg]
- Wave frequencies: 0.1, 0.2, 0.3, ..., 2.0 [rad/s]

The wave headings are extended to 360° using symmetry considerations. The motion.py, waveAndMotionInducedPropellerInflow.py and propellerVentilation.py scripts will interpolate between these results to the actual ship speed, wave heading and wave frequency (or frequencies in case of a wave spectrum).

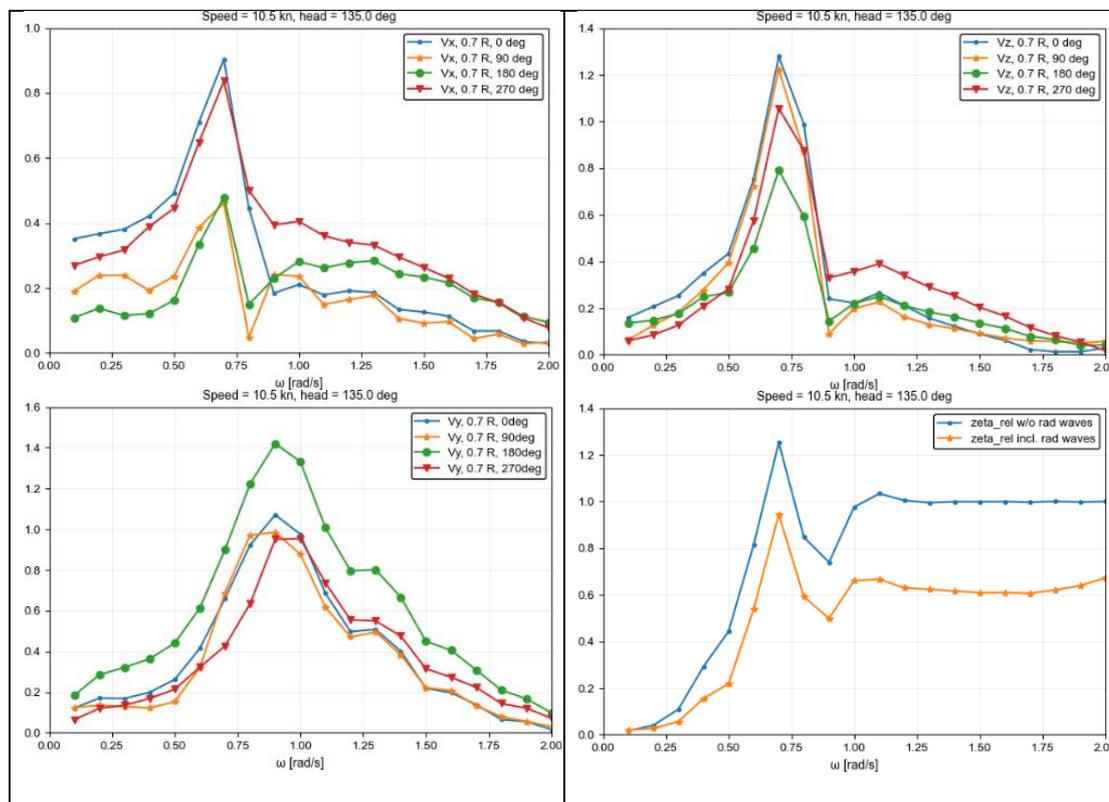


Figure B-6: Relative water velocities at selected reference points and relative wave height at propeller centre.

B.2.3 Functional Mock-up Interface

Within XMF the Functional Mock-up Interface (FMI) consist of two parts: a number of lines that are included in the main.xmlf file that is the starting point the XMF configuration, and the mandatory modelDescription.xml file that defines the interface for the *outside world*.

The lines in the main.xmlf file map the various parameters of the FMI to the right properties of the various sub-models.

The modelDescription.xml file defines the interface for the *outside world* according to the FMI standard. The model is suited for co-simulation (not for model exchange). The calling process should call the dynamic link library fmxri.dll. This dll is the bridge between the FMI and XMF Runtime Interface (XRI). By default, the start time of a simulation is 0 [s] and the time step is 0.1 [s].

Table B-2 lists all model variables that occur in the FMI. It also indicates the causality of variables: independent, output, input or parameter, and it also provides brief descriptions. Please check the modelDescription.xml file to check if parameters are fixed (cannot be changed after initialization) or tuneable (can be changed during the simulation) and to find the default (i.e. start) value of the parameters.

Table B-2: All parameters (input, output, parameter) that occur in the FMI

Name	Causality	Description
time	independent	Simulation time
dt	output	Simulation time step
telegraph	output	Telegraph [-1, ... , 1]
desired_rudder_angle	output	Rudder angle required by autopilot
prop_torque	output	Hydrodynamic torque on the propeller
prop_inertia	output	Inertia (propeller + entrained water) of the propeller
x_pos	output	X position of the ship COG
y_pos	output	Y position of the ship COG
z_pos	output	Z position of the ship COG
x_ori	output	Roll orientation of the ship COG
y_ori	output	Pitch orientation of the ship COG
z_ori	output	Yaw orientation of the ship COG
x_vel_sf	output	Ship-fixed velocity in x-direction
y_vel_sf	output	Ship-fixed velocity in y-direction
z_vel_sf	output	Ship-fixed velocity in z-direction
x_rot_sf	output	Ship-fixed roll rate
y_rot_sf	output	Ship-fixed pitch rate
d_rot_sf	output	Ship-fixed yaw rate
delta	output	Actual rudder angle
zeta	output	Instantaneous wave height at the ship's cog
prop_rpm	input	RPM of the propeller
prop_pd	input	Pitch over diameter ratio of the propeller
rudder_angle_desired	input	Required rudder angle
wave_height	parameter	Significant wave height
wave_period	parameter	Peak period of the wave spectrum
wave_dir	parameter	Direction in which the waves are travelling (ENU coordinate system)
wave_gamma	parameter	Peak enhancement factor of wave spectrum: 3.3 for JONSWAP, 1.0 for Pierson-Moskowitz
wave_seed	parameter	Random seed value for irregular wave realization
wind_speed	parameter	Wind velocity
wind_dir	parameter	Wind direction (going to - ENU coordinate system)
desired_ship_speed	parameter	Desired ship speed for autopilot
desired_yaw	parameter	Desired yaw (ENU) for autopilot

Appendix C

Total Cost of Ownership calculation

C.1 TCO complete calculation and parameter values

Below is the full total cost of ownership calculation for the Short Sea Transport Vessel use case.

Sources for parameter values are indicated in the rightmost column. Assumptions for parameter values come either from the NavigaTE model by the Maersk McKinney Moller Center for Zero Carbon Shipping (MMMCZCS), from MARIN, from TNO, or from the vessel profile as described in this report.

Table C-1: TCO calculation for the Short Sea Transport Vessel

			diesel ICE	diesel-electric	hybrid	source for parameter value
lifetime		years	25	25	25	MMMCZCS
TCO	Total CAPEX	USD/year	818.530	943.018	914.758	
	Total OPEX	USD/year	4.837.076	4.755.972	4.755.972	
CAPEX						
	Total CAPEX	USD/year	818.530	943.018	914.758	
Hull						
	Base CAPEX	USD/year	640.000	640.000	640.000	
	Base CAPEX	USD / vessel	16.000.000	16.000.000	16.000.000	TNO
Propulsion						
	Total propulsion system CAPEX	USD/year	168.888	293.400	264.960	
	Internal combustion engine CAPEX	USD/year	60.800	-	45.600	
	IC Engine CAPEX	USD/vessel	1.520.000	-	1.140.000	
	IC Engine power max	MW	4,00	-	3,00	vessel profile
	ICE engine cost	USD/MW	380.000	380.000	380.000	MARIN
	Aux engine / Genset CAPEX	USD/year	8.208	68.400	27.360	
	Aux / genset CAPEX	USD/vessel	205.200	1.710.000	684.000	
	Aux / genset cost	USD/MW	380.000	380.000	380.000	MARIN
	Aux Engine power max	MW	0,54	4,50	1,80	vessel profile
	Engine related systems CAPEX	USD/year	99.880	225.000	192.000	
	Electric systems, gensets, gearbox C	USD/vessel	1.362.000	4.500.000	3.600.000	
	systems cost	USD / MW	300.000	1.000.000	750.000	MARIN
	SCR + aftertreatment CAPEX	USD/vessel	1.135.000	1.125.000	1.200.000	
	SCR + aftertreatment cost	USD / MW	250.000	250.000	250.000	MARIN
Fuel supply and storage						
	Fuel supply + storage CAPEX	USD/year	9.642	9.618	9.798	
	Total tank CAPEX	USD/year	2.918	2.918	2.918	
	Tank capex	USD/vessel	72.950	72.950	72.950	
	Tank system cost	USD/m3	125	125	125	MMMCZCS
	Fuel tank size	m3	583,60	583,60	583,60	vessel profile
	Total supply system CAPEX	USD/year	6.724	6.700	6.880	
	Supply system cost fixed	USD/vessel	100.000	100.000	100.000	MMMCZCS
	Supply system cost variable	USD/vessel	68.100	67.500	72.000	
	Supply system cost variable	USD / MW	15.000	15.000	15.000	MMMCZCS
OPEX						
	Total OPEX	USD/year	4.837.076	4.755.972	4.755.972	
Fuel cost						
	Total Fuel OPEX	USD/year	2.893.762	2.893.762	2.893.762	
	Fuel cost	USD/GJ	21,47	21,47	21,47	MMMCZCS
	fuel consumption total	GJ/year	134.759	134.759	134.759	
	fuel consumption total	MWh	37.433	37.433	37.433	
	efficiency kwh in / kwh out	%	51%	51%	51%	MMMCZCS
	Energy required	MWh / year	19.091	19.091	19.091	vessel profile
Maintenance						
	Maintenance OPEX	USD/year	243.315	162.210	162.210	
	Maintenance engines	USD/year	243.315	162.210	162.210	
	Maintenance engines	USD/MWh	6,50	4,33	4,33	TNO
	Energy consumption by engines	MWh/year	37.433,03	37.433,03	37.433,03	
Ancillary OPEX						
	Ancillary OPEX	USD/year	1.700.000	1.700.000	1.700.000	MMMCZCS

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