Conceptual design and verification of the power, propulsion, and energy system for a future surface combatant

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Abstract

Although it is debatable to what extend Naval Vessels will have to comply with strict regulations concerning exhaust emissions, concerning fuel supply there is a unanimous consensus about the need for independence from countries in conflict areas. Alternative fuels might provide this independence along with a reduction of in radiated noise. In this paper a concept design of a Power, Propulsion and Energy (PPE) System of a Surface Combatant with the focus on significant reduction of greenhouse gas emissions is composed and simulated. Following the Model-Based System Engineering (MBSE) approach a user needs analysis resulted in a logical and physical PPE system design, focusing on four different military mission types. The design is a combined solution of Dual Fuel Methanol Internal Combustion Engines and Fuel Cells that run on compressed hydrogen. It shows advantages in efficiency, emissions and radiated noise. It can run in different modes, including a Zero Emission mode. To verify the design a time-dependant Simulink model of the PPE system was built and coupled with a model of the propeller and hull in MARIN's eXtensible Modelling Framework *(XMF), which includes sea-states and ship motions. A particular Test Case was performed for a highly dynamic military operation involving a turning circle at high speed, while repetitively firing a railgun. The simulation shows the PPE system is capable to deliver and control the required power, at the edge of stability of the implemented DC distribution system. Following the W-model, a future iteration of the virtual model cycle can further improve system behavior.*

Keywords: Conceptual Design, Digital Models, MBSE, Simulation, Methanol, Hydrogen

1. Introduction:

The use of fossil fuels in the maritime sector contributes considerably to pollution and emission of greenhouse gasses (GHG); about 2.5% of the total worldwide GHG emission has a maritime origin. In order to prevent further climate change, both the IMO and the EU have defined ambitious and compulsory targets for the reduction of emissions in the near future. For the maritime sector the transition from fossil fuels to cleaner and more sustainable fuels and alternatives implies a big challenge.

In addition to the ambitions to reduce exhaust emissions, new energy carriers and their associated Energy-to-Power converters, like fuel cells can create independency of fossil fuels coming from countries in conflictual area's. Further, new Energy-to-Power converters have great potential for reduction of the signatures of combatants.

In the maritime energy transition there are many unknowns. Making a ship sustainable is not as simple as only changing the fuel, or electrifying the complete Power, Propulsion and Energy (PPE) system. Which fuels to choose? Which power & energy system are suitable for my operation? How reliable are these new systems and what emission reductions can we achieve?

To answer these and many more questions, MARIN initiated the ZERO JIP [1]which started Q4 2020. It is a Joint Industry Project lead by MARIN with 23 participants, three research partners (TNO, TUD, HAN) and two stakeholders (NMT, KVNR). The aim of the ZERO JIP is: *to design, build and test the prototype Engine Rooms of the Future to assure reliable future operations in realistic conditions while meeting functional and emission requirements.* This is done for 8 Use Cases (ships with their specific missions). Those 8 Use Cases were defined with all participants at the start of the project. The start point for each Use Case was the compilation of user needs; what is required from the ship? Based on this a suitable concept design was made. After making a digital model of the concept, simulations show if the design matches the requirements.

 https://doi.org/10.24868/11199

This paper describes the results of the conceptual design of the PPE system of a Surface Combatant and simulates a Test Case to verify the capabilities of the designed system for highly dynamic military operations. An artists impression of the surface combatant is shown in Figure 1-1.

Figure 1-1 Artists impression future Surface Combatant

For understanding the power needs and creating architectural design of the future Surface Combatant, the Model Based System Engineering (MBSE) method is applied as explained by Veldhuis et. al in [2]. It uses a coherent model to come in multiple steps from user needs to a validated design. This new way of working can be represented by the W-model, a new age addition to the well-known V-model as shown in Figure 1-2. The W-model introduces two additional legs between the 'Component Design' and 'Manufacture and Assembly' steps. These are the model verification and design specification legs. The use of model-based verification testing allows designs to be checked against requirements. This can be started at an early conceptual design stage, thereby reducing project risks through the early identification of issues. This virtual model cycle is the focus of this paper. For the surface combatant design the left leg was executed in the MBSE tool Capella, while the second leg is a combination of dynamic Simulink models, and MARIN's proprietary wave, propeller and ship models. The developed models can be extended with real-world measurement data through the testing, commissioning and operational phases of the vessel to create digital twins of the vessel. These can then be used to optimise operations.

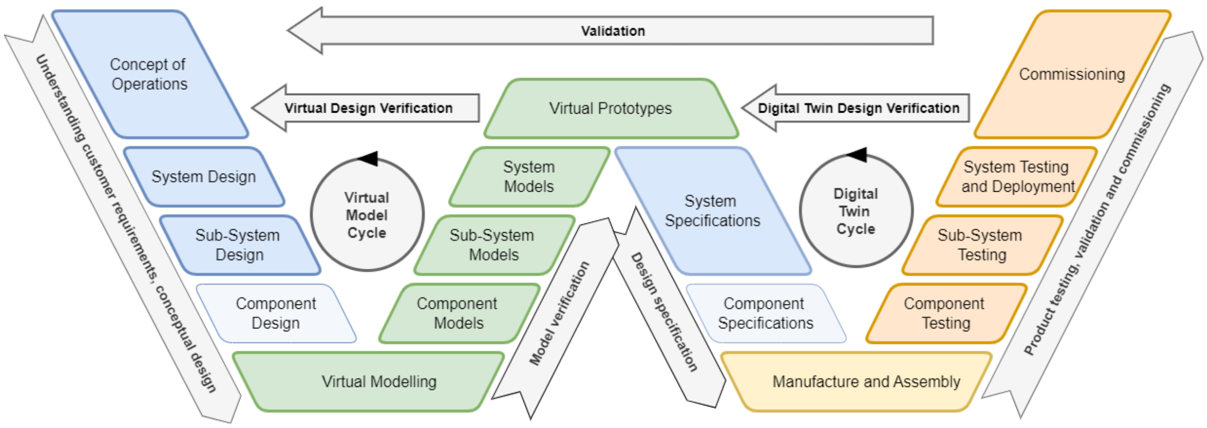

Figure 1-2 W-model for the Life Cycle approach

2. Needs Understanding, Technology Selection, and Concept Design

Before a concept design can be created, it is necessary to have a clear view on the requirements of the PPE system. For this the user-needs must be understood, for which an operational analysis is performed. Based on this a system analysis can make clear which functions the PPE system has to perform and what the system boundaries are.

2.1. Needs Understanding

2.1.1. Operational Analysis

The operational analysis identified the role of the vessel as being - air-defence with advanced weaponry. For the design of the PPE system, the focus of the operational analysis was the energy requirement for different mission types as well as the identification of challenging dynamic operational conditions that the vessel is expected to perform in.

Four representative typical mission types were drafted by MARIN. Those were assessed, improved, and finally approved by the ZERO participants. The resulting four different mission types are summarized, as shown in Table 2-1.

Table 2-1 Summary of the Operational Analysis

Reference Vessel	Max Vessel Speed	Military Service Scenario	Max Crew size	Mission Types	Autonomy/ Endurance	Exhaust Emissions
Successor Air Defence Frigate Δ = 5200 [MT]	25 [Kts]	The Ship shall be capable of sailing at 18 [Kts] in heavy seas (Sea State 6) while intermittently re-charging Electro-Magnetic and Optical Sensors and Weapons with a frequency of 0.2 [Hz]	50	I – Intercontinental Transit	3500 [NMi]	70% Climate Neutral and IMO Tier III
				II – Short Military Voyage	4.5 [Days]	
				III – Long Military Voyage	14.5 [Days]	
				IV – Zero Emission Transit	120 [NMi]	Zero Emission

The main difference between BIO II and BIO III is that BIO III has a longer endurance, making the operational profile of BIO II more dynamic. Both BIOs contain the task "Perform Military Operations". The two BIOs are shown in Figure 2-1.

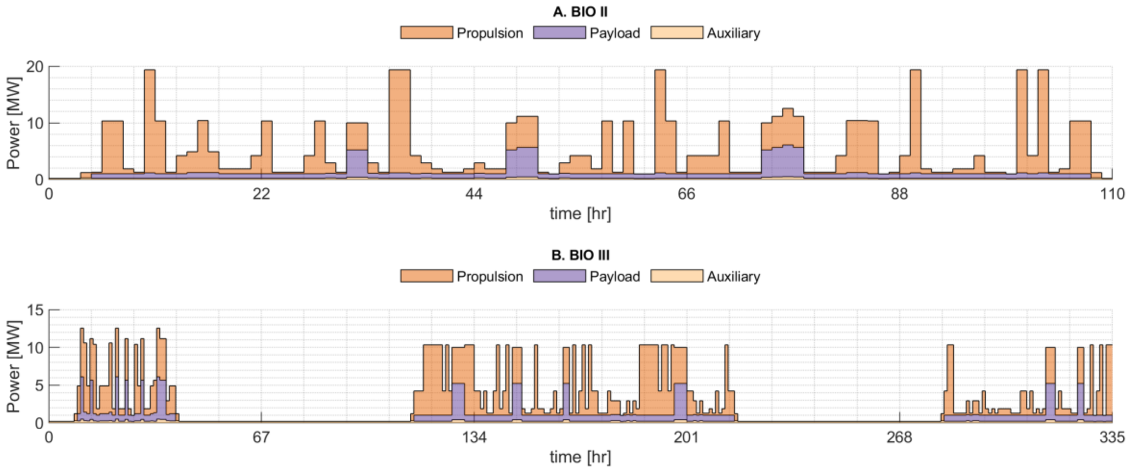

Figure 2-1 Bunker Independent Operations II and III

Additionally, it was concluded that the capability concerning conditions of military service scenario detailed in Table 2-1 is the most challenging for the PPE system and simulation testing should demonstrate its capability to meet these conditions. This challenging condition is translated into an operational requirement:
"The Ship shall be capable of sailing at 18 Kts in sea state 6 while intermittently re-charging Electro-Magnetic and Optical Sensors and Weapons with a frequency of 0.2 Hz"

2.1.2. System Analysis

The second part of Understanding the Stakeholder Needs consists of the System Analysis. This analysis answers the questions 'Which functions should the system perform?'; 'What is required of those functions?', and 'What are its interactions with the Actors lying outside the system boundary?' Answering these questions also means setting a strict system boundary.

The system analysis identified three main functions for the PPE system – providing propulsion power, providing payload (military systems) power, and providing auxiliary power. The test case that is described in this paper covers specific requests for propulsion, payload and auxiliary power. Doing a high speed turning circle while intermittently re-charging Electro-Magnetic and Optical Sensors and Weapons, means the PPE system should be

 https://doi.org/10.24868/11199

able to provide the requested propulsion power for the sailing manoeuvre, and at the same time the payload power for sensors and weapons.

The results of the System Analysis are summarized in Table 2-2. The left part shows the data per service (Payload, Propulsion, Auxiliary), the right part of the table shows the data per Mission Type.

Table 2-2 Summary of the results System Analysis

<table>
<tr><th colspan="5">Max Consumed Power [kW]</th><th rowspan="3">Total Consumed Energy [MWh]</th><th colspan="2">Exhaust Emissions</th></tr>
<tr><th colspan="3">Per Service</th><th colspan="2">Per Mission Type</th><th rowspan="2">GHG</th><th rowspan="2">Pollutants</th></tr>
<tr><th>Payload</th><th>Propulsion</th><th>Auxiliary</th><th>Mission Type</th><th>Total</th></tr>
<tr><td rowspan="4">8000</td><td rowspan="4">18162</td><td rowspan="4">800</td><td>I – Intercontinental Transit</td><td>12547</td><td>1512</td><td>70% Climate Neutral</td><td>IMO Tier III</td></tr>
<tr><td>II – Short Military Voyage</td><td>19362</td><td>575</td><td>70% Climate Neutral</td><td>IMO Tier III</td></tr>
<tr><td>III – Long Military Voyage</td><td>12547</td><td>1039</td><td>70% Climate Neutral</td><td>IMO Tier III</td></tr>
<tr><td>IV – Zero Emission Transit</td><td>2202</td><td>27</td><td colspan="2">Zero Emission</td></tr>
</table>

Since the services do not peak simultaneous, maximum power per mission is lower than the sum of maximum service powers. The total consumed energy at this stage does not include efficiency losses and bunker margin.

From Table 2-2 it can be concluded that Mission Type I - Intercontinental Transit has the highest effective energy and is therefore determinative for the amount of climate neutral energy carrier. The PPE system has to meet 70% Climate Neutrality and IMO Tier III emissions requirements for Mission Types I, II, and III. Mission Type IV - Zero Emission Transit is determinative for the amount of zero emission energy carrier.

While future weapon systems like railgun have a wide range of energy requirements ranging from hundreds of kilojoules to hundreds of megajoules [3], [4], [5], this paper considers a 10 MJ railgun modelled on the PEGASUS [4]. It is assumed that the capacitor modules within the railgun system deliver the required pulsed power and the role of the PPE system is the recharging of these capacitors. To meet a firing frequency of 0.2 Hz, the railgun system is charged with 2.5 MW for 4 seconds allowing the system to be operated every 5 seconds. While the charging profile can be controlled to reduce the dynamic load on the power system, in this case a step power profile is used to simulate an extreme scenario.

2.2. Architectural Design of the PPE System

2.2.1. Selection of suitable Technologies

After the Needs were clear and registered, an exploration of possible PPE-system technologies and configurations was done. This step typically answers questions, like which technology solutions meet the requirements? What are the expected total size and weight of those solutions and do they, in theory fit into the ship? For this MARIN’s Ship Power & Energy Concept (SPEC) tool was used. The result of this analysis was the selection of a hybrid power and propulsion system with DF-methanol ICEs, Fuel Cells supplied with compressed hydrogen, and Batteries.

The Methanol (CH_3OH) ICE solution complies with the requirement of climate neutrality for mission types I, II, and III. The Dual Fuel variant is allowed because of the 70% climate neutrality and preferred by the stakeholders for having fuel flexibility. The Compressed Hydrogen (Comp H_2) Fuel Cell solution complies with requirement of Zero Emission for mission type IV. The battery (Electric Storage) is selected for Dynamic Support of the Fuel Cell, but can also provide power equalization to the DF Methanol Generator Sets. Hybrid Propulsion, i.e., a propulsion system with a DF Methanol ICE and an Electrical Machine connected to each shaft, was mainly a CapEx and volumetric consideration as the maximum propulsion power is not requested simultaneous with the maximum payload power, the main ICEs can also provide payload power in the propulsion mode 'Shaft Generation'.

2.2.2. Logical Architecture

The PPE solution, as described in Section 2.2.1, was worked out in more detail as Logical System Architecture. In the Logical Architecture the system functions were refined into subfunctions and assigned to logical components. The result is the system topology as shown in Figure 2-2.

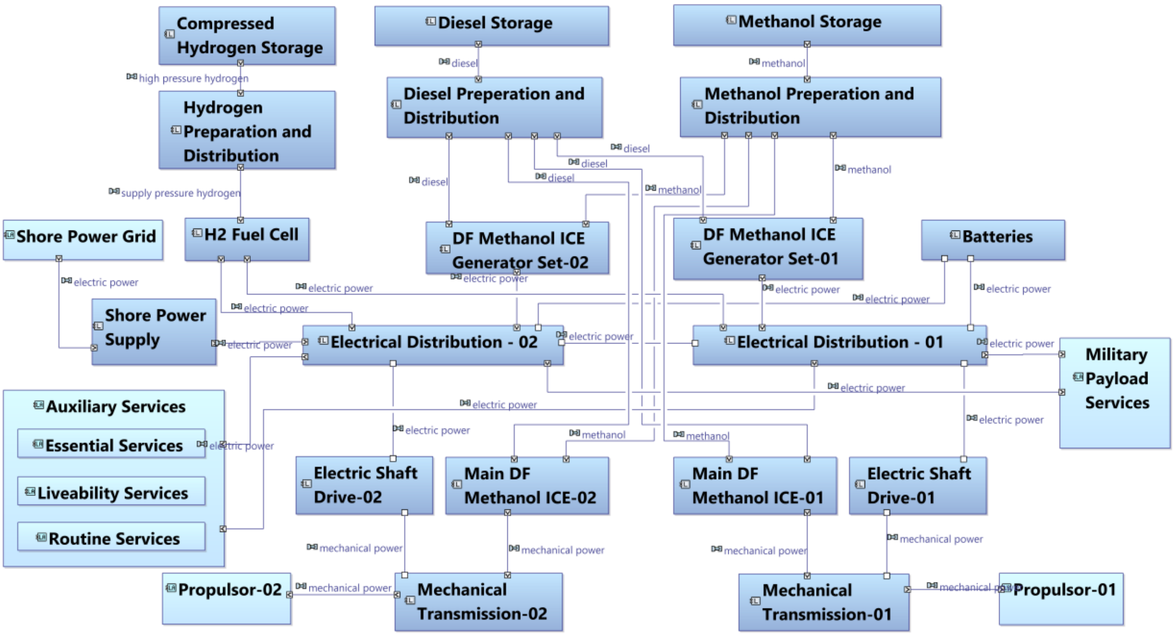

Figure 2-2 Logical Architecture of the Power, Propulsion and Energy system of the Surface Combatant

The architecture contains multiple operating modes, like Mechanical Propulsion, Electric Propulsion, Cross-Shaft Propulsion, and Shaft Generation. While the cross-shaft operation is considered for economic cruising, in this paper we focus on the propulsion mode shaft-generation. At a ship speed of 18 [Kts] the Internal Combustion Engines are not yet at their maximum power. The architecture of how the engines, electric shaft machines and the electrical distribution system are coupled enables the remainder of the available power of the main Internal Combustion Engines to be used as Payload Power (electro-magnetic and optical sensors and weapons).

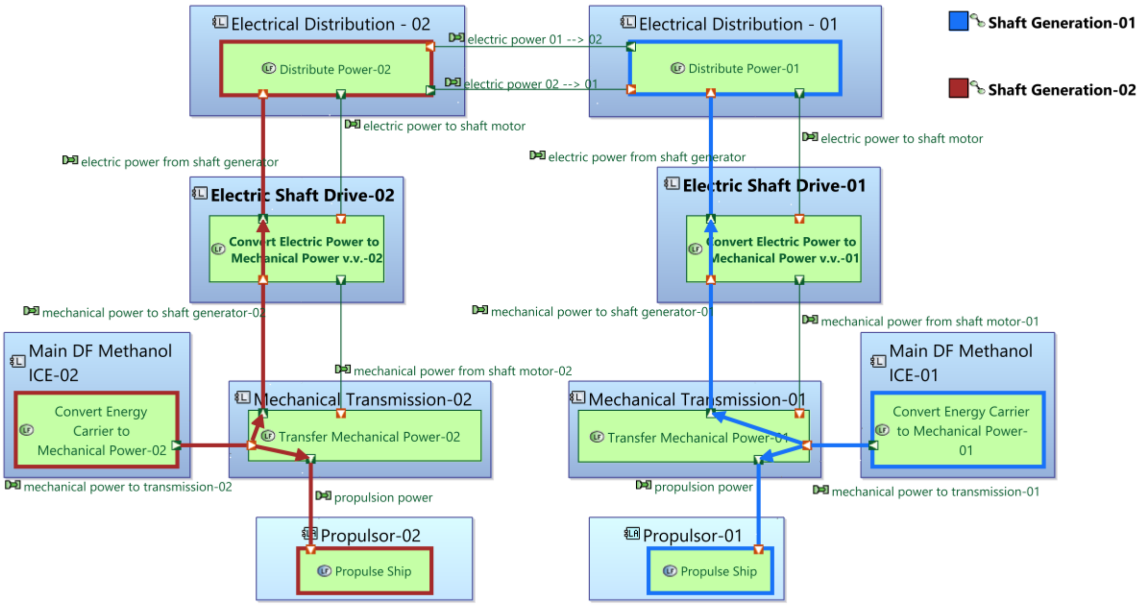

Figure 2-3 Logical Architecture of the Electric Shaft Drives. The Functional Chains of the Shaft Generation mode are shown.

2.2.3. *Physical Architecture*

The topology of the Logical Architecture was designed and extended into a Physical Architecture, as shown in Figure 2-4. Power of the propulsion engines was chosen such that the vessel can reach its maximum speed on these engines only, allowing a diesel-only sailing fallback scenario. Sizing of all other components was chosen by balancing the required size, weight and resulting bunker volume. Distributing the requested power as shown in Table 2-2 over multiple smaller power sources increases efficiency during operation.

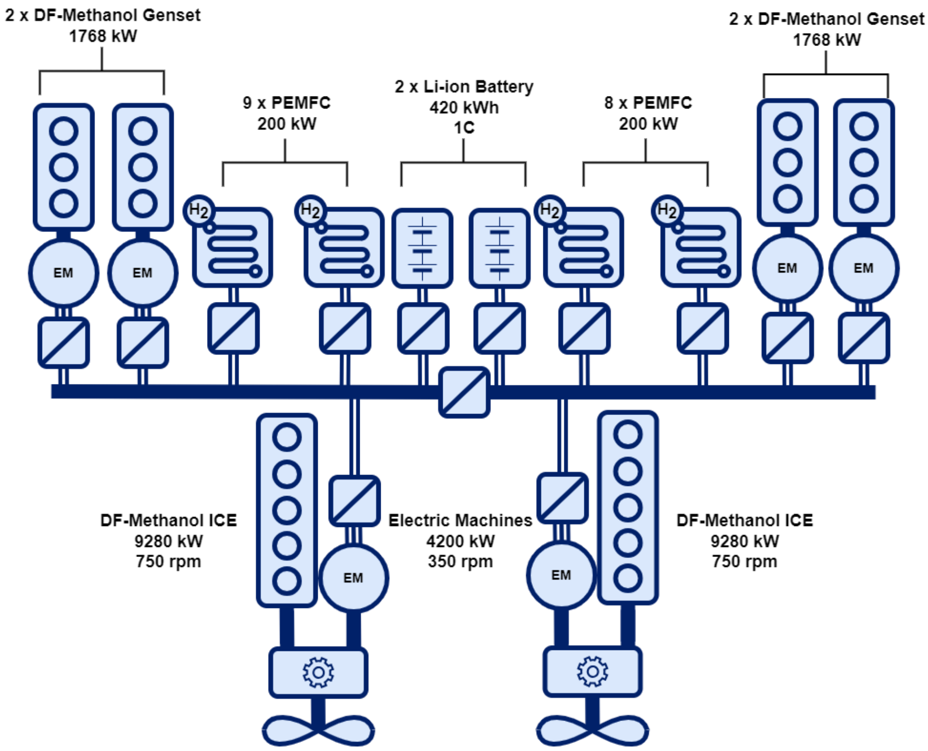

Figure 2-4 Physical Architecture of the Power, Propulsion and Energy System of the Surface Combatant

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The Geometrical Arrangement of the PPE system is shown in Figure 2-5. The Building Groups that are arranged correspond to the Physical Architecture as shown in Figure 2-4.

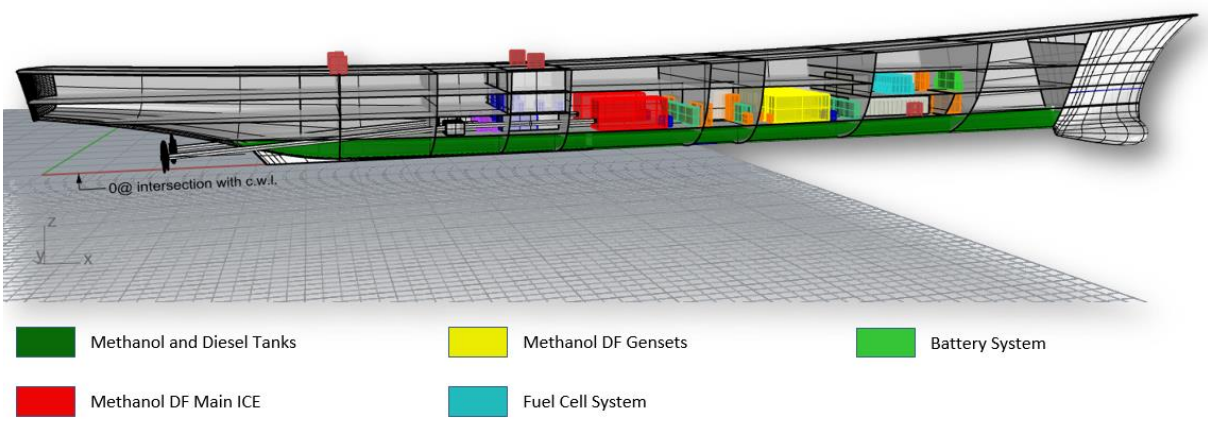

Figure 2-5 Geometric Arrangement of the PPE system

Mission Type I "Intercontinental Transit" has been determinative for energy storages sizing since it is the most energy demanding one. The autonomous design range has been set at 3500 nmi which corresponds to an endurance of 328 hours, including a 10% bunker margin. The ICEs in the design run on a blend of 5% in volume of Diesel (pilot fuel) and 95% in volume of methanol (main fuel). Considering the energy densities of the different fuel, the resulting energy fraction is given in Table 2-3.

Table 2-3 DF-Methanol ICE Energy Fractions

	Unit	Diesel	Methanol
Energy density	MJ/kg	42	19.7
	MJ/l	35.8	15.60
Contained Energy density	MJ/kg	29.6	14.50
	MJ/l	33.2	13.60
Density	kg/m3	840	792
Volume fraction		5%	95%
Energy fraction		**11%**	**89%**

When examining the developed power to consumer efficiency of the Main Internal Combustion Engine (ICE), a weighted average efficiency has been computed to determine the energy consumption during Mission Type I. This efficiency was calculated by factoring in the developed power to consumer efficiency of the Main ICE's for each individual task that takes place throughout the mission, with each task's contribution weighted based on its duration. The resulting weight and volume of the fuels are given in Table 2-4.

Table 2-4 Fuel storage sizing

Fuel	**Total Required Energy Carrier**	**Weight**		**Volume**	
		Uncontained	Contained	Uncontained	Contained
	MWh	tonne	tonne	m^3	m^3
Diesel	463	40	56	46.5	50
Methanol	3744	684	930	864	991

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3. Simulation of the concept

As described by the W-model in Figure 1-2, the virtual model cycle is used to test that the designed Power, Propulsion and Energy (PPE) system meets the developed requirements. For this, a number of virtual vessel models are created of varying fidelity levels according to the questions to be answered. This paper addresses the dynamic performance of the PPE system, hence, the dynamic models for the PPE system and the ship-propeller are briefly described in the section.

3.1. The PPE system

The virtual model of the PPE system is constructed based on the Physical Architecture shown in Figure 2-4. However, as the simulated test case considers the Operational Task "Perform Military Operations," the Fuel Cells have not been included as they are not operated in these tasks. The remaining components are modelled in Matlab-Simulink using approaches that have been widely reported in literature[6], [7] and are not repeated in this paper .

The architecture of the designed PPE system includes a hybrid propulsion system with a Controllable Pitch Propeller (CPP). The operating chart of this system is shown in Figure 3-1.

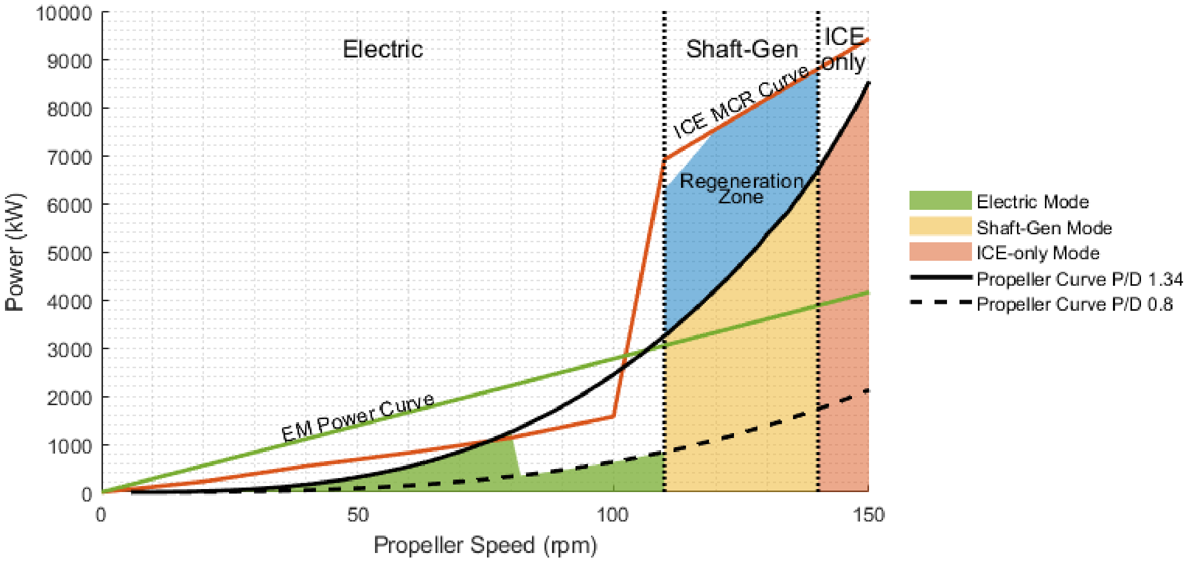

Figure 3-1 Propulsion Operating Modes. Three modes of operation are possible – electric mode, between 0 and 110 rpm, shaft generation mode between 110 and 140 rpm, and ICE-only mode. In the Shaft-Generation mode, the main propulsion ICEs deliver the propulsion power while the excess available power is fed to the distribution system by the electric shaft machines.

The propulsion system can be operated in four modes – electric, shaft-generation, cross-shaft, and ICE only. For the simulations presented in this paper, only electric, shaft-generation, and ICE only are considered. In the electric mode, the propulsion power is provided by the electric machines alone, this propulsion power along with auxiliary and payload power is provided via the DC distribution system by the connected DF-Methanol Gensets, Fuel Cells and Batteries. In the Shaft-Generation mode, the main DF-Methanol ICEs provide the propulsion power, and the electric machines feed the excess power back to the DC distribution system for the auxiliary and payload services. In the ICE-only mode, the propulsion and power systems are decoupled, with the main DF-Methanol ICEs providing all the propulsion power and the gensets and batteries providing the auxiliary and payload power for the services connected to the distribution system. To achieve operation with the constraints of the power curves of the electric machine and the ICE as well as the available power on the DC distribution system, the pitch of the CPP is actuated between P/D ratio of 1.34 (the design ratio) and 0.8 when the propeller speed is between 80 and 110 rpm. The propulsion system is operated in torque control, with the torque and pitch setpoint generated by the combinator curve.

The power system is managed by the Energy Management System (EMS) and the Power Management System (PMS). The EMS generates power setpoint advice for the available power sources on the distribution system and the PMS ensures stable operation by converting this advice to control commands to be followed by the lower control layers. The lower control layers operate using droop control to achieve the operating point decided by the

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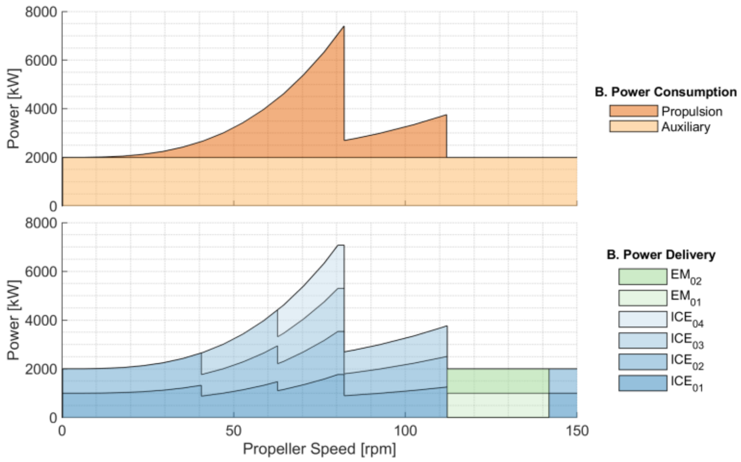

Figure 3-2 Example of the operation of the EMS and PMS. The EMS uses a simple rule-based approach to advice the power allocation between the sources on the DC distribution system.

EMS and PMS. The EMS used in these simulations is a simple rule-based system that acts on the load on the distribution system to allocate power amongst the different power sources. The operation of the EMS and PMS is shown in Figure 3-2.

In the electric mode, the power system (comprising of 4 DF-methanol gensets and 2 batteries) provides all the power demand. The gensets are turned on according to the load with the constraint of a spinning reserve of 50% of the nominal power of a single genset in addition to the batteries to allow fast ramp-up of payload power during military operations. The operated gensets share power equally and the battery is used as a peak-shaver and power ramp support along with its role of providing spinning reserve. When the system transitions to the Shaft-Generation mode, the electric machines provide power to the power system loads (i.e., the auxiliary and payload services) from the excess power available in the propulsion lines. This can be seen in Figure 3-2, where between the propeller speeds of 110 and 140 rpm, the complete auxiliary power of 2 MW is provided by the electric machines. In the ICE-only mode, the propulsion and power systems are decoupled and the load on the DC distribution system is delivered by the combination of DF-methanol gensets and batteries with identical rules as in the electric mode.

There are three separate services that the PPE system must provide power for – propulsion, auxiliary and payload. The propulsion services are modelled using a complete ship-propeller-environment model as described in Section 3.2. The auxiliary and payload services are modelled as power consumers on the DC distribution system. The power consumed by these services have been identified in the Needs Analysis, as explained in section 2.1. Additionally, as the test case demonstrated in this paper involves intermittently re-charging Electro-Magnetic and Optical Sensors and Weapons (as noted in Table 2-1), additional power consumption for this sensor and weapon system is considered in the payload services.

3.2. Ship and propeller simulation method

The manoeuvring while sailing in waves is simulated using MARIN's time simulation framework XMF. The ship and propeller simulations predict the load variations for the PPE system, while the effects of any limitations of the PPE system are taken into account (2-way coupling). A more elaborate description of the ship propeller simulation method can be found in Moulijn et al. [8].

3.2.1. *Two-timescales method*

The ship and propeller are modelled using a two-timescales method that was first introduced by Yasukawa & Nakayama [9]. The manoeuvring motions and the motions due to low frequent wave drift forces are solved by a time domain simulation method. The wave frequent motions and propeller inflow variations are calculated by means of a linear frequency domain seakeeping method which are superimposed on the (low frequent) results of the time simulation method.

The wave forces (and moments) acting on a ship that is sailing in waves can be split in two components: first order (wave frequent) forces and second order drift forces. The first order forces have a zero mean value, the variations happen at frequencies that are equal to the ship-wave encounter frequency, and the magnitude is proportional to the height of the waves. The second order forces, also called drift forces, are proportional to the wave height squared (at least up to moderate wave heights, hence second order). The drift forces have a non-zero mean value. When the ship sails in irregular waves, the drift forces are varying at a much lower frequency than the wave frequency. These low frequent variations are related to the occurrence of wave groups. Sometime the ship is encountering several high waves. This results in large drift forces. A little later the sea is more quiet and the drift forces are low. The mean value of the drift force component in sailing direction is often called *added resistance due to waves*.

The basis of the ship and propeller simulation model is a calm water manoeuvring time simulation model. An additional force is introduced that represents the (mean and low frequent) drift forces. This force causes low frequent ship speed variations and consequent propeller inflow variations. The wave frequent ship motions and propeller inflow variations are calculated by means of a 3D linear frequency domain seakeeping code. This method calculates the disturbed wave pattern around the ship, which appears to be crucial for an accurate prediction of the propeller inflow variations. The wave frequent motions and inflow variations are simply superimposed on the low frequent motions and inflow that are predicted by the time simulation method. The seakeeping method also predicts the drift forces.

3.2.2. *Propeller load variations*

The propeller model in the simulations is based on open water characteristics. A 4 quadrant form of the open water characteristics is used [10], which has the advantage that the model always provides an adequate solution (also for off-design conditions like backing or a non-rotating propeller). The load variations are caused by the inflow variations to the propeller due to manoeuvring and/or ocean waves.

Special attention was paid to the propeller inflow model in the manoeuvring simulation method. When a ship is sailing under drift and/or in a turn, the inflow to the propellers is very different from the inflow when the ship is sailing straight. Figure 3-3 shows a visualization of a CFD prediction of the flow around a naval surface combatant that is sailing under 25° of drift to port.

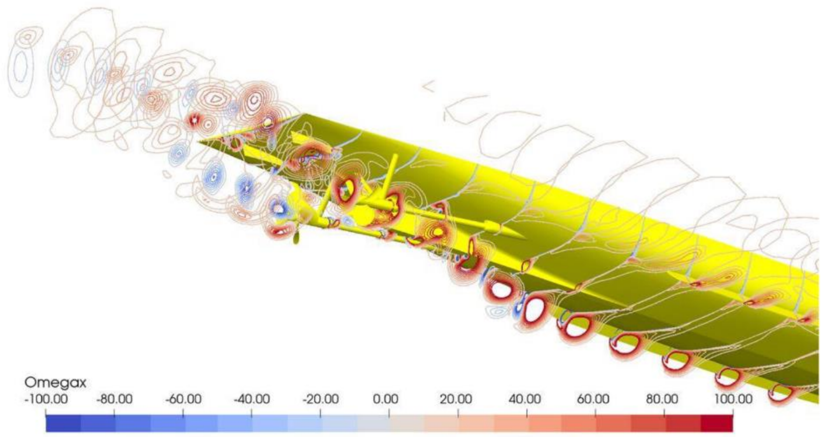

Figure 3-3 Vortex flowing through the starboard propeller of a naval surface combatant

The effect of the resulting swirl (i.e. averaged inflow rotation) in the wake fields on the effective RPM of the propellers is included in the manoeuvring simulation model. It can cause a strong difference between the load on the inside and the outside propellers of a ship that this sailing a turn. More details about this inflow model can be found in Moulijn et al. [8].

The effect of the ocean waves on the propeller model is predicted by means of the linear frequency domain seakeeping method named SEACAL. This is a 3-dimensional method (unlike strip-theory). This method accurately predicts the waves and water motions around the ship due the undisturbed incoming waves, the diffracted waves and the radiated waves due to the motions of the ship. The effect of forward speed on the waves is included.

3.2.3. *Validation*

The two-timescale simulation method to predict the propeller loads and ship motions of a ship that is manoeuvring in waves was validated against an extensive dataset for the DTMB 5415M naval surface combatant. The results are presented in Moulijn et al. [8]. Main conclusions are that this method gives reasonably good results for head and bow quartering waves. In stern quartering waves the agreement is less good, yet useful.

3.3. Coupling of the Ship and propeller to the PPE simulation

The ship and propeller simulation is running in co-simulation with the time simulation of the PPE system. This implies that information between the two simulations is exchanged at fixed common time steps, typically at the time step of the simulation that is running at the lowest frequency, which is the ship/propeller simulation in this case. The hydrodynamic torque that acts on the propeller is send to the PPE simulation. The shaft rotation is solved

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in the PPE simulation, where the rotational inertia of the propeller and its entrained water are taken into account. Subsequently the resulting propeller RPM is send back to the ship/propeller simulation.

With this method the effect of the propeller load variations on the PPE system are predicted. The method also predicts the effects of any limitations of the PPE system on the manoeuvring behaviour of the ship. When the PPE system cannot maintain the required RPM this will result in a lower thrust and the speed and heading keeping capabilities of the ship will reduce.

4. Test Case 'Highly dynamic military operation, involving a turning circle at high speed, while repetitively firing a railgun'

To demonstrate the use of virtual models for design verification and refinement, a test case involving a military manoeuvre is simulated using the models described in Section 3. The turning circle manoeuvre is performed sailing at an average speed of 18 knots in sea state 6 while the pulsed power weapon system is recharged for operation at a frequency of 0.2 Hz. The environmental conditions for the simulation are derived from NATO definitions. This is a significant wave height of 5 m, and a wave period of 12.4 s. The test case description is summarised in Table 4-1.

Table 4-1 Test Case Description

Description	unit	Value
Operational Task	-	Military Operations
Manoeuvre	-	Turning Circle
Sea State	-	6
Significant Wave Height	m	5
Wave Period	s	12.4
Required Average Ship Speed	kts	18
Auxiliary Services Power	kW	520
Payload Services Power	kW	5600
Railgun Recharge Power	kW	2500 for 4s
Railgun Firing Frequency	Hz	0.2

The ship performance for this test case is shown in Figure 4-1. The ship course shows that a turning circle manoeuvre is performed with firing operations occurring for a period of 100 s during the manoeuvre. It can also be seen that the vessel maintains an average speed of approximately 18.3 knots in the manoeuvre thus meeting the requirement of the average speed being greater than 18 knots. As the ship accelerates to this speed (i.e., between 0 and approximately 250 s), it starts in the electric mode where the electric machine provides the propulsion power. It then transitions to the shaft generation mode where the DF-methanol ICEs provide propulsion power and the electric machines feed the additional available power to the DC distribution system. It is seen that during the firing operations between 700 and 800 s, the electric machine exhibits power fluctuations due to the highly dynamic load of the rail gun. The main DF-methanol propulsion ICE is slower to respond, therefore, dynamics are introduced in the power delivered to the propeller resulting in speed and torque variations of the propeller. Therefore, while it is clear that while in the electric mode dynamics on the propulsion system would affect the power system, these simulations show that in the shaft-generation mode dynamics on the power system do have an effect on the propulsion system as well.

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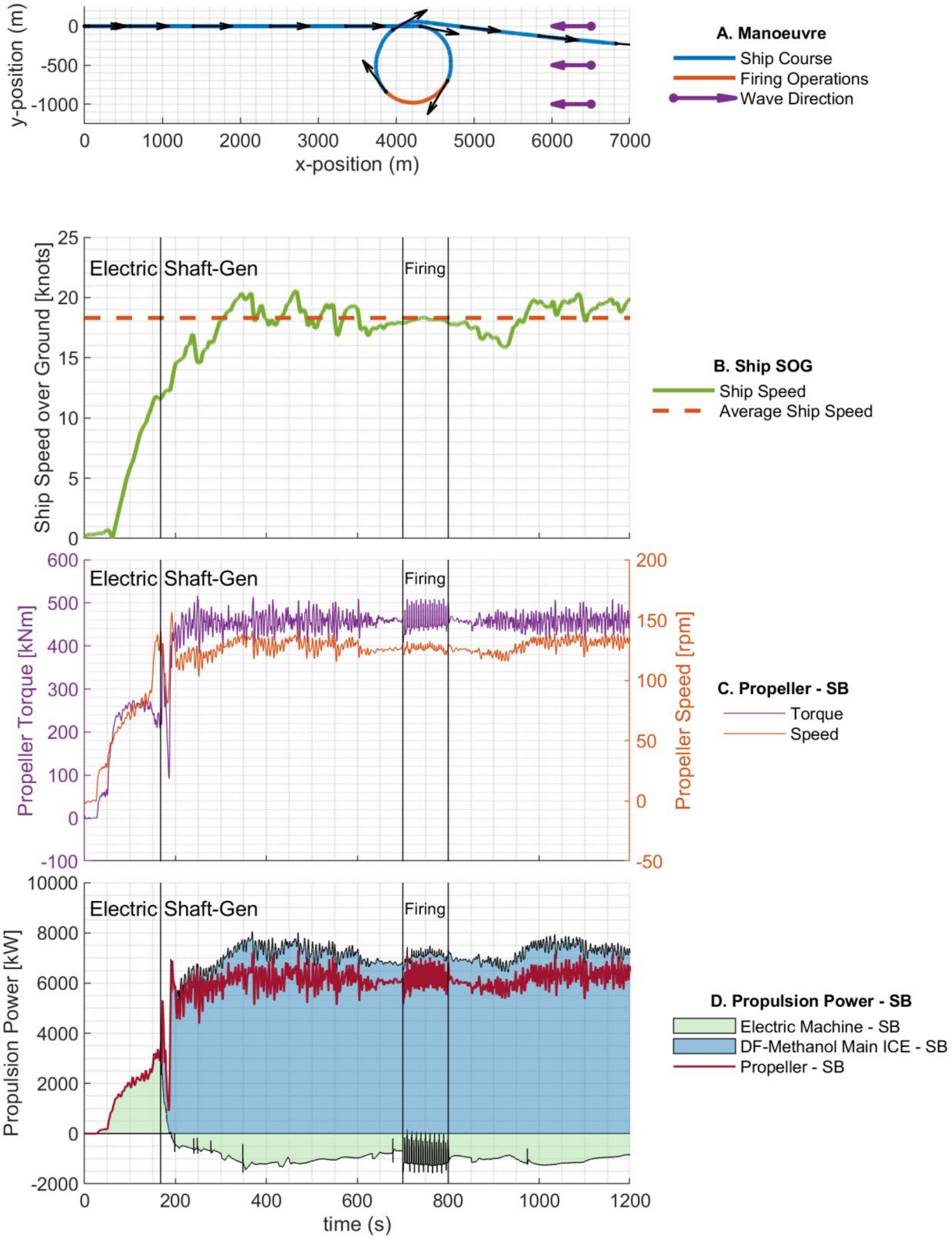

Figure 4-1 Ship performance for the simulated test case. The vessel operates in shaft generation mode where the Electric Machine operates as PTO and feeds excess power from the propulsion to the DC-distribution system. The vessel meets the test case speed requirement of maintaining an average speed of 18 knots when performing a turning circle manoeuvre in sea state 6 while recharging a railgun.

https://doi.org/10.24868/11199

Figure 4-2 shows the performance of the PPE system focussed on the period of firing. To meet the dynamics introduced by the railgun there are two sources with high dynamic capabilities – the electric machines acting as generators and the battery systems. These sources have high ramp rate capabilities and increase power output to meet the demand. The power delivered by the batteries is limited by their nominal power capabilities while that for the electric machines is limited by the excess power available on the propulsion system. The DF-methanol gensets also contribute to the power dynamics, however, because they are slow acting sources their contribution is limited. These dynamics are reflected in the DC-bus voltage and while the system remains in operation, it is on the edge of the operating region and the large voltage variations could result in power quality issues though the power system. While these simulation results show that the designed system meets the set requirement, there are opportunities for design refinement:

- Batteries with higher discharge capabilities could be used to take up the dynamics loads leading to reduced dc-bus voltage disturbances. With more power available on the grid, the railguns could be charged with a lower ramp in power.
- Additional supercapacitors could be added to the system and designed according to a required firing pattern. The supercapacitors can be sized to meet the energy requirement for a number of salvos followed by a longer charging period where the batteries charge the supercapacitors with lower ramp-up and ramp-down rates.
- More power could be made available to the DC-bus from the propulsion system via the electric machines. This could be implemented by additional settings in the combinator curve where the pitch is reduced for firing the railgun in heavy seas. This would make additional power available for the DC-grid at the cost of a possible reduction in the achievable ship speed.

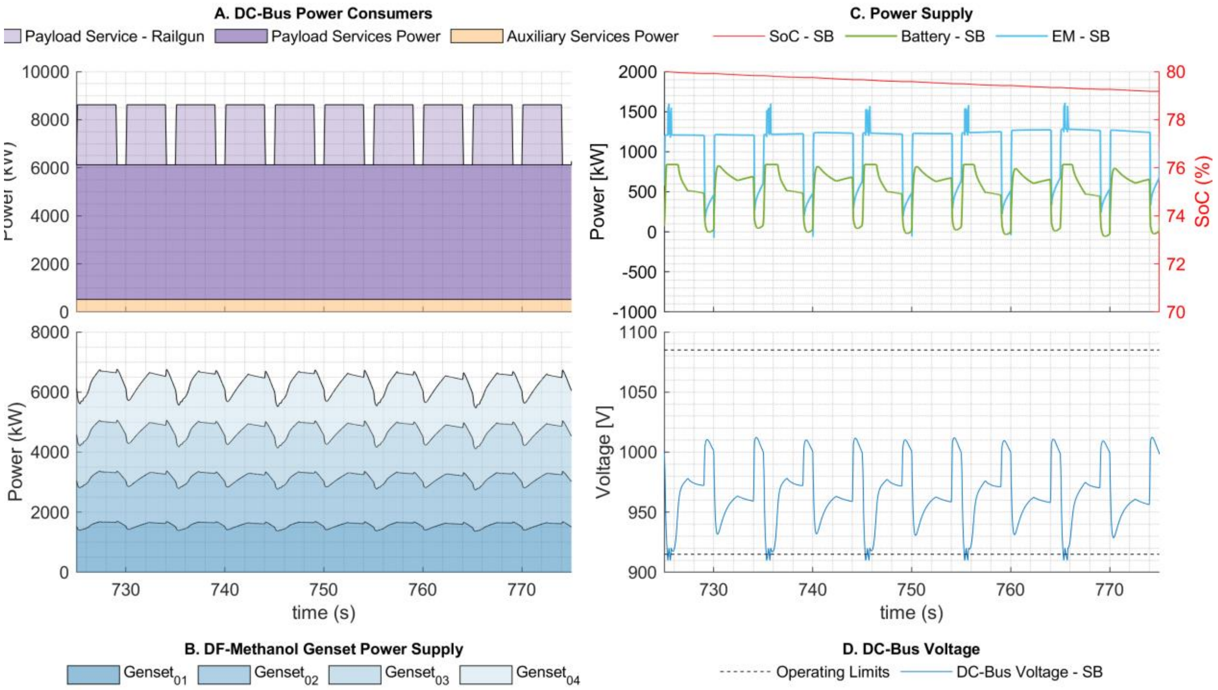

Figure 4-2 PPE System performance for the simulated test case focussed on the recharge operations of the railgun. The fast load dynamics are met by the batteries and electric machines acting as generators. While the system remains in operation, large voltage variations on the DC-bus are observed.

From the simulations it is clear that the electric machines contribute to meeting the dynamic demands of charging the railgun. It can therefore also be concluded that when sailing in the electric mode, without the possibility of feeding power to the DC-grid using the electric machines, the availability of dynamic power sources is limited to the batteries and the firing frequency of 0.2 Hz cannot be met. Therefore, a firing frequency of 0.1 Hz with a charging power of 1.25 MW for 8 s is simulated and the results presented in Figure 4-3. In this case too there are sharp dynamics seen on the DC-bus due to the charging profile which may be reduced with the addition of supercapacitors or batteries as discussed above or by implementing a combinator curve that allows sailing in the shaft generation mode at low vessel speeds for these firing operations.

It is clear with the simulation of this test case that the developed design should be refined to provide better performance during such challenging operations as sailing in heavy sea with re-charging of electro-magnetic and optical sensors and weapon systems. The results show the value of performing dynamic simulations to verify requirements involving dynamic situations that static calculations do not consider leading to valuable insight for further design iterations.

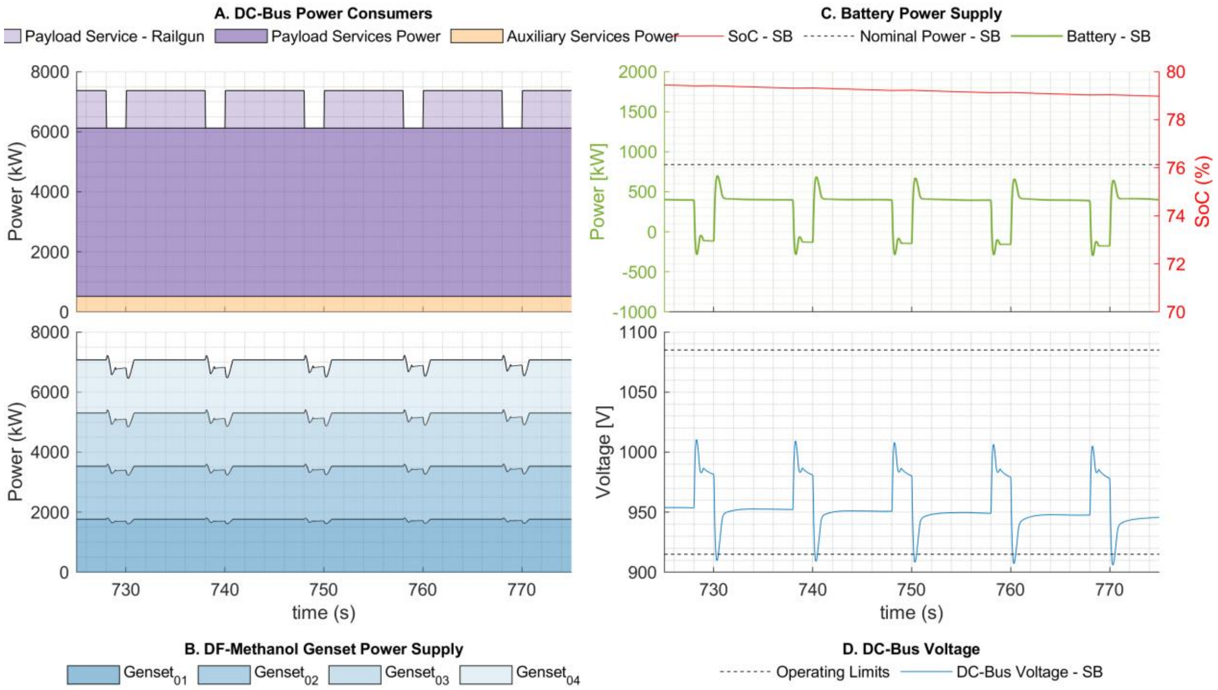

Figure 4-3 PPE performance focussed on railgun recharge operations while sailing in electric mode. Due to limited fast acting sources being available in the electric mode, the designed system in not capable of recharging the railgun for firing at 0.2 Hz. The results for a firing pattern with the railgun firing at 0.1 Hz is simulated.

5. Evaluation of Exhaust Emissions, Radiated Noise and detectability

After designing and testing the primary functionalities of the vessel, in this section two secondary characteristics of the ship's PPE system will be assessed; its exhaust gasses, radiated noise, and detectability. These aspects can be analysed from two different perspectives. For defence capabilities, they play a tactical role in detectability and susceptibility, while both also have an environmental impact. For military applications it is debatable whether exhaust gas emissions are of primary concern. Nevertheless a voluntary compliance [11] with Annex VI – Warships of the MARPOL Convention is frequently mentioned nowadays.

The proposed PPE design differs from conventional diesel powered systems in multiple ways. It has an intelligent topology, it makes use of methanol and hydrogen, and it can run in different operating modes. This has a significant impact, which will be analysed in this section. The analysis of CO_2 emissions is based on calculations performed during the conceptual design phase. All other aspects are considerations based on academic and industry knowledge and insights in the concepts and implemented components. Future research including further modelling and measurement of emissions and noise is on MARIN's research agenda.

5.1. Greenhouse gas emissions

The main concern with respect to global warming is the emission of CO_2 originating from fossil fuels, acting as a greenhouse gas in the atmosphere. The reduction can be achieved along two different pathways. A fuel with no or low carbon content can be used, in this way minimizing the tank to wake emissions. Another approach is to apply a fuel which is originating from renewable sources. Because no fossil fuel is extracted from earth as a source for such fuels, no new carbon (CO_2) is added to the atmosphere. Also for carbon-free fuel it is relevant that they are originating from renewable sources, otherwise their well to wake impact is limited.

In the proposed PPE design both pathways are followed. When operating on the fuel cells, or short-term on the batteries, no local emissions are produced. When either the propulsion engines or the gensets are used, exhaust gas is emitted by the dual fuel methanol engines.

To have a significant impact on greenhouse gas emissions, the dual fuel engines should run on renewable methanol. Today less than 1% of available methanol is green, the remainer is from fossil fuels[12]. With the ongoing adaption of methanol as shipping fuel to increase sustainability of the sector, this percentage is expected to grow. Besides an increase in bio-methanol production, the bulk of the growth is expected to originate from e-methanol; the hydrogen and captured carbon production route for synthetic methanol. To be sustainable, the used hydrogen has to be produced from renewable electricity.

5.1.1. Results for the concept

In the proposed concept the bulk of the greenhouse gas reduction comes from the application of renewable methanol and hydrogen. The exact number of the reduction is strongly dependent on the used sources to produce the fuel, and on the boundaries taken into account when calculating Well to Wake (WtW) CO_2 equivalent emissions. Considering a fossil reference of 99g CO_2 equivalent per MJ for HFO, for methanol a typical range between 5 and 46 gCO_2eq/MJ is reported [13]. In line with this, the ZERO project considers a 90% reduction of greenhouse gas emissions when applying methanol. Since in the designed concept dual fuel engines running on a 95% Methanol Energy Fraction (MEF) during medium and high load, still 5 percent of the energy is supplied by diesel, MFO or HFO. This limits the reduction of greenhouse gas emission by the choice of renewable methanol as a fuel to 86%. On low load the MEF value for most engines is even lower, but the versatile design of the PPE system can be controlled such, that engines are not used at very low load conditions. This is achieved by the introduction of electric, cross-shaft, and shaft-generation modes for the PPE system.

A further reduction could be achieved by replacing the fossil marine fuel oil by renewable Hydrotreated Vegetable Oil (HVO). This can be a direct substitution, so would not require further technical changes to the PPE system.

The fuel cells are used as the only power source in the zero emission operating mode, and can act as a support power in the other operating modes. They operate on hydrogen, so no direct CO_2 emission is taking place. For the well to tank emissions of hydrogen, the source for hydrogen production is relevant. In the worst case scenario, grey hydrogen is produced from fossil fuel, at an estimated 81 g CO_2 per MJ. This is only a small advantage compared to HFO. In the best case scenario green hydrogen is produced from offshore wind electricity, at 4.9 g CO_2 per MJ [14].

Since the ship's performance, weight, size and are changed, and only limited information of the diesel powered reference ship can be shared, it is not possible to make a direct comparison on absolute numbers regarding greenhouse gas emissions of the PPE system. As an alternative, a relative comparison was made, in which the efficiency improvement was estimated from the initial concept design for the four mission types. Combined with the well to tank emission of the used fuel (Fuel-based reduction), the total results were calculated. The resulting Well to Wake CO_2 reductions are shown in Table 5-1

Table 5-1 Emission reduction from fuel and PPE system efficiency increase with respect to the reference vessel operating on diesel, for all mission types

	Fuel-based GHG reduction[%]	Efficiency increase	Relative CO_2 emissions	Relative CO_2 reduction
Mission Type 1	86 %	10 %	12 %	87 %
Mission Type 2	86 %	20 %	11 %	89 %
Mission Type 3	86 %	20 %	11 %	89 %
Mission Type 4	95 %	60 %	2 %	98 %

 https://doi.org/10.24868/11199

It is good to notice that the bulk of the improvements come from the implementation of the renewable fuels. Although significant efficiency improvements can be achieved with new PPE system designs, they only have a limited effect on the total CO_2 reduction, because of the very low the WTW CO_2 impact of the chosen fuels. Nevertheless it is still preferable to increase system efficiency as much as possible. High efficiency results in lower fuel consumption and thus lower fuel costs. It has a direct impact on autonomy and/or the required bunker volume and mass, which ease the ship design. Finally, other emissions also scale with fuel consumption, and thus in general benefit from higher efficiency.

For mission type 1, 2 and 3, the Greenhouse Gas requirement was to be 70% climate neutral. Since the combination of fuel and engine performs better than the requirement, there is some space to sail a part of the missions with the engines in diesel-only operation. This reduces the required bunkering volume, and/or increases the autonomy of the ship. The ability to use diesel-only operation also increases fuel flexibility and thus availability of the total PPE system.

5.1.2. Non-CO_2 greenhouse gas emissions

Besides CO_2, also the emission of N_2O and methane are getting more and more attention, because of their high Global Warming Potential (GWP) [15]. For methanol dual fuel engines they are not considered as critical exhaust gas components, and occasionally reduced levels [16], [17] of N_2O are reported. Because of limited available information on the implemented engines, these exhaust gas components were not further included in this study.

5.2. Harmful emissions

The concept can run in Zero emission mode, powered by the fuel cells. When in other modes power is delivered by the dual fuel methanol gensets or main engines, in which exhaust gas emissions have to be considered. This is done on a theoretical level, since no emission modelling or measurement was performed within this project.

5.2.1. NOx

Regarding other emissions, in the maritime world most attention goes to the emission of NO_x. This is for example recognized in IMO Tier 3 with a minimum level of level 2g/kWh. For most diesel fuelled engines this requires the use of exhaust gas aftertreatment, specifically Selective Catalytic Reduction (SCR). Although this is a very effective measure, it has a significant impact on required building space, and complicates logistics because of the involved urea (Adblue, DEF) consumption. Several research campaigns show that moving from diesel to methanol dual fuel significantly reduces NO_x emissions, but without further measures Tier III levels are still challenging [17], [18], [19]. The lowering of NO_x emissions has two different causes. The injected methanol has an almost four times higher heat of vaporization. Combined with the more than two times higher required injection mass, in total eight times more heat is extracted from the air charge of the engine. This results in a lower process temperature, and thus lower NO_x production. The other cause can be found in the details of how a fuel combusts in an engine. Diesel burns in a very concentrated fuel-rich flame, which creates a very high peak temperature, hotter than the NO_x formation threshold. The methanol burns as a lean premixed flame through the cylinder, resulting in lower combustion temperature and thus lower NO_x formation.

5.2.2. SO_x

Sulphur oxide emissions can be fully contributed to the sulphur content of the used fuel. To reduce the emission of SO_x, IMO forces a maximum global limit of 0.5% for shipping fuels or the usage of scrubber exhaust gas aftertreatment. Methanol does not contain any sulphur, so its combustion does not emit SO_x [13]. Only the used pilot fuel can create sulphur emissions. As a result a reduction equal to the Methanol Energy Fraction can be expected from the combustion engines. The fuel cells do not emitting any SO_x,

5.2.3. PM

Particle emissions (black smoke), originate from incomplete breakdown of carbon chains in hydrocarbon fuels during combustion. Since methanol does not contain any carbon to carbon bonds, it does not generate PM emissions. Only the used pilot fuel could contribute to PM emissions. Since this is only a very small amount, the dual fuel methanol engines are able to comply with todays PM emission standards without the need for a Diesel Particle Filter (DPF).

 https://doi.org/10.24868/11199

5.2.4. HC & CO

Although not significant for diesel engines, the emission of uncombusted hydrocarbons and carbon-monoxide of a dual fuel engine can be considerable [20]. This is inherit for lean burn premixed combustion. Since no specific engine, including its emission data was used for the concept design, it cannot be decided whether an oxidation catalyst (DOC) [21] is required for the conceptual PPE system to comply with emission regulations.

5.3. Detectability

5.3.1. Radiated noise

The last two decades have seen an increasing interest in the reduction of underwater radiation noise (URN). The main driver here is protection of marine life. IMO addresses the topic both in their Marine Environment Protection Committee (MEPC) and in their Ship Design Committee (SDC). The EU Marine Strategic Framework Directive 2008/56/EC defines noise specifically as a pollution, which has to be restricted. For naval applications the URN relevance is on detectability and susceptibility, specifically by sonar.

For underwater radiated noise two main sources can be recognized; propeller induced cavitation and noise from onboard machinery, which either directly or through airborne transmission to the hull, excites the water. The reduction of cavitation is a delicate interplay between hull design, propeller design, and power control. On top of MARIN's hull and propeller experience, the wide control options for the proposed PPE system extend the possibilities for cavitation reduction.

Since noise measurements or predictions were not part of this study, we focus on available studies and conceptual impact. Regarding the machinery noise, three scenarios can be recognized.

- Direct propulsion by the combustion engine. With a large combustion engine running, significant machine noise is being produced. The medium speed 4 stroke engine is known to allow a more flexible and thus less noise-conducting mounting because of a lower weight than a 2 stroke engines. The dual fuel engine has a more gradual combustion profile, also slightly reducing noise vibration and harshness. (NVH).
- Electric propellor drive, powered by the gensets. Since no direct coupling with the mechanical drive is required, here a more sound isolated mounting can be applied. In a study by TNO[22] this configuration was recognized as being more silent than diesel direct. During operation the hybrid mode could specifically be selected (and optimized) for that purpose.
- Electric propellor drive, powered by fuel-cells. Although the balance of plant of the fuel cells includes air blowers which can be relatively loud, not much sound is generated in strongly transmitting low frequency spectrum <125Hz [23]. The fuel cell mode is often referred as zero emission mode, but it can also be used as low noise mode.

Smith and Rigby [24] mentioned that low frequency noise (<125 Hz [23]) is mainly related to the propulsion engine firing rate and the propeller blade-rate harmonics. Higher frequencies originate from machinery, propeller and flow noise, and cavitation.

In a recent study the relation between electrification and airborne and underwater noise radiation was investigated [25]. This was done for three different hybrid ferries, consisting of an electric drive which could be powered by a diesel generator or batteries. Although the measurements were done at relative low speed in calm water, it nevertheless gives an impression of the impact of different power systems on radiated noise. In air the difference can be seen on around the engine's base frequency. In the water the gensets only have a limited impact on the URN. Here it was concluded that the step from direct drive to genset operation has a larger impact on URN then the elimination of gensets in favor of another electricity power source.

5.3.2. Infrared

In a follow up NATO standard ShipIR/NTCS could be followed to come to a quantitative conclusion on infrared detectability. Regarding the exhaust gasses, the main contribution comes from the presence of carbon dioxide and water vapour at higher temperature. Although the methanol engine in general has a lower CO_2 concentration, a higher H_2O concentration and a slightly lower temperature, there is no change in the order of magnitude of these influences. Taking into account that it is common to passively cool the exhaust gas to close to ambient temperature, the impact of changing from diesel to methanol on the detectability by temperature will not be further discussed here.

Relevant is the possibility of the proposed PPE system to operate without running the combustion engines. Care has to be taken that this transition takes some time before it eliminates the impact of detectability, because of the heated exhausts, ducts and related components. They require time to cool down.

5.3.3. Exhaust gas components

Besides the measurement of temperature by IR, the Short Wave Infrared (SWIR) and Near Infrared (NIR) can also be used to detect specific component concentrations in the atmosphere. This is for example globally done for the detection of super-emitters of methane [26]. From a satellite only a limited resolution can be achieved, but more local detection could be done by for example an observation airplane or drone. In such a scenario, the increase of hydrocarbons from a dual fuel engine is a disadvantage. On the other hand, the close to zero soot emission prevents direct optical observability caused by black smoke.

6. Conclusions

This paper presents the conceptual design of a future surface combatant operating on methanol and hydrogen designed to meet the requirement of a 70% carbon neutral operation and the ability to sail short zero-emission missions. It further demonstrated the use of virtual models to test the ability of the design to meet requirements at an early design stage by simulating a test case of the vessel sailing in heavy seas while repeatedly firing a pulsed electro-magnetic weapon system. The concept design and requirement verification was followed by a qualitative analysis of the emission performance of the developed design. This study draws conclusions on a number of aspects related to the design of a complex future surface combatant.

From the standpoint of the design method, the study shows that a complex concept requires a systematic development method. The W-model employed in the study uses a thorough investigation of user needs to develop logical and physical design architectures. These architectures are tested in simulation to ensure that they meet the requirements developed in the design process. It also highlighted the use of such simulations in design refinement.

From the standpoint of simulation for requirement verification, the paper shows that by coupling dynamic PPE system models to hydrodynamic models in MARINs XMF framework an integrated verification could be performed. It showed how these two disciplines interact and have an effect on each other thereby making such integrated testing an important capability for testing new PPE and ship systems.

From the standpoint of the suitability of the developed design, the paper shows that while highly dynamic electro-magnetic weapon systems like railguns pose real challenges to the power system, future PPE systems could meet these challenges by using smart design and control approaches that leverage the use of fast power sources like batteries. It also shows the ability of the developed design to achieve a reduction of close 90% in greenhouse gas emissions while maintaining fuel-flexibility and autonomy extension with the conservation of a diesel-only sailing mode. It also shows the multi-mode concept that includes fuel cells and gensets allows multiple ways of reducing underwater radiated noise. In summary, the paper shows that demanding military operations can be performed, in a reliable way, by low-greenhouse gas Power, Propulsion and Energy systems.

Acknowledgements

The authors would like to thank the ZERO JIP participants for their contribution to this research, their critical notes and valuable information that is shared to come to these results.

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