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Optimisation of a Hybrid-Parallel Power Train for a Aframax Tanker to Minimise Emissions in Every Operative Condition

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Abstract. The regulatory constraints imposed on the maritime sector regarding the complete elimination of greenhouse gas emissions by 2050 are driving extensive research into alternative fuels and renewable energy sources. In this context, biomethane might be a viable solution. Nevertheless, due to its higher price, it is even more important to enhance the energy efficiency of the ship's power train to reduce consumption and minimize pollutant emissions during operation. Considering a hybrid-parallel power train, many possible configurations exist in terms of running internal-combustion engines, power exchanged through shaft electric motor/generator and power to/from batteries, to provide a given propeller thrust and onboard electric load for auxiliaries, outfitting and accommodation. This study proposes a method for the optimization of a ship's power train of a biomethane-fuelled Aframax tanker with two propulsion four-stroke dual-fuel engines, a Controllable Pitch Propeller (CPP), two shaft motors/generators, one genset and an energy storage unit. Given each couple of thrust required by the ship and electric load and considering the engines' specific fuel consumption curves and their limit, the study aims to determine the optimal combination of propeller pitch and power exchanged by each system component to minimise hourly fuel consumption. These results will be useful in giving guidance to the crew about how to manage the power train and to run probabilistic simulations of ship operation.

Keywords. ship power train, hybrid propulsion, optimization, emissions reduction, bio-methane

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1. Introduction

The international shipping sector is now subject to very stringent decarbonisation targets. The International Maritime Organisation's (IMO) 2023 Strategy commits to net-zero Green House Gases (GHG) "by or around 2050" with intermediate targets (20–30% CO_2 cut by 2030, 70–80% by 2040 vs 2008). In line with this, mandatory short-term measures took effect in 2023: every large ship must now calculate an Energy Efficiency Existing Ship Index (EEXI) and report an annual Carbon Intensity Indicator (CII) with an A–E rating [1]. These requirements are designed to reduce the CO_2 intensity (g CO_2 per tonne-mile) of shipping by more than 40% by 2030.

The European Union (EU) has introduced complementary rules. Since January 2024, the EU Emissions Trading System (ETS) covers CO_2 from all ships of 5000 GT or above calling at EU ports [2,3]. At the same time, the FuelEU Maritime Regulation (part of the Fit-for-55 package) mandates progressively stricter limits on the life-cycle GHG intensity of marine fuels [4]. For example, FuelEU requires a 2% reduction in average fuel GHG-intensity by 2025 and up to 80% by 2050. These measures support the EU target of a 55% reduction in shipping emissions by 2030 and a climate-neutral fleet by 2050.

Against this regulatory backdrop, hybrid-electric propulsion has emerged as a key decarbonisation technology. Hybrid systems combine diesel engines, batteries (or other storage) and power electronics to optimise energy use. Studies show that such systems – through optimized energy management – can markedly cut fuel consumption and emissions, aiding decarbonisation goals [5,6]. In practice, batteries enable "peak shaving" (letting engines run at efficient loads) and even pure-electric operation during low-power or port manoeuvres. Likewise, switching to LNG fuel (or blends) dramatically reduces SO_x/NO_x and particulate outputs – studies report 92-99% SO_x and 80-85% NO_x savings (with around 20-30% CO_2 savings) versus heavy fuel oil [7] and using renewable bio-methane can reduce life-cycle CO_2 by roughly 75–90% [8]. Although hybrid systems add complexity and cost, they align directly with IMO and EU efficiency rules and enable flexible fuel use.

Effective real-time utilisation of hybrid propulsion systems requires computationally efficient and robust models that are suitable for onboard optimisation and rapid scenario analysis. High-fidelity transient models, while accurate, are often too computationally demanding for real-time applications [9,10]. As a result, researchers have turned to simplified, reduced-order models that neglect fast dynamics but retain the essential features of power and energy flow within the ship's power train [11]. These models have demonstrated the ability to deliver accurate predictions of energy consumption and power exchange with significantly reduced computational costs. They can serve as the foundation for decision-support tools aimed at optimising operational strategies such as speed and load management, helping ships comply with CII and EU ETS constraints while minimising fuel consumption and emissions.

In this context, the present work introduces a novel optimisation framework tailored to bio-methane-fuelled Aframax tankers with hybrid-parallel power trains. The proposed methodology leverages an interior-point algorithm to solve a constrained optimisation problem that simultaneously adjusts the propeller's pitch ratio and the power exchanged via the shaft motor/generator. Designed for real-time applications and rapid simulation, this framework enables dynamic optimisation of the power train configuration under varying operating conditions, supporting both efficient energy use and regulatory compliance.

2. Methodology

This section introduces the dual-fuel hybrid-parallel power train architecture developed for an Aframax-class tanker. Subsequently, the formulation of the optimisation problem is presented, aimed at identifying the most efficient operating configuration of the system. The modelling approach adopted for both the propulsion and power generation subsystems is then described in detail.

2.1. The Power Train

The configuration of the power train under investigation is illustrated in Figure 1. Its

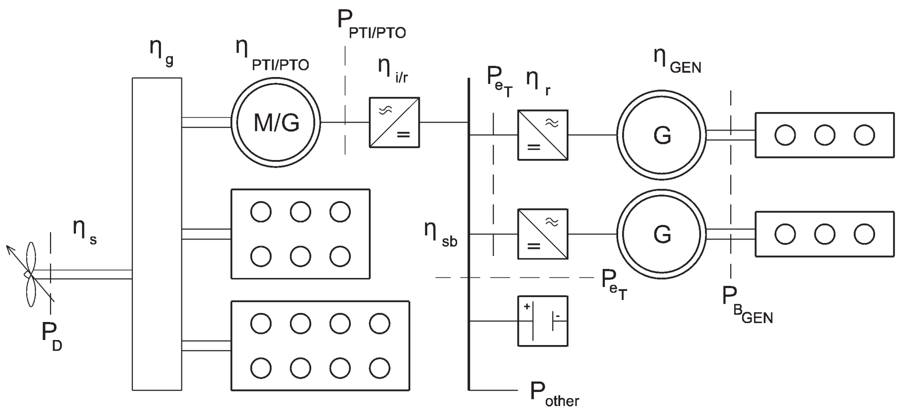

Figure 1. HSFO equivalent consumption for different speeds, ship resistance and electrical power demand

main features are as follows:

- A single Controllable Pitch Propeller (CPP);
- A gearbox with a reduction ratio r_g, connected to:
  - a reversible electric machine capable of operating in either Power Take Off (PTO) or Power Take In (PTI) mode;
  - one or more four-stroke, medium-speed, dual-fuel propulsion engines;
- Main switchboards and a distribution system operating in Direct Current (DC);
- An electric rectifier/inverter enabling the connection of the PTO/PTI unit to the main switchboards;
- Two or more dual-fuel generator sets connected to the main switchboards via a rectifier;
- An energy storage system integrated into the DC main switchboards.

2.2. Optimisation problem

Given a specific operational state of the power train, characterised by a fixed ship speed V_s, total hydrodynamic resistance R_T, and electric power demand P_e (i.e., the power required by auxiliaries, outfitting services, hull systems, and including the power exchanged with the energy storage system), the following optimisation problem is formulated to determine the most efficient configuration of the system:

$$\begin{cases} \text{find} & \mathbf{x} \\ \text{minimise} & f(\mathbf{x}) \\ \text{subject to} & \begin{cases} \mathbf{g}_{min}(\mathbf{x}) \leq 0 \\ \mathbf{g}_{max}(\mathbf{x}) \leq 0 \\ \mathbf{g}_{prop}(\mathbf{x}) \leq 0 \end{cases} \end{cases} \tag{1}$$

The optimisation variables are the propeller's pitch ratio and the electric power exchanged through the PTI/PTO system:

$$\mathbf{x} = \left(\frac{P}{D}, P_{PTI} \right) \tag{2}$$

The objective function $f(\mathbf{x})$ quantifies the overall emission rate of the power train:

$$f(\mathbf{x}) = \sum_{i=1}^{n} GWP_i \left(\dot{m}_{s_i}(\mathbf{x}) + \sum_{j=1}^{m} EF_{ij} \cdot \dot{m}_j(\mathbf{x}) \right) \tag{3}$$

where:

$$\dot{m}_j(\mathbf{x}) = \left[(1 - s_{prop_i}) \cdot \dot{m}_{prop_j}(\mathbf{x}) + (1 - s_{gen_i}) \cdot \dot{m}_{gen_j}(\mathbf{x}) \right] \tag{4}$$

$$\dot{m}_{s_i}(\mathbf{x}) = \left(s_{prop_i} \cdot \dot{m}_{prop_j}(\mathbf{x}) + s_{gen_i} \cdot \dot{m}_{gen_j}(\mathbf{x}) \right) \tag{5}$$

Here, s_i denotes the slip fraction, applicable only to volatile pollutants (e.g., methane; otherwise set to zero), n is the number of pollutants considered, GWP_i is the global warming potential of the i-th pollutant, m is the number of fuel types, and EF_{ij} is the emission factor of the j-th pollutant for the j-th fuel type. To ensure that the optimisation variables remain within feasible bounds, linear inequality constraints are defined as:

$$\begin{aligned} \mathbf{g}_{max}(\mathbf{x}) &= \mathbf{I} \times \mathbf{x} - \mathbf{x}_{max} \\ \mathbf{g}_{min}(\mathbf{x}) &= -\mathbf{I} \times \mathbf{x} + \mathbf{x}_{min} \end{aligned} \tag{6}$$

where $\mathbf{I}$ is the identity matrix, and $\mathbf{x}_{\text{max}}$ and $\mathbf{x}_{\text{min}}$ represent the upper and lower bounds of the decision variables. The bounds on the pitch ratio are defined according to the propeller geometry, while the limits on PTI/PTO power are defined as:

$$\max(-P_e, -P_{PTO}^{max}) \leq P_{PTI} \leq \min(P_{G_{max}} - P_e, P_{PTI}^{max}) \tag{7}$$

where $P_{G_{max}}$ is the installed generation power, whereas P_{PTO}^{max} and P_{PTI}^{max} denote the maximum allowable electric power for PTO and PTI modes, respectively. Additional non-linear constraints are imposed to ensure that each propulsion engine operates within its permissible range. These constraints verify that the engine rotational speed n is within the allowable limits and that the load at the current rotational speed does not exceed the engine's maximum load curve $l_n^{\text{max}}(\mathbf{x})$. For each propulsion engine, the following conditions must be satisfied:

$$\mathbf{g}_{prop}(\mathbf{x}) = \begin{cases} g_n^{min}(\mathbf{x}) = n_{min} - n(\mathbf{x}) \\ g_n^{max}(\mathbf{x}) = n(\mathbf{x}) - n_{max} \\ g_l^{min} = -l_n(\mathbf{x}) \\ g_l^{min} = l_n(\mathbf{x}) - l_n^{max}(\mathbf{x}) \end{cases} \tag{8}$$

To solve the optimization problem, the interior-point algorithm is employed, as described in [12,13,14,15].

2.3. Propulsion System

Given the total resistance R_T, ship speed V_s, and a generic value of the pitch ratio P/D for the CPP, the propeller rotational speed n_{CPP} and the required torque Q can be determined using standard propulsion calculations [16]. Accordingly, the required engine rotational speed n is derived by accounting for the reduction ratio r_g of the gearbox as:

$$n = n_{CPP} \cdot r_g \tag{9}$$

Furthermore, in PTI mode, the brake power developed by the propulsion engines is calculated as follows:

$$P_B = \frac{Q \cdot 2\pi \cdot n}{\eta_s \cdot \eta_g} - P_{PTI} \cdot \eta_{PTI} \cdot \eta_g \tag{10}$$

whereas in PTO mode it is given by:

$$P_B = \frac{Q \cdot 2\pi \cdot n}{\eta_s \cdot \eta_g} + \frac{P_{PTO}}{\eta_{PTO} \cdot \eta_g} \tag{11}$$

Here, η_s, η_g, η_{PTI} and η_{PTO} denote the efficiencies of the shaft line, gearbox, PTI and PTO systems, respectively. If multiple propulsion engines are installed, the brake power P_B is proportionally allocated among them according to their Maximum Continuous Rating (MCR). Therefore, the required propulsion load for the engines can be expressed as:

$$l_n = \frac{P_B}{\sum_k MCR_k} \tag{12}$$

Given the load, the fuel consumption for the j-th fuel type is calculated using the Specific Fuel Oil Consumption (SFOC) curves as a function of engine speed n and load l_n:

$$\dot{m}_{prop_j} = \sum_k SFOC_j(n, l_n) \cdot l_n \cdot MCR_k \cdot 10^{-6} \tag{13}$$

When engines operate in dual-fuel mode, the consumption rates of both the primary and pilot fuels are determined using the respective SFOC values.

2.4. Generation System

Given the electrical power demand P_e, the ship's generators are required to supply the following total electric power when the power train operates in PTI mode:

$$P_{e_T} = \frac{P_e + \frac{P_{PTI}}{\eta_i}}{\eta_{sb}} \tag{14}$$

whereas in PTO mode, the total electric power is:

$$P_{e_T} = \frac{P_e - P_{PTO} \cdot \eta_r}{\eta_{sb}} \tag{15}$$

Here, η_i denotes the efficiency of the inverter, η_r the efficiency of the rectifiers, and η_{sb} the efficiency of the main switchboards and distribution system.

Assuming the minimum number of generators operate at equal load, the brake power of each active generator is given by:

$$P_{B_{gen}} = \frac{P_{e_T}}{\eta_{gen} \cdot \eta_r} \tag{16}$$

The load and fuel consumption $\dot{m}_{prop_j}$ can be determined following the same procedure as for the propulsion engines (Equations 12 and 13), noting that generators run at constant rotational speed and thus only a single $SFOC_j(l_n)$ curve applies.

3. Application

In this section the test ship is presented along with the test cases for which the optimisation has been carried out.

3.1. Test Ship

To demonstrate the practical applicability of the proposed methodology, a case study is conducted using an Aframax-class oil tanker with a deadweight of approximately 114,000 tonnes. In order to reduce the vessel's environmental impact, the ship is designed to operate on marine gas oil (MGO) or bio-methane, rather than conventional heavy fuels. The main particulars of the case study vessel are summarised in the Table 1.

Unlike the typical propulsion setup for this class of vessel, which usually features a single low-speed two-stroke engine directly driving a fixed-pitch propeller, the case study explores an alternative solution: a hybrid power train with a single-screw configuration where a CPP is driven by two four-stroke medium-speed engines, connected through a reduction gearbox. This gearbox also allows for the integration of up to two power take-off/power take-in (PTO/PTI) units, providing additional flexibility for hybrid operation and energy efficiency optimisation. In addition to the main propulsion system, the vessel is equipped with two diesel generators dedicated to meeting onboard electrical loads. Main informations about engines and diesel generators are summarised in Table 2.

Table 1. Main particulars of Test Ship

Dimension	ID	Value	Unit
Length between perpendicular	L_{BP}	245	m
Length overall	L_{OA}	250	m
Design beam	B	44	m
Design draft	T	15	m
Design speed	V_s	13	kn
Deadweight	DWT	114000	t

Table 2. Characteristics of the test ship's engines and electric generators

N	Model	Type	Fuel	P_{min} (kW)	P_{max} (kW)
1	Wärtsilä 14V31DF	Propulsion Engine	MGO/biomethane	1680	8400
1	Wärtsilä 8V31DF	Propulsion Engine	MGO/biomethane	960	4800
2	Wärtsilä 9L20DF	Generator	MGO/biomethane	400	1980

The propulsion system drives a four-bladed CPP with a design pitch-diameter ratio of 0.754. The propeller has an approximate diameter of 7 metres and an expanded area ratio (A_E/A_0) of 0.620, selected based on the ship resistance curve increased by a sea margin, and dimensioned to allow the engines to reach 750 rpm at MCR.

Table 3 shows the assumptions concerning machinery efficiencies and performance coefficients considered in the hybrid power train optimisation process.

Table 3. Main particulars of Test Ship

Description	ID	Value
shaft line and thrust bearing efficiency	η_s	0.970
gearbox efficiency	η_g	0.995
gearbox reduction factor	r_g	8.20
PTI units mode efficiency	η_{PTI}	0.970
PTO units mode efficiency	η_{PTO}	0.970
Inverter efficiency	η_i	0.975
Switchboard efficiency	η_{sb}	0.999
Generation efficiency	η_{gen}	0.970

3.2. Test cases

The optimisation process has been applied in multiple conditions of the power train identified by a combination of values of ship speed V_s, ship resistance R_T and electric power demand P_e. Four distinct electric power demands P_e have been considered: 1000, 2000, 3000, and 4000 kW. Seven different ship operating speeds V_s were analysed, ranging from 3 knots up to the design speed of 13 knots. Based on the known calm water resistance curve of the vessel as a function of speed, the total resistance R_T at each specific speed was determined. To simulate increased resistance under rough sea conditions and fouling accumulation, other two values of resistance have been added to the calm water one, augmented by 10% and 25%, respectively. The methodology was applied across all combinations of power demand, vessel speed, and the three resistance scenarios. For each condition, the optimal combinations of propeller pitch ratio and PTI/PTO power demand were calculated to minimise the hourly fuel consumption of both the mechanical propulsion engines and the diesel generators.

Both propulsion engines and diesel generators were modelled assuming biomethane as the primary fuel, with MGO used as pilot flame. For comparative purposes, an equivalent fuel consumption in terms of Heavy Solphure Fuel Oil (HSFO) was also calculated, taking into account the lower heating values (LHV) of the fuels considered, according to the following formula:

$$HSFO_{eq}fc = \sum_{j} \dot{m}_{prop_j} \cdot \frac{LHV_j}{LHV_{HSFO}} \tag{17}$$

where LHV_j identify the j-th fuel lower heating value, LHV_{HSFO} identify the HSFO lower heating value.

4. Results and Discussion

Figure 2 summarises the hourly HSFO-equivalent fuel consumption for the various power demands, vessel speeds, and resistance scenarios analysed.

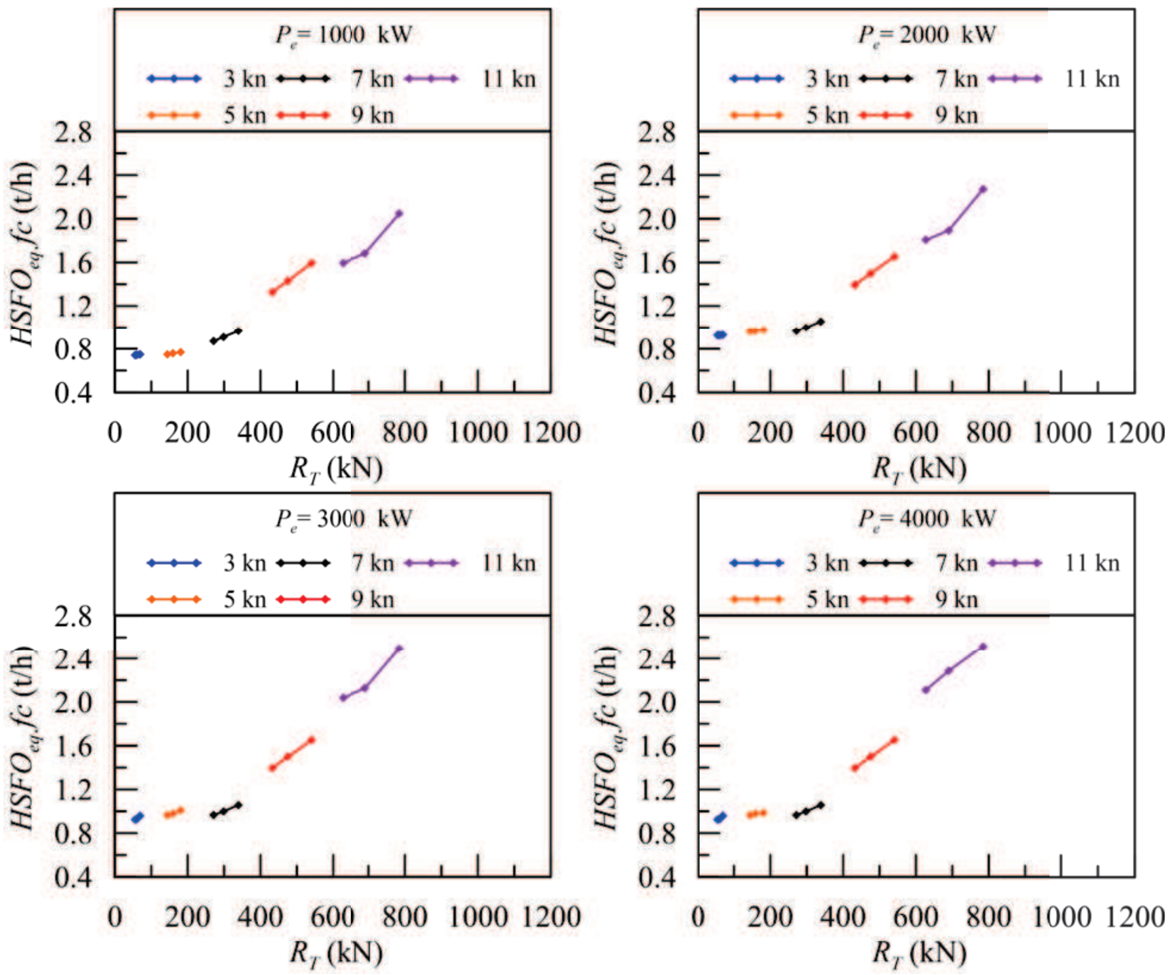

Figure 2. HSFO equivalent consumption for different speeds, ship resistance and electrical power demand

As expected, for a given speed, both resistance and fuel consumption rise as engine power increases. For instance, at 13 knots, the curve shifts significantly upwards and to the right from the 1000 kW to the 4000 kW graph, indicating a steep rise in both resistance and fuel consumption. This highlights the increasing energy cost of maintaining high speeds, especially under greater resistance.

At lower speeds (such as 3 to 7 knots), the increase in resistance and fuel consumption remains relatively modest across all power levels. However, at higher speeds (9 knots and above), the impact of increased resistance is much more pronounced. In particular, the 11 and 13 knot curves show that even a modest rise in resistance leads to a substantial increase in fuel consumption, particularly at higher power demands. At the vessel's maximum speed (13 knots), the power train is unable to overcome the increased resistance. As a result, a constant fuel consumption value is reported, corresponding to the maximum available propulsion power, even though the target speed is not achieved. In all other scenarios, the PTI/PTO system supports the propulsion engines in operating close to their optimal efficiency point, thereby reducing overall fuel consumption and emissions.

The optimisation process is computationally efficient, requiring approximately one minute to complete on a standard laptop. This makes it well-suited for integration into reduced-order modelling frameworks.

5. Conclusions

The analysis confirmed that maintaining high speeds leads to a significant increase in both resistance and fuel consumption, particularly at higher engine power levels. This effect becomes evident where even small rises in resistance result in markedly higher fuel usage. Conversely, at lower speeds, the impact of increased resistance is modest and more manageable from an energy perspective. The findings also highlight that, under certain operating conditions, the use of PTO/PTI systems combined with controllable pitch propellers can effectively compensate for resistance increases due to adverse weather, provided the engine's maximum load is not exceeded. These results underscore the value of flexible propulsion management in optimising fuel efficiency and operational performance under variable scenarios.

The study's significance extends beyond individual vessel optimisation, as the developed methodology can be integrated into broader fleet management systems and incorporated into the probabilistic simulation frameworks established by previous research. The deterministic optimisation results provide essential input data for Monte Carlo simulations, enabling more accurate fleet-wide emissions assessments and supporting strategic decision-making in sustainable shipping operations.

This study serves primarily to demonstrate the feasibility of the proposed methodology and is subject to several limitations. Specifically, it assumes constant efficiencies for the main power train components and considers the energy exchanged by the energy storage systems solely through the electric power term P_e. Future work will focus on integrating this optimisation process into a broader simulation framework, enabling a comparative assessment of emissions and operating costs between the proposed power train and a conventional configuration featuring a fixed-pitch propeller driven by a two-stroke engine.

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