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A comparison among innovative hybrid propulsion systems to reduce the environmental impact of a small passenger ship

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ABSTRACT

Fossil fuels contribute to GHG emissions into the atmosphere. The need to solve this critical global problem has driven the search for alternative energy options to pave the way towards a more sustainable future. This paper analyzes the environmental and economic performance of a small cruise ship operating in the North Atlantic Ocean. The paper compares natural gas-electric and hybrid propulsive configurations, considering LNG and E-LNG produced using renewable electricity. The carbon footprint analysis is based on equivalent CO_2 emissions according to a Well-to-Wake approach and includes emissions of the on-shore power for battery charging. A novel index for the energetic classification of ships is proposed, considering their equivalent CO_2 emissions using a Well-to-Wake approach. The hybrid propulsive systems show a fair fuel-saving potential, ranging from 3.5% to 5.3%. The E-LNG-powered propulsion is three times more expensive than LNG, while GHG emissions produced using E-LNG are 4.5 to 6 times lower. The battery pack is a major cost item in hybrid systems. Moreover, GHG evaluation through the novel index penalizes hybrid propulsion systems compared to traditional carbon dioxide emission assessment since the former includes ground connection used for battery charging.

Introduction

International shipping significantly contributes to global Greenhouse Gas (GHG) emissions, responsible for approximately 3% of global CO_2 emissions [1]. While shipping enables the mass movement of goods, it also incurs high water and air pollution costs. There is a substantial amount of evidence on the wide range of health effects of air pollution, which include respiratory, cardiovascular, and metabolic diseases, stroke, lung cancer, impaired fertility outcomes, preterm birth, reduced birth weight, and premature mortality. For 2019, an estimated 4.1 million deaths, or 7% of premature mortality worldwide, are attributable to ambient air pollution, ranking air pollution as a leading risk factor in the Global Burden of Disease Study [2,3]. Maritime transport accounts for about 3% of global greenhouse gases emissions, as well as 13% of nitrogen oxide (NO_X) and 12% of sulfur oxide (SO_X) emissions, but also emits other pollutants, including particulate matter (PM), black carbon (BC) and methane (CH_4), all known to be harmful to human health [2,4,5].

The shipping sector accounts for about 90% of world freight trade. For this reason, even marginal improvements in energy efficiency, operating procedures, and emissions reduction within shipping can yield substantial environmental benefits. Maritime transport, therefore, represents a unique opportunity to take significant steps towards a more sustainable future. Adopting innovative technologies, transitioning to cleaner fuels, and implementing effective policies can improve the sector's energy efficiency and reduce its environmental impact. Collaborative efforts among governments, international organizations, and the shipping industry are crucial to promoting these improvements and ensuring that shipping facilitates global trade in an environmentally responsible manner. The regulatory framework is pushing towards implementing sustainable strategies in all industrial fields, focusing on massive and constant reduction of greenhouse gas emissions. In particular, reducing environmental pollution is one of the primary drives of the International Maritime Organization (IMO) in issuing regulations [1]. As a result of these regulations, the industry's approach is rapidly changing. This change is particularly evident in the propulsion system design field, where the demand for solutions that are not only technologically advanced but also environmentally sustainable is increasingly high [6]. In compact vessels operating primarily over

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Abbreviations

AK	Annual Cost
$BESS$	Battery Energy Storage System
$BSGC$	Brake-Specific Gas Consumption
$CAPEX$	CAPital EXpenditure
CII	Carbon Intensity Indicator
$E\text{-}LNG$	Electric-Liquefied Natural Gas
GHG	Greenhouse gas
GII	Greenhouse gas Intensity Indicator
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
NPV	Net Present Value
$OPEX$	OPerational EXpenditure
SGC	Specific Gas Consumption

short distances, such as coastal areas or inland waterways, previous research indicates that adopting zero-emission propulsion systems with lithium-ion batteries charged through on-shore power grids can reduce environmental impact. This strategy can significantly reduce emissions in these scenarios [7]. Given the complexity and extent of the problem, there is no one-size-fits-all solution. Instead, there is a wide range of possible solutions with different impacts on emission reduction. These solutions range from optimizing hull shapes to adopting alternative propulsion systems, using alternative fuels and energy sources, and adopting unconventional operational measures [8–10].

The scientific literature proposes a wide variety of studies. The energetic, environmental and economic performance of hybrid-electric systems installed onboard large cruise ships were evaluated by considering alternative fuels such as liquefied natural gas [11], and methanol ammonia and methane-hydrogen blends [12]. The results showed that costs and emissions can be reduced if LNG or ammonia are used. Methanol is a valuable option only for a short-term energy transition perspective since the compliance with regulations lapses before 2028, while from an economic point of view, methane-hydrogen blends turned out to be disadvantageous due to the high price still affecting green hydrogen. Another study [13] proposed the installation of battery packs as a backup power source to meet the reliability requirements of navy ships and to reduce operating costs, consumption, pollutant emissions, and life cycle costs. Conventional fossil fuels have been compared to fossil-based alternative fuels E-fuel, showing the environmental benefits of E-fuels and the additional costs involved for ship propulsion [14], as well as high energy consumption in a Well-to-Wake context, partially compensated in case a large and cheap availability of renewable electricity: in this case, synthetic fuels could be more commercially attractive than hydrogen and ammonia [15]. The impact of using ammonia as fuel has been analyzed in the ship propulsion context, focusing on the variations in range, general arrangements, stability [16], or the impact on life cycle cost [17]. A methodology to assess the feasibility of methanol as a fuel for ship propulsion, with significant attention to its environmental and economic impact, has been proposed [18], suggesting that the renewable methanol is a viable option for reducing shipping emissions at a high economical price. However, the economic barriers must be overcome by strengthening environmental targets for shipping or if fuel oil prices revert to higher levels [19]. A methodology for estimating the environmental performance of a ship in the preliminary design phase simulating different hybrid power plant configurations has been proposed [20], comparing the propulsive configurations based on appropriate key performance indicators. LNG distribution and on-board installation systems in the Arctic have been investigated, focusing on global and local environmental benefits, technical solutions, safety, and cost-related issues [21].

Researchers focused heavily on developing optimization methods, both for sizing hybrid propulsion systems [22] and managing them to minimize cost [23], fuel consumption [24], and environmental impact [25–27], as well as for dynamic positioning operations [28] and route optimization [29]. A major limitation of the current regulation framework is the assessment of GHG emissions using a Tank-To-Wake approach. However, since global warming results from greenhouse gas emissions at every level of the production chain, regulating by considering a local perspective may cause each sector to shift the problem onto others. For example, in the automotive sector, fleet electrification would achieve significant milestones in reducing GHG Tank-To-Wheel emissions, reaching a 90% reduction from 1990 levels in the most ambitious scenarios. However, upstream electricity CO_2 emissions for battery and plug-in hybrid electric vehicles could add up to 40% of Tank-to-Wheel emissions, suggesting that complementary policies are needed to avoid shifting transport emissions to other sectors [30]. Even in the maritime sector, the regulation's Tank-to-Wake approach is criticized since it may misrepresent fuels' total climate impact. To avoid this misrepresentation, a life cycle assessment is proposed to extend the perspective to a Well-to-Wake greenhouse gas emissions approach [31].

This paper attempts to show how a Well-To-Wake approach is necessary for the purposes of a more complete understanding and evaluation of the ship emissions problem, moving beyond the local approach commonly used in the maritime field. The study includes the assessment of the environmental impact of ships and propulsion technologies and their effect on fuel consumption, pollutant emissions, and economic feasibility, extending the existing research in maritime emissions reduction techniques and introduces a novel index to assess ship environmental performance, providing valuable insights for sustainable maritime transportation. As a case study, the paper examines the ecological and economic advantages and drawbacks of two proposed propulsion systems, natural gas-electric and hybrid, with four on-board usage strategies of the Battery Energy Storage System ($BESS$), considering economic and environmental impact. In particular, both configurations are evaluated using two different fuels, Liquefied Natural Gas (LNG) and Electric-Liquefied Natural Gas ($E\text{-}LNG$). The analysis compares best-case and worst-case energy production scenarios, i.e., Seattle's electricity grid, sourced mainly from renewable sources, and Poland's electricity grid, sourced mainly from highly impactful fossil sources such as coal. The economic analysis evaluates the costs of realizing the propulsive system and the operating costs resulting from its use. A novel index, called Greenhouse gas Intensity Indicator (GII), in analogy with the Carbon Intensity Indicator (CII) adopted by the IMO, is proposed to assess the global warming impact of proposed solutions through a Well-to-Wake approach.

A comparison with the CII has been performed to highlight the differences between the two approaches. This investigation offers a comprehensive understanding of the environmental impacts of the marine propulsion system under study, providing valuable insights into the advantages and disadvantages of using natural gas-electric and hybrid systems and different low-carbon alternative fuels and contributing to ongoing efforts to formulate sustainable solutions for the maritime industry. The article is organized as follows: Section "Methodology" describes the mathematical models and methodology used to obtain the results analyzed to compare the different configurations; Section "Case study ship" presents the case study ship, its main characteristics and propulsive configuration (Section "Main data and propulsive configuration"), and the mission profile and route of the ship and describes the simulation campaign carried out (Section "Mission profile and simulation campaign"); Section "Results" describes the results obtained, focusing on fuel consumption (Section "Consumption comparison"), economic aspects (Section "Economic analysis"), and pollutant emissions (Section "Emission assessment"), both in terms of greenhouse gases, using equivalent CO_2, and local pollutants, e.g., NOx and CO; Section "Greenhouse gases Intensity Indicator - GII" presents the GII, a novel index proposed for the ship's energy classification; Eventually, conclusions of the research are drawn, indicating its limitations, practical application and future directions.

Methodology

This section describes the mathematical models and methodology used to compare propulsive solutions in terms of fuel consumption, pollutant emissions, and costs. In particular, the following subsections describe the mathematical model of the propulsion system performance, the procedure to assess the fuel consumption and emissions, the economic assessment, and the proposed greenhouse gas intensity indicator (GII), respectively.

Mathematical modeling of the propulsion system

A hybrid system includes energy sources and devices of different natures integrated into a single system. The case under consideration involves full-electric propulsion including natural gas internal combustion engines, generators, electric motors, power electronics, and batteries. The approach to modeling the main components is described below.

The heat engines are modeled using the Brake Specific Gas Consumption ($BSGC$) to express the fuel mass flow rate as a function of the power output [32]. The fuel mass flow rate $\dot{m}_f$ is computed according to the following equation:

$$\dot{m}_f = \frac{P_B \ BSGC(P_B)}{LHV_{fuel}} \tag{1}$$

where P_B is the brake power output, and LHV_{fuel} is the lower heating value of the fuel. There is a wide variety of approaches to battery modeling in scientific literature [33], such as the Shepherd's model [34]. This study relies on a simplified purely resistive equivalent circuit model, representing the dependency of the battery voltage from the current considering the internal resistance of the battery, and integrating the battery power in time to deduce the state of charge [27,35].

The generator power management strategy is rule-based, aiming to minimize gas consumption. Since the $BSGC$ is monotonically decreasing (Fig. 7), the minimum consumption is achieved by running the minimum number of generators to meet the required load and equally splitting the load on the active generators. In addition, to avoid overloading the machines, a new generator is turned on when the load percentage of the active generators reaches 95% of their maximum power output. The main aim of the proposed strategy is to minimize fuel consumption. This would not be possible if more generators than required were running, as each generator would work with a reduced load percentage and high specific gas consumption. Fig. 8 summarizes the rule-based power management strategy: The top graph shows the number of running generators as a function of the ship's speed; the steps indicate the start of a new generator set to meet the required power as the ship's speed increases. The middle and bottom graphs show the load percentage delivered by each generator and their specific gas consumption (SGC), respectively, as a function of ship speed. The two graphs are closely related, as lower specific consumption corresponds to a higher load percentage and vice versa. SGC is calculated dividing the $BSGC$ by the fuel's lower heating value.

In hybrid configurations, the battery is used as the only energy source during port stops and is recharged by generators during the navigation phase. The models described have been implemented in Python and applied to simulate different battery management strategies on a discrete-time mission profile, as described in Section "Case study ship". The mission profile is modeled as a series of steady states, in which the required power is constant.

The remaining electrical devices, including motors, generators, and converters, were modeled with an energy approach utilizing constant efficiencies.

Fuel consumption and pollutant emissions

The fuel consumption of the entire mission is calculated by integrating the fuel mass flow rate calculated according to Eq. (1), relying on the procedure presented in [35].

Two different strategies are used for environmental impact assessment, depending on the type of pollutant being considered. A Well-to-Wake approach is adopted to assess the impact produced on global warming by adopting equivalent CO_2 as the performance indicator, which then considers the contribution of all greenhouse gases. On the other hand, a Tank-to-Wake approach is adopted for emissions of other pollutants since their polluting effect has local implications. The mass of the ith pollutant emitted from the fuel burned on-board is calculated according to the following equation:

$$m_i = EF_i \ m_f \tag{2}$$

where EF_i is the fuel-based emission factor of the ith pollutant. By adopting the Well-to-Wake approach, in terms of equivalent CO_2, the emissions produced by the power grid to conduct cold ironing operations in the Port of Seattle must be added to this contribution. This contribution is calculated according to the following equation:

$$m_{CO_{2eq},ci} = EF_{CO_{2eq}} \ E_{ci} \tag{3}$$

where $EF_{CO_{2eq}}$ is the energy-based emission factor of the on-shore electric grid, and E_{ci} is the energy absorbed for the cold ironing operations.

Economic analysis

The economic analysis is performed in terms of the total annual cost (AK) of each propulsive configuration, calculated as the sum of $CAPEX$ (CAPital EXpenditure) representing the annual capital cost and $OPEX$ (OPeration EXpenditure), which is the annual operating costs of the ship. The $CAPEX$ is calculated according to [6]. The discount rate, i.e., the interest paid on the invested capital, is assumed to be 12% per year. A payback time of 20 years is assumed for the system, which is the estimated life years of the ship. On the other hand, the batteries have a shorter life, requiring replacement after ten years. Therefore, a payback time of 10 years is considered for this component, at the end of which is scheduled their replacement, thus a new investment. The $OPEX$ is calculated by summing the annual cost of burned fuel, the annual cost of shore power, the annual cost of lubricating oil, and the annual maintenance cost.

An investment analysis based on Net Present Value (NPV) [36–40] is performed for each case analyzed to assess the return on the additional investment required to install the batteries. The analysis is performed on a differential basis, meaning only differences in system configurations and respective operating and investment costs or cost reductions/revenues compared to the baseline system have been evaluated. The battery pack is considered an investment, which is the capital expenditure related to the purchase and installation of the equipment. This initial investment would lead to future cash flows, reducing expenses over the ship's life due to fuel savings. The rest of the ship's energy system is assumed to be unaffected by operating and maintenance costs by installing the batteries. The difference between annual revenues and expenditures determines the annual cash flows of the investment. Future annual cash flows are assumed to be a fixed income over the life of the investment. An investment with a positive NPV is profitable, whereas a higher NPV denotes a higher investment return in absolute terms. The NPV is calculated using the procedure presented in [37]. The interest rate is assumed equal to 12%.

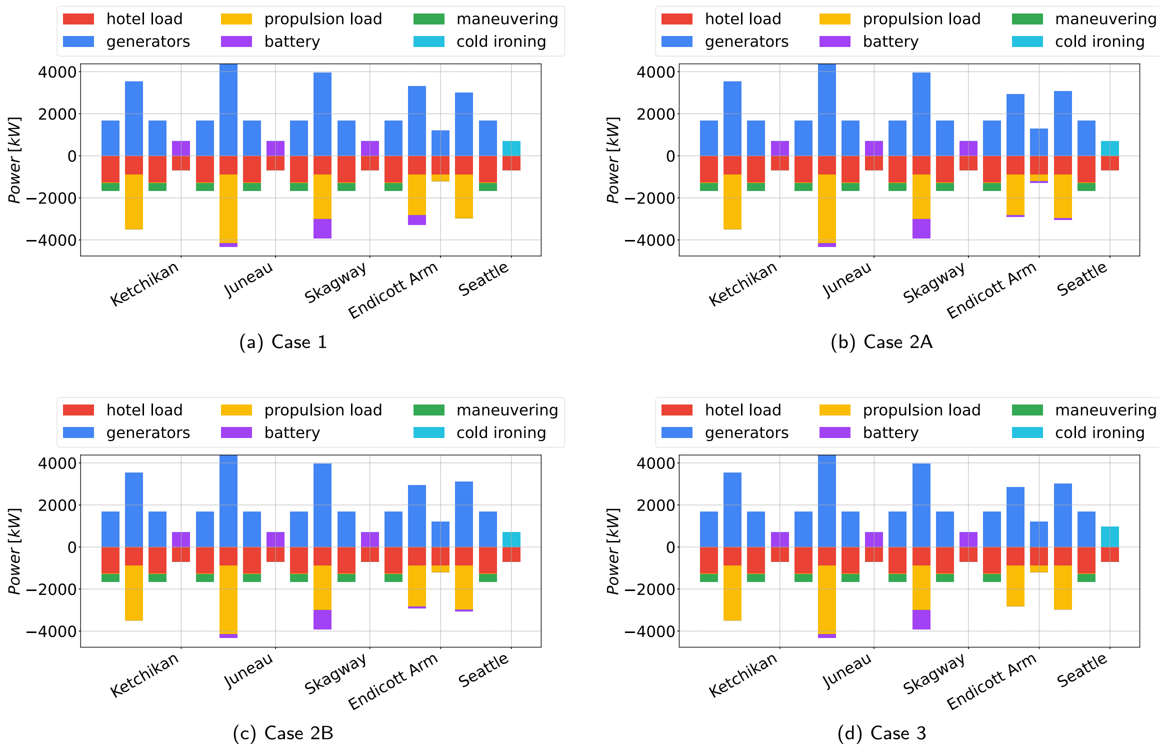


Fig. 1. Power split for different cases. Positive bars represent the power delivered, while negative bars represent the power absorbed.

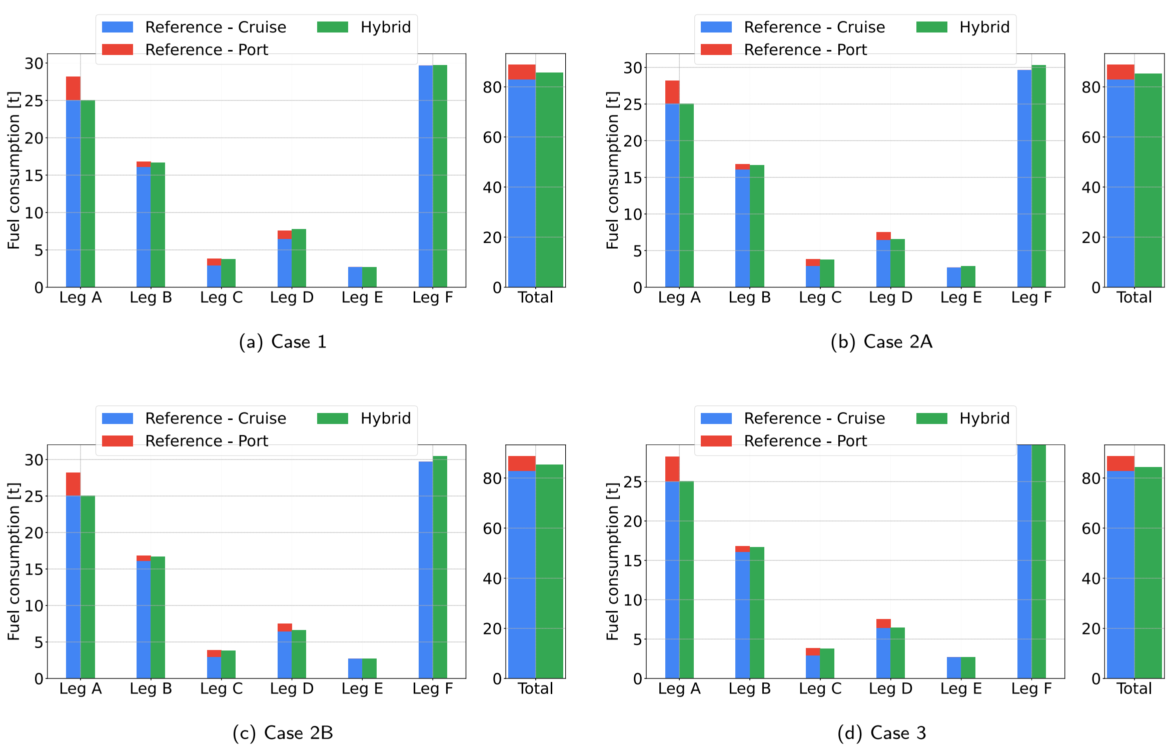


Fig. 2. Fuel consumption for different cases: detailed for each route and total cruise.

Greenhouse gas Intensity Indicator - GII

A novel index called Greenhouse gas Intensity Indicator is proposed to classify the ship based on its carbon footprint, in analogy with the CII adopted by IMO [41].

While CII accounts for carbon dioxide emissions, GII considers every greenhouse gas the ship produces by evaluating the equivalent CO_2 emissions. In addition, emissions produced by the onshore grid to recharge the batteries are also considered, embracing a Well-to-Wake approach instead of a Tank-to-Wake approach. Since the attained CII is required to be less than a threshold value and progressively reduced year by year, a similar approach is suggested for the proposed GII, and then, in analogy with the IMO procedure, a yearly correction determined by the reduction factor is applied. The complete procedure is reported in Appendix A. "GII calculation procedure". Rating boundaries are established to assign a category from A to E.

Case study ship

Main data and propulsive configuration

The case study ship is a small luxury cruise ship operating in the Arctic area, which main data are shown in Table 2 in Appendix B. "Additional figures and tables". The vessel can accommodate 127 passengers and 85 crew, with 60 cabins. While the original ship is equipped with traditional mechanical propulsion, a natural gas-electric and hybrid propulsion is adopted as a case study in this work to assess the variation in its performance by evaluating different fuel production methods and integrating a battery pack and connection to the on-shore power grid. In particular, the configuration without batteries has been considered a baseline, while a hybrid system using different power management strategies has been adopted to make comparisons. In addition, the propulsion system has been studied, including a power supply with traditional liquefied natural gas derived from fossil sources and electric-liquefied natural gas produced from renewable sources, which has a reduced carbon footprint on a global level. The two fuels are chemically equivalent in terms of local emissions.

The LNG-electric propulsive system includes four generators, with a nominal output of 1555 kW and a nominal speed of 1000 rpm, allowing a cruising at 16 kn, keeping one of the generators in standby mode. The electric grid powers two electric propulsion motors, moving two fixed-pitch propellers, a 364 kW bow-thruster, and the hotel load. A 10 MWh battery pack and a shore connection complement the generation system, aiming to reduce the ship's environmental impact in terms of pollutant emissions. In fact, during port stops, the hotel load is powered by the battery pack or shore connection, removing the problem of pollutant emissions. During navigation, the energy consumed by the $BESS$ is recharged using diesel generators. This way, the ship arrives at its destination with the batteries charged and ready to supply the energy needed for the next port stop. Such a strategy reduces global greenhouse gas emissions, eliminating toxic emissions for human health in living areas. Fig. 9 provides a schematic representation of the propulsion system in the complete hybrid configuration, including the on-shore connection, while Fig. 10 presents a map of the cruise itinerary in the northeastern United States, starting from the port of Seattle, WA. The cruise to Alaska includes stops at Ketchikan, Juneau, and Skagway ports. Then, a low-speed cruise is planned in Endicott Arm Fjord, returning to the Port of Seattle after nine days of cruising.

Mission profile and simulation campaign

Figs. 11(a) and 11(b) show the mission profile of the ship in terms of total power required and speed. In Fig. 11(a), the required power for navigation is summed with the electrical power required for the hotel load, which is assumed to be 889 kW for the navigation phases, 1637 kW for maneuvering, and 697 kW for the port stops. In addition, the power required to recharge the batteries during navigation shall be considered in the case of hybrid configuration. The total maneuvering time for entrance and exit from ports is assumed to last one hour.

Fig. 11(a) shows that no further stops are planned until arrival in Seattle harbor after the dock stops in Skagway. Summarizing, the route of a cruise trip is defined as follows:

- Route leg A - from Seattle to Ketchikan: 654 nm of cruising at 15 Kn for a total time of 44 h;
- Dock-stop: 6 h
- Route leg B - from Ketchikan to Juneau: 392 nm of cruising at 16 kn for a total time of 25.5 h;
- Dock-stop: 7.5 h;
- Route leg C - from Juneau to Skagway: 83 nm of cruising at 14 Kn for a total time of 7 h;
- Dock-stop: 9 h;
- Route leg D - from Skagway to Endicott Arm: 195 nm of cruising at 13.5 Kn for a total time of 14.5 h;
- Route leg E - low-speed cruise in Endicott Arm fjord: 101 nm of cruising at 7.2 Kn for a total time of 14 h;
- Route leg F - from Endicott Arm to Seattle 834 nm of cruising at 13.8 Kn for a total time of 61 h;
- Dock-stop: 26 h;

Four alternative strategies have been analyzed for the last section of the voyage. A reference case without $BESS$ on-board has been included for comparison. The paper analyzes the following five cases:

- Case 0 is the reference case. There are no batteries on board; therefore, during the port stop, the hotel load is supplied by generators.
- Case 1 features a full recharge of the $BESS$ after the last stopover on the following route leg before the low-speed cruise in Endicott Arm (Fig. 1(a)).
- Case 2 A features $BESS$ recharging during the entire navigation to the port of Seattle, including the low-speed cruise in Endicott Arm (Fig. 1(b)).
- Case 2B features distributed recharging as in Case 2 A, but without recharging during the low-speed cruise (Fig. 1(c)).
- Case 3 involves the arrival in Seattle with dead batteries, which are recharged via the shore network (Fig. 1(d)).

In the new configuration, it was assumed that the connection to the on-shore power grid in the port of Seattle would be for the 26-h break between two consecutive cruises. These results have been analyzed considering the same propulsive configuration powered with two different types of fuel, Liquefied Natural Gas and Electric-Liquefied Natural Gas. The analyzed fuels have the same chemical composition but differ in production.

Results

This section compares the propulsive configurations and energy management strategies described in Section "Case study ship" through the results obtained from applying the mathematical models and the methodology described in Section "Methodology" to the case study ship.

Consumption comparison

Fig. 2 compares the baseline (Case 0), and the new configurations. In route leg A, fuel consumption is higher in the reference configuration because fuel consumption for the stopover in Seattle has been included in the computation. Conversely, the new configuration only considers fuel consumption for reaching the next port. The use of batteries is beneficial in route legs B and C, while differences among the cases can be observed in route legs D, E, and F. Regarding route leg D, Case 1 results in higher consumption than the reference case because a full battery recharge is required, while the other cases feature lower consumption compared to Case 0. The consumption in route leg E is the same for all cases except for Case 2A, which is higher because it requires the $BESS$ recharge. Compared to the reference case, route leg F features higher consumption for all cases except Case 3, which is the only one involving arriving with dead batteries in Seattle. The total fuel savings achieved with the hybrid propulsion system in the different cases range from 3.5% for Case 1 to 5.3% for Case 3.

Table 1
Total costs for different cases.

Case	Fuel	Hybrid version	AK [M€/year]
Case 0	LNG	–	1.66
	E-LNG	–	3.22
Case 1	LNG	1	1.74
		2	1.81
	E-LNG	1	3.23
		2	3.30
Case 2A	LNG	1	1.72
		2	1.79
	E-LNG	1	3.22
		2	3.29
Case 2B	LNG	1	1.72
		2	1.79
	E-LNG	1	3.22
		2	3.29
Case 3	LNG	1	1.72
		2	1.79
	E-LNG	1	3.20
		2	3.28

Economic analysis

The economic analysis accounts the costs of the propulsion and power generation plant components, comparing the different configurations and fuels studied. The specific costs of batteries in the literature differ significantly from each other, unrelated to the capacity installed on-board. The comparison includes both the minimum and maximum values found in the literature. Specific costs of plant components are shown in Table 3 in Appendix B. "Additional figures and tables" [6,36,42].

The total cost of the reference plant configuration - corresponding to Case 0 (four engines with no batteries on board) - results in 7.82 M€. Hybrid version 1 features the lowest battery-specific cost (260 €/kWh) and implies a 4% increase in total plant cost, while Hybrid version 2 features the highest battery-specific cost of (640 €/kWh) is associated with an 8 percentage points increase.

The $CAPEX$, calculated through the procedure described in Section "Methodology", results in 1047 k€/year for the reference configuration, while the hybrid versions 1 and 2 feature an estimated $CAPEX$ of 1097 and 1169 k€/year, respectively.

The maintenance and lubricating oil costs are constant for the investigated plant configurations, so they can been neglected from the $OPEX$ calculation in the comparison of the different configurations. According to this assumption, the operational expenditure costs are reduced to the annual cost of fuel and energy needed from the on-shore power grid to recharge the $BESS$. The specific fuel costs have been assumed to be 345 €/t for LNG, and 1225 €/t for E-LNG [43]. A specific value of 0.086 €/kWh has been assumed for the on-shore energy used for cold ironing operations. Twenty missions per year have been assumed to evaluate the annual operating costs. The results are shown in Table 4: E-LNG powered propulsion is more than three times more expensive compared to LNG propulsion.

Table 1 shows the total cost AK for the different propulsive cases, fuel burned, and battery-specific costs. The results show that the reference configuration is the cheapest. However, the increased cost of hybrid systems seems reasonable, especially considering the lower cost of the battery pack, although $BESS$ replacement after ten years should be evaluated. Cases involving synthetic fuel are the most disadvantageous, as the current cost of E-LNG is much higher than that of fossil LNG.

To improve the economic analysis, an NPV-based investment evaluation has been performed, as described in Section "Methodology".

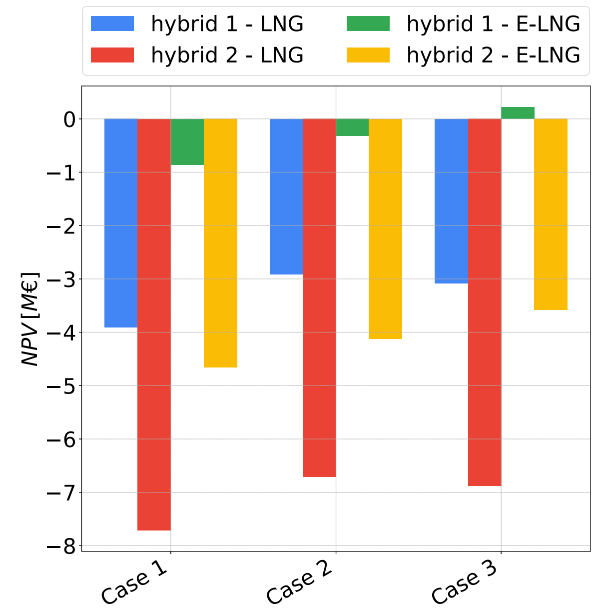


Fig. 3. Net Present Value for the different hybrid configurations in each case considered compared to the respective baseline (Case 0 - LNG, Case 0 - E-LNG).

Case 0 with both fuels has been adopted as reference configuration to highlight the contribution due to the adoption of the hybrid systems to the costs. The obtained results are shown in Fig. 3. The results show that using a hybrid propulsion system is not cost-effective compared to the reference configuration, except in Case 3, in which the lower battery cost and synthetic fuel were used. A slight cost increase is highlighted in cases where E-LNG is used compared to LNG cases. This is due to the higher cost of fuel, and therefore, for the same savings in consumption, there is a much more significant cost savings, which better compensate for the installation of batteries.

Emission assessment

This section compares the emissions of different propulsive configurations in different use cases. A Well-to-Wake approach has been adopted to analyze greenhouse gas emissions, whose effects on the environment are global. For emissions of other pollutants, i.e., carbon monoxide (CO) and nitrous oxides (NO_x), a Tank-to-Wake approach has been adopted since their harmful effects have local implications.

The different fuels analyzed are chemically equivalent. Therefore, it is necessary to adopt a Well-to-Wake approach to compare the environmental impact of different configurations. The fuel-based emission factors of the equivalent CO_2 of different fuels, expressed in grams of CO_{2eq} produced per gram of fuel burned, are assumed 3.34 for the fossil-based natural gas, and 0.52 for the synthetic E-LNG, considering emission produced from production to final use [43]. This reflects the critical assumption that the production is based on 100% renewables, a prerequisite far from reality today since e-fuels are as green or gray as the electricity in the production region. Furthermore, for E-LNG, uncombusted methane gives the same challenges as fossil LNG. The on-shore connection used for cold ironing operations is that of the Seattle port. Considering the energy production carried out mainly from renewable sources in that area of the United States, its emission factor has been considered as the best case, with 27 grams of Equivalent CO_2 produced per kWh of energy delivered. Poland's on-shore grid emissions have also been considered to quantify a worst-case-scenario impact of emissions from the on-shore grid, assuming 930 $g_{CO_{2eq}}$/kWh. Fig. 4 shows the GHG emissions – expressed in tons of equivalent CO_2 – for the different cases, for the considered fuels and energy mix. The

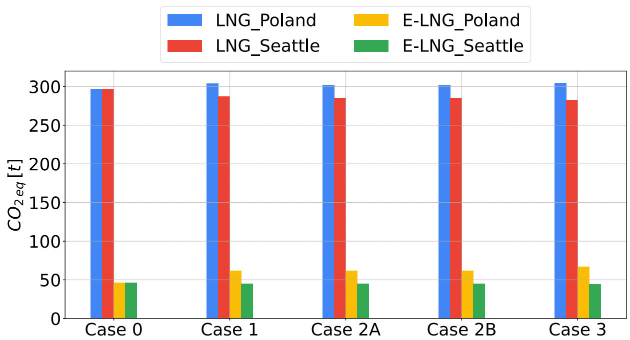


Fig. 4. CO_{2eq} emissions for different cases denoting fossil and synthetic fuel and the two different on-shore grids.

most significant emission reduction is achieved using fuel derived from non-fossil sources. Emissions produced using $E\text{-}LNG$ are 4.5 to 6 times lower than those produced by burning LNG in the different cases. The on-shore power grid contribution to emissions is small compared to the fuel contribution because cold ironing operations are only carried out during the dock stop in Seattle. However, it is worth noting that the percent reduction is higher if Seattle's on-shore power grid is used since emissions from fuel take a larger share of the overall weight in that case. In the cases where the Polish on-shore power grid is considered, an increase in emissions is even reported, thus highlighting that, from a GHG emissions point of view, the on-board electric generation system is better than recharging the battery pack via shore connection powered by polluting sources.

NO_x and CO emissions are excluded from the calculation of equivalent CO_2 because they are not greenhouse gases and do not contribute to global warming. However, these emissions have a local effect. The differences between the two fuels have not been considered because the emissions produced are the same locally since the two fuels are chemically equivalent. Given the purely local effect of the emissions, a Tank-to-Wake approach has been adopted. Energy-based emission factors, expressed in g/kWh, have been used to quantify emissions of these types of pollutants since these emissions depend not only on consumption but also on the load rate of the engines. Thus, a reduction in fuel consumption does not necessarily match a reduction in emissions, as in the case of greenhouse gases. The specific consumption curves of NO_x and CO for different engine loads are shown in Fig. 12 [44]. It is worth noting that the emission factors are high if the engine is used at low loads. This trend is more evident for carbon monoxide emissions, resulting from incomplete oxidation of carbon during nonoptimal combustion at low loads.

Figs. 5(a) and 5(b) show the percentage variations in emissions compared with Case 0 of NO_x and CO, respectively. In the first three cases, NO_x emissions increase compared to the reference configuration because of the higher power used to recharge the battery system. In Case 3, however, there is a NO_x reduction of just over one percentage point. This is due to the battery not being recharged and the gensets not running in port during the stopover. In the case of carbon monoxide, Case 1 emissions are higher than in the reference case. In the other cases, however, emissions are reduced, with a maximum for Case 3, in which there is a more than one percentage point reduction. These results compare total NO_x and CO emissions. However, the purpose of using the hybrid system is to eliminate these humanly harmful emissions during the port stops.

Greenhouse gases Intensity Indicator - GII

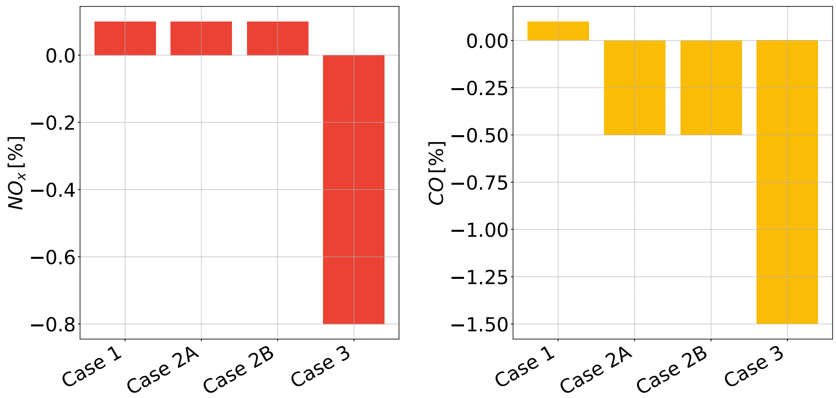
For the case study ship, the parameters proposed by IMO for cruise ships, i.e. $a = 930$ and $c = 0.383$, have been adopted in Eq. (5) presented in Appendix A. "GII calculation procedure". Applying the approach described in Section "Methodology" to the case study ship, class A should be achieved in 2023 if the $GII/GII_{required}$ is less than 0.87, while higher GII would collocate the ship in class B, C, or D according to increasing threshold values of 0.95, 1.06, and 1.16, respectively. Eventually, class E is obtained if the GII is higher than 1.16.

Fig. 13 shows the rating obtained for the different cases under study. For Case 0, rating A is obtained using synthetic fuel, and rating B using fossil fuel. As for hybrid configurations, the worst cases feature fossil fuel and Polish energy mix. In these cases, the ship would still be rated B in 2023, but its rating would worsen over the years due to increasingly restrictive thresholds until rating C is obtained in 2026. In contrast, the best cases are those where $E\text{-}LNG$ is considered. Regardless of the onshore grid energy mix and year, the A rating was obtained by a wide margin. Regarding the Seattle power grid and fossil fuels, the rating decreased from A for 2023 to B for 2026, except for Case 1, which had a B rating as early as 2023. Fig. 6 presents a comparison between the CII and GII. The values shown for each configuration are normalized to the respective reference case (Case 0). The CII considers only CO_2 emissions produced by burning fuel, so the lower the fuel consumption, the lower the CII. All GHG emissions are considered using the proposed GII, including those produced using the on-shore power grid. Therefore, when a hybrid configuration involving on-shore charging is adopted, the energy source from which the energy used to recharge the batteries is produced takes on a weight. Fig. 6 highlights that the GII obtained for the hybrid configuration and the Polish power grid is higher than the baseline without batteries, even if the fuel consumption is reduced. This disadvantage for the hybrid configuration is more evident when the fuel used is E-LNG since the emissions from the electric grid will be much greater than those produced by fuel consumption. Fig. 6 shows only a CII, which refers to fossil-based LNG configurations. The CII obtained considering synthetic fuel is not reported since, considering the Tank-to-Wake approach would have the same trend as that reported for fossil-based fuel.

Conclusion

This paper analyzed the performance of a marine propulsion plant using two different types of fuel: Liquefied Natural Gas and Electric-Liquefied Natural Gas. A small cruise ship operating in the Arctic was used as a case study. In particular, the paper discussed the ecological and economic benefits and drawbacks of two propulsion configurations with LNG and $E\text{-}LNG$ fuels, featuring $BESS$ and on-shore connection to support the electric load during dock stops. The proposed plant configurations were tested and compared using a typical ship mission profile. Moreover, different on-shore power grids were considered to assess the Well-to-Wake carbon footprint of the systems under study.

All hybrid systems featured good fuel consumption performance. However, the economic analysis showed that the reference configuration is cheaper than the others. Moreover, the use of synthetic fuel increases the cost significantly. Conversely, the $E\text{-}LNG$-powered hybrid configuration has a clear edge from the environmental point of view. Hybridization generally results in lower GHG emissions when considering Seattle's on-shore power grid, while there is a slight increase in overall emissions considering Poland's grid. Using synthetic fuel reduces GHG emissions, with a more significant reduction considering the less impactful on-shore power grid. Hybrid propulsion systems reduce pollutant emissions in ports to zero, reducing the local impact on human health, even in ports without shore connections. Eventually, the GHG Intensity Indicator based on Well-to-Wake emissions of equivalent CO_2, in analogy with the CII issued by the IMO, was proposed for the energy classification of ships. In a possible simulated future scenario, all cases have a GII below a hypothetical limit set at three years (2026). Solutions based on non-fossil synthetic fuels present a clear edge in this regard. The importance of using clean energy to supply power to the ship at the dock or to recharge batteries is evident, as this index also considers this element. Hybrid solutions recharging



(a) NO_x emissions for different cases (b) CO emissions for different cases

Fig. 5. Percentage variation of pollutant emissions for different cases compared with the reference configuration.

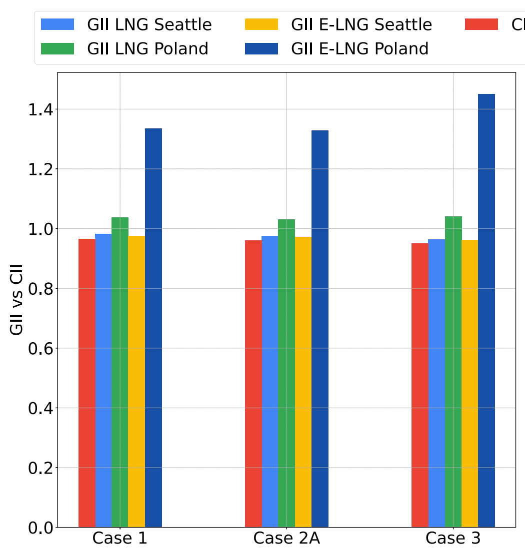


Fig. 6. Comparison of CII and GII for each case, normalized to the respective reference configuration.

batteries using energy produced from fossil sources such as coal are penalized.

From the results obtained, there is no evidence of a solution over-performing the others from every point of view. Adopting a hybrid system is always advantageous, considering fuel consumption. However, if GHG emissions are considered, the hybrid configuration has an edge over the baseline only if energy produced from renewable sources is used to recharge the batteries. The real advantage from the carbon footprint point of view comes from the use of non-fossil fuels. The hybrid system's battery charging and discharging strategy has a significant impact, especially regarding non-greenhouse gas emissions, which are significantly lower if the ship reaches the destination port with discharged batteries and recharges them with the on-shore power grid. However, it is essential to emphasize that adopting a hybrid system eliminates the port emissions of these gases, which are harmful to human health. Therefore, the advantage is maximum in this case since shifting CO and NO_x emissions from the sensitive area to the open sea significantly reduces the problem. From an economic point of view, the most advantageous solution is the reference configuration, as the difference in fuel consumption is not so significant as to justify the installation of a battery pack, mainly if E-LNG is used as fuel. While no technology has shown an indisputable advantage over the

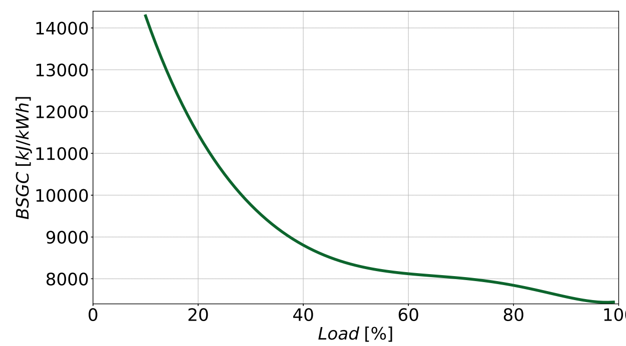


Fig. 7. Brake Specific Gas Consumption as a function of engine load.

others, combining different technologies suggests the possibility of exploiting the merits of each and compensating for its shortcomings. In addition, the results show how Well-to-Wake evaluation allows a more comprehensive view of the problem and should be used to compare different solutions. The increase in problem complexity brought about by integrating different technologies and modes of performance evaluation will require the support of numerical simulation and the use of digital twins, allowing the different possible configurations to be explored more effectively to support system design, optimization, and control.

CRediT authorship contribution statement

Luca Maloberti: Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Raphael Zaccone:** Writing – review & editing, Validation, Methodology, Conceptualization. **Jacopo De Gaetano:** Software, Investigation. **Ugo Campora:** Supervision, Resources, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. GII calculation procedure

This appendix presents the GII calculation procedure. The GII of the ship is calculated through the following equation:

$$GII_{attained} = \frac{M}{GT\ D_t} \tag{4}$$

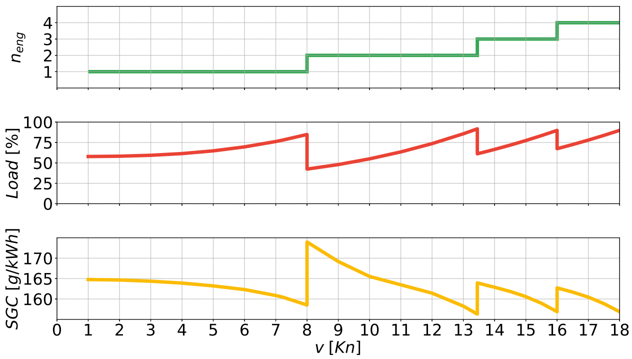


Fig. 8. Rule-based power management strategy.

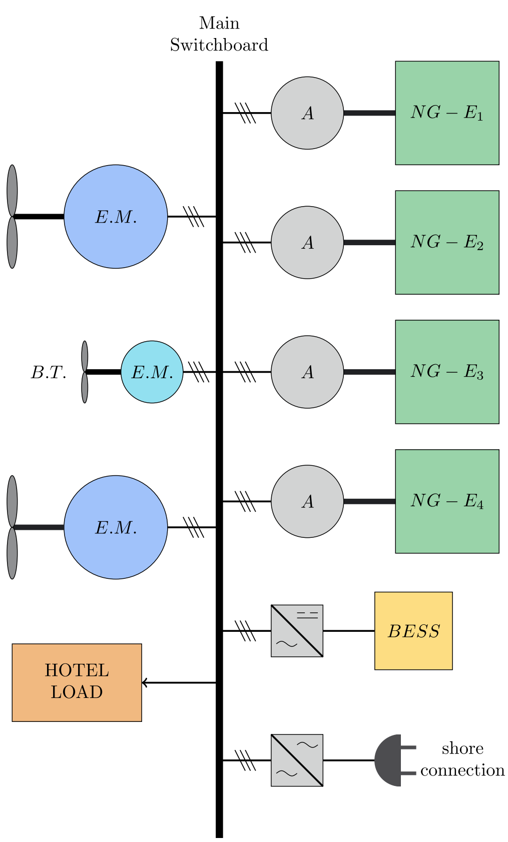


Fig. 9. Propulsion system configuration scheme.

where M is the total mass of CO_{2eq} produced in grams, GT is the Gross Tonnage, and D_t is the total annual distance traveled, expressed in nautical miles.

In analogy with the CII, the reference GII is evaluated according to the following equation:

$$GII_{reference} = a\,Capacity^{-c} \tag{5}$$

where a and c are parameters defined for the ship type. The capacity for a cruise ship is the Gross Tonnage (GT). The same values are assumed to compute the reference GII.

A correction determined by the reduction factor is eventually applied:

$$GII_{required} = \frac{100 - Z}{100}\,GII_{reference} \tag{6}$$

The reduction factor Z is assumed to start from 5% in 2023, and 2% will be added yearly.

Fig. 10. Cruise mission profile map.

Table 2
Main characteristics of the case study ship.

Length overall L_{OA}	90.6 m
Mean scantling draft T	4.2 m
Moulded breadth B	15.3 m
B/T	3.64
Displacement ∇	3440 t
Passengers	127
Crew	85
Cabins	60
Generator power	4×1555 kW
Generator speed	1000 rpm
Bow thruster	364 kW
Fuel	LNG
Battery capacity	1.07 MW h
Shore connection	Yes

Table 3
Specific cost of plant components.

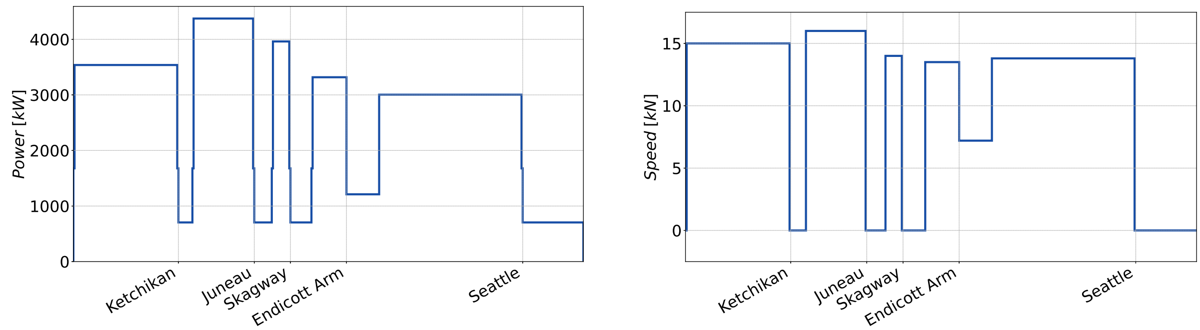
Component	Specific cost
Heat engine	490 €/ kW
LNG tanks and auxiliaries	300 €/kW
Electric generators	130 €/kW
Azipod	700 €/kW
Bow thruster EMs	140 €/kW
Bow thruster	30 €/kW
Battery pack	260–640 €/kWh
AC/DC converter	140 €/kW

Table 4
Operation expenditure for different cases.

Case	$OPEX$ LNG [k€/year]	$OPEX$ E-LNG [k€/year]
Case 0	612.7	2176
Case 1	644.3	2134
Case 2A	620.2	2121
Case 2B	620.2	2121
Case 3	624.3	2108

Appendix B. Additional figures and tables

See Figs. 7–13 and Tables 2–4.



(a) Required power mission profile

(b) Speed mission profile

Fig. 11. Mission profile power and speed.

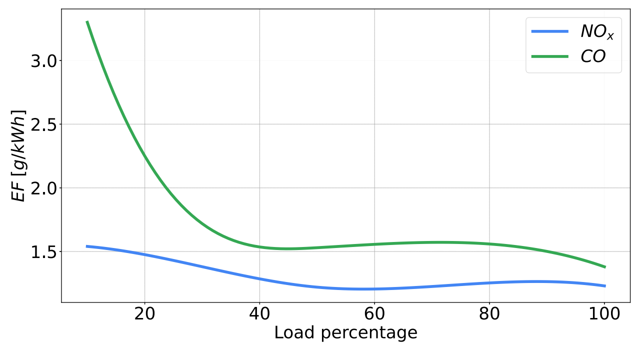
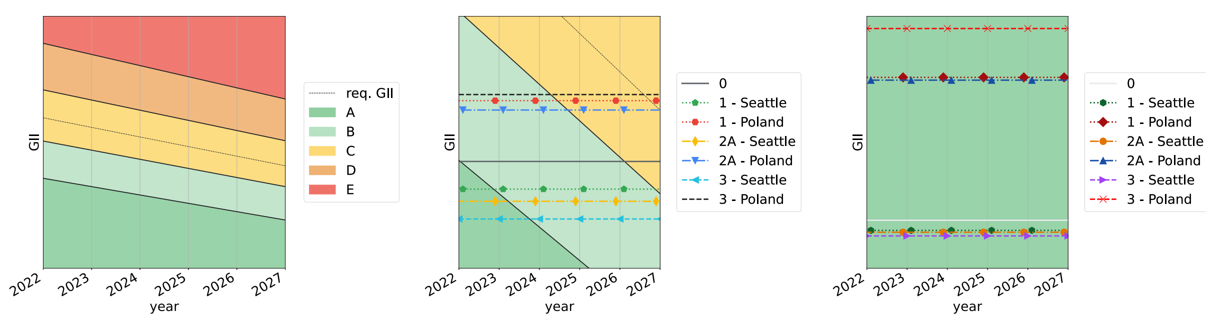


Fig. 12. NO_x and CO emission factors as a function of the engine load.



(a) *GII* class boundaries

(b) *GII* for *LNG*

(c) *GII* for *E-LNG*

Fig. 13. Energy classification obtained for different cases according to the GII.

Data availability

No data was used for the research described in the article.

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