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Ship Power Plant Decarbonisation Using Hybrid Systems and Ammonia Fuel—A Techno-Economic–Environmental Analysis

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Abstract: The shipping sector decarbonisation has attracted great attention due to the sector contribution to worldwide carbon emissions. This study aims at investigating the techno-economic–environmental performance of different ship power plants to identify sustainable solutions for a case study cargo ship. Four scenarios, considering conventional and hybrid power plants, the latter with installed batteries, both using marine gas oil and ammonia fuels, are analysed to estimate the pertinent lifetime key performance indicators characterising their economic and environmental performance. Additionally, taxation schemes of varying extent are considered, and a sensitivity analysis is carried out on the most uncertain input parameters, namely, fuel prices and capital cost. This study results demonstrate that the hybrid plant using ammonia exhibits the lowest environmental footprint associated with 66% carbon emission reduction, whilst increasing the lifetime cost by 40%. Taxation schemes close to 340 EUR per CO_2 tonne are required to render it economically viable whilst meeting the IMO targets for 2050 on CO_2 emissions reduction. The sensitivity analysis reveals that the economic parameters is highly sensitive to fuel price and the capital expenditure.

Keywords: ship power plant; short-sea shipping; decarbonisation; ammonia fuel; hybrid propulsion; techno-economic–environmental analysis

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1. Introduction

The marine industry has been adopting innovative solutions with the prospect of reducing the shipping operation environmental footprint. More specifically, decarbonisation practices have been within the purview of several regulatory organisations [1]. The International Maritime Organisation (IMO) has already introduced various practices, such as the Energy Efficiency Design Index (EEDI), the carbon intensity indicator (CII) and the Ship Energy Efficiency Management Plan (SEEMP), to reduce carbon dioxide (CO_2) emissions, whereas emission control areas (ECAs) in North America and Northern Europe have already been established to mitigate sulphur oxides (SOx) and nitrogen oxides (NOx) emissions [2]. Furthermore, the United Nations (UN) have already agreed on a deal with the ambitious goal of reducing total annual greenhouse gas (GHG) emissions by at least 50% compared with 2008 in new and existing vessels [3].

Nonetheless, since more that 95% of merchant ships utilise conventional fuels for propulsion [4], it is challenging to achieve the future targets of carbon emission reduction with the existing technologies [5]. As a result, alternative solutions should be adopted to supersede the existing technologies' characteristics with the target of mitigating emissions, increasing energy efficiency and improving the plant lifecycle parameters [6,7].

In this respect, various measures have been proposed, including the use of alternative fuels and the modification of power plant configurations using a combination of environmentally friendly components [8]. The considered alternative fuels include ammonia, hydrogen and methanol, which can reduce or even eliminate harmful emissions [9,10]. However, since these fuels are relatively new to marine engines, potential challenges exist in terms of combustion and safety-related issues [8,11]. Additionally, several technologies have been proposed for complementing ship power plants, including energy storage systems, renewable energy systems, fuel cells, dual-fuel engines and renewable energy systems. These can be combined in different topologies by exploiting the concept of hybridisation and effectuating further improvements in terms of fuel consumption and emission reduction [12,13].

Although several of these alternative solutions exhibit potential, further investigations are required to assess their techno-economic aspects and lifetime environmental characteristics, thus identifying the most environmental and economical sustainable solutions. In this respect, comparative assessments of power plant alternatives are considered essential in the design process.

This study investigated the economic feasibility of several ship power plant decarbonisation technologies to achieve the IMO 2050 goal of GHG emission reduction. Specifically, a hybrid power plant with installed batteries and the adoption of ammonia fuel, as well as their combination, were analysed, whereas the impact on the lifetime economic and environmental parameters was quantified. Additionally, incentivisation policies based on carbon taxation were evaluated to render these technologies feasible.

Literature Review

Ship power plant hybridisation using batteries has been an acknowledged technology towards shipping operation decarbonisation. Hybrid applications combine both mechanical and electrical components by exploiting their benefits under different operating conditions. Hybrid power plants include both internal combustion engines and energy storage systems, typically, batteries, flywheels and supercapacitors [12]. The most notable topologies that are currently employed include series, parallel and series–parallel architectures [4]. Several studies have highlighted the benefits of hybrid power plants, including savings in fuel consumption, emission reductions, and improvements in plant reliability and maintainability, as well as the enhancement of ship manoeuvrability [9,14,15]. Hybrid configurations are more beneficial (associated with increased fuel savings), when the power plant operates with low loads and under highly dynamic conditions, where the internal combustion engines are usually inefficient, especially during berthing and manoeuvring [16,17]. Furthermore, potential fuel savings can be attributed to the use of advanced energy management strategies, which can also subsequently reduce emissions [18,19]. Table 1 summarises the results of pertinent studies of hybrid applications in the marine sector, including tugboats, ferries, fishing vessels and cruise ships. The achieved fuel reduction concerns the fuel savings dictated using energy management strategies without considering the initial battery charging.

Table 1. Ship hybrid power plant characteristics.

Reference	Ship Type	Installed Engine Power * (kW)	Total Battery Size (kWh)	$\frac{\text{Battery Size}}{\text{Engine Power}}$ (kWh/kW)	Fuel Savings (%)
[19]	Tugboat	7360	240	0.0326	10
[20]	Tugboat	1200	500	0.4167	17.6
[21]	Tugboat	1100	100	0.091	9
[22]	Fishing boat	450			12.1
[23]	Cruise ship	48,000	5000	0.104	11.8
[24]	Hybrid ship	2000			7.9
[14]	Ferry	900	700	0.778	11

* The total installed engine power considers both for propulsion and auxiliary engines.

2. Materials and Methods

This study methodology consists of seven steps, which are is presented in Figure 1. Step 1 focused on determining the key performance indicators for the techno-economic–environmental analysis. Those included the net present value (NPV) (Equation (1)) for evaluating the overall economic sustainability of the investigated case studies and the

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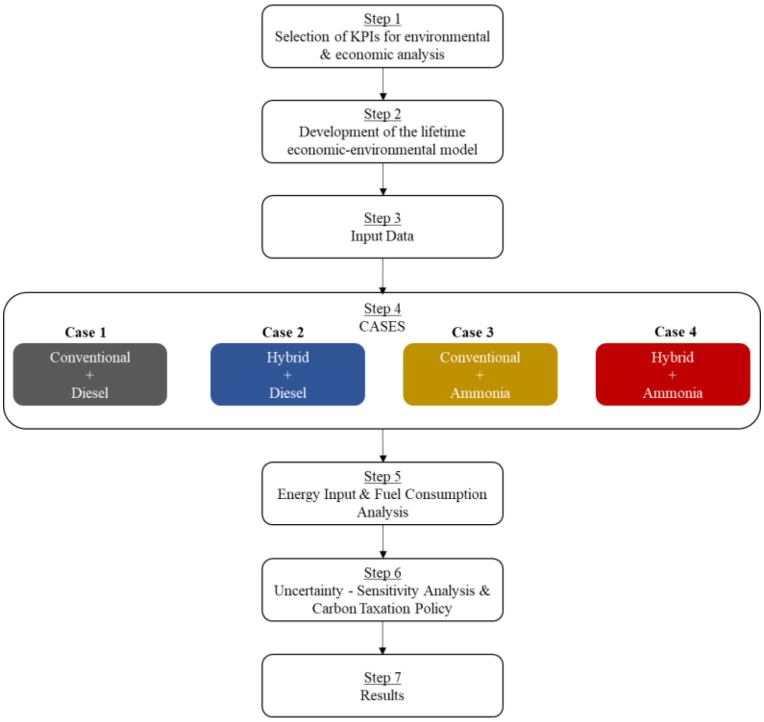

Figure 1. Flowchart of the methodology followed in the study.

2.1. Economic and Environmental Parameters

The net present value was calculated according to the following equation:

$$NPV_i = \frac{OPEX_i + CAPEX_i}{(1+dr)^t} \quad (1)$$

where *NPV* is the net present value of the designated environmental profits, *CAPEX* refers to the capital cost of the investigated cases, *OPEX* denotes the operational expenditure of the investigated cases, *dr* is the annual discount rate (assumed to be 12%), whereas *t* is the vessel service lifetime (assumed to be 30 years). Subindex *i* indicates the specific case.

The carbon intensity indicator was calculated according to:

$$CII_i = \frac{\sum_{j=1}^{n_{en}} FC_{i,j} \cdot EF_{CO_2 i,j}}{dwt \cdot d} \left[\frac{kg_{CO_2}}{t\ nm}\right] \quad (2)$$

where FC refers to the fuel consumption of the ship engines, EF_{CO2} is the CO_2 emission factor, d is the ship voyage distance in nm, dwt is the vessel deadweight in tonnes and n_{en} is the number of engines. Subindex j indicates the engine considered.

Table 2. Main input parameters [19,26–28].

Parameter		Value
Service lifetime	(years)	30
Vessel type		Cargo
Length/breadth/draught	(m)	106/15.5/6.63
Distance	(nm)	2300
Vessel deadweight	(t)	6000
Diesel engine CAPEX	(EUR/kW)	493
Diesel engine OPEX	(EUR/kWh)	0.012
After-treatment unit CAPEX	(EUR/kW)	40
Battery CAPEX	(EUR/kWh)	800
MGO CO_2 EF [1]	(kg CO_2/kg fuel)	3.02
MGO NO_x EF [1]	(kg NO_x/kg fuel)	0.0961
MGO Price	(EUR/t)	674
Ammonia CO_2 EF	(kg CO_2/kg fuel)	0
Ammonia NO_x EF	(kg NO_x/kg fuel)	0.003
Ammonia fuel price	(EUR/t)	900

[1] EF: emission factor.

Table 3. Main particulars of the investigated case studies.

	Case 1	Case 2	Case 3	Case 4
Propulsion System	Conventional	Hybrid	Conventional	Hybrid
Fuel	MGO	MGO	Ammonia	Ammonia
FurtherCharacteristics	CAPEX: • Main and auxiliary engine • After-treatment unit OPEX: • Main and auxiliary engine maintenance • MGO fuel cost	CAPEX: • Main and auxiliary engine • Battery and subsystems of hybrid propulsion • After-treatment unit OPEX: • Main and auxiliary engine maintenance • Battery maintenance • MGO fuel cost	CAPEX: • Main and auxiliary engine • After-treatment unit OPEX: • Main and auxiliary engine maintenance • MGO fuel cost • Ammonia fuel cost	CAPEX: • Main and auxiliary engine • Battery and subsystems of hybrid propulsion • After-treatment unit OPEX: • Main and auxiliary engine maintenance • Battery maintenance • MGO fuel cost • Ammonia fuel cost

According to the pertinent literature review results presented in Table 1, the average fuel saving in the case of hybrid propulsion was about 11% with a standard deviation of 3%. The considered ship energy storage system consisted of a 400 kWh Li-ion battery. An electric machine operating as either motor or generator was employed to drive the ship propeller (along with the ship main engine) receiving power from the battery or charging the battery receiving power from the ship main engine, respectively. The battery size was chosen based on the pertinent literature review, which indicated that the typical battery size (energy capacity) is around 0.23 kWh per kW of installed power. Other considered components included the DC/AC converter and the electric machine; the latter was mounted on the gear box of the ship shafting system.

This study also considered the required carbon tax for the different cases compared with the baseline, which was calculated according to the following equation:

$$C_{tax} = \frac{\Delta NPV_i}{\Delta m_{CO_{2i}}} \tag{3}$$

where $\Delta NPV_i = NPV_{case1} - NPV_{case_i}$ and $\Delta m_{CO_{2i}} = m_{CO_{2case1}} - m_{CO_{2case_i}}$, $i = 2, 3, 4$.

2.2. Case Studies

Four cases studies (cases henceforth) were investigated considering the conventional and hybrid power plants with the use of MGO or ammonia fuel. The power plant configurations of the investigated cases are provided in Figure 2, whereas their characteristics are summarised in Table 3. Case 1 (baseline) considered the conventional propulsion system of the investigated ship using MGO fuel for the main and auxiliary engines. Case 2 examined the hybrid propulsion system with installed batteries, DC/AC electric conversion system and electric machine (operating as motor or generator). The battery could provide both power for propulsion needs as well as power for auxiliary and hotel load services, where the various modes were dictated by the use of an energy management strategy. The same power plants were considered for Case 3 (conventional) and Case 4 (hybrid), but with the use of ammonia fuel. In Case 3, the maximum ammonia usage was 50% for both the ship main and auxiliary engines, on an energy basis, substituting MGO fuel. Hence, this alternative could achieve the IMO 2050 targets for 50% CO_2 emission reduction [29]. Case 4 considered the hybrid system of Case 2 with ammonia fuel use. Likewise, in Case 3, MGO fuel substitution up to 50% (energy-wise) was investigated. Several assumptions were made pertinent to vessel operation and technical characteristics. In all cases, no lubrication consumption was included, whilst the installation costs were included in the capital costs. In the case of ammonia, the engine maintenance cost was considered to be the same as that for diesel operation. This study did not consider any storage tank or vessel structure strengthening. The application of the investigated power plant for new-built ships was only considered. The employed operating profile is demonstrated in Figure 3.

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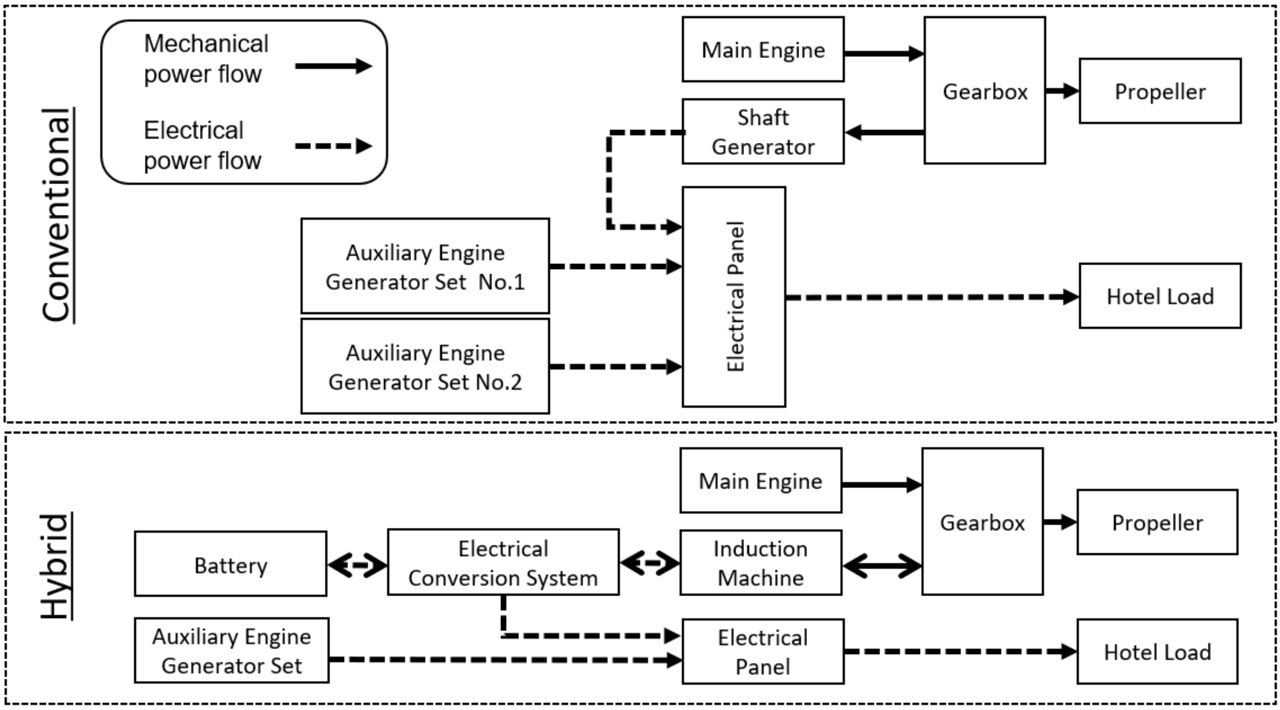

Figure 2. Layouts of the conventional and hybrid ship power plants.

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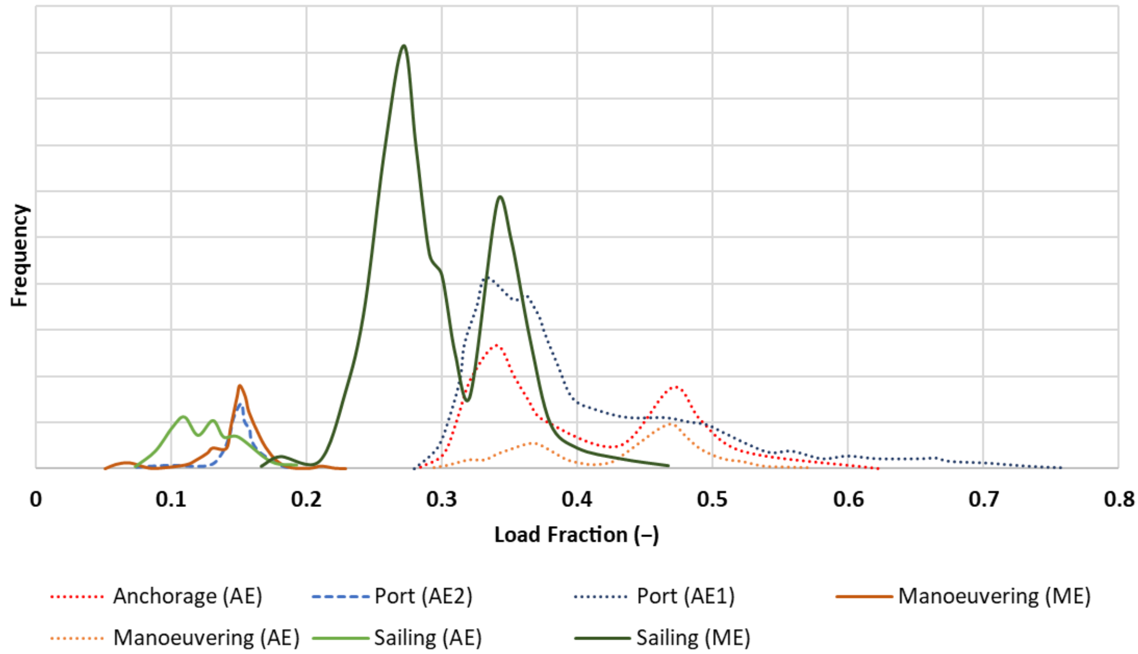

Figure 3. Operating profile of the considered plant (ME, main engine; AE, Auxiliary Engine)—ME provides power to cover both the ship propeller and hotel load demands.

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The main properties of MGO and ammonia fuels are summarised in Table 4. Ammonia has less than half the energy content of MGO fuel, implying increased fuel storage requirements for covering the ship energy demand [30,31]. This, in conjunction with the lower ammonia density, results in increased fuel storage volume. Considering the investigated vessel storage capacity (based on ship plans), as well as tank particulars from pertinent studies [32], the containerised solution of fuel storage was recommended for the investigated ship, which ensured fuel supply security. The investigated ship propulsion and auxiliary engine main particulars are listed in Table 5. The efficiency of these engines when operating with ammonia was assumed to be the same as that with diesel fuel operation [33].

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Propulsion System	Conventional	Hybrid	Conventional	Hybrid
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Table 4. Fuel properties [28].

Property	MGO	Ammonia
LHV (MJ/kg)	42.7	18
Density (kg/m^3)	838	602

Table 5. Engine characteristics of the study vessel.

Parameter	Main Engine	Auxiliary Engine
Type	4 stroke medium speed	4 stroke high speed
Cylinders	6	6
Rated power (kW)	1900	180
Rated speed (rpm)	750	1800
Bore/stroke (mm)	255/400	111/145

2.3. Uncertainty Analysis

The uncertainty analysis was carried out to estimate the uncertainty in the model output results due to the uncertainty in the input parameters. This study adopted the global method, which considers the combination of all input parameter uncertainty [34].

Each case was analysed stochastically considering the uncertainties presented in Appendix A using the Latin hypercube sampling (LHS) method [35] to generate a sparse uniform population with 10^6 samples. The derived results included the probabilistic distribution curves of each output (CII and NPV) for each investigated case, showing their dispersion in relation to the input uncertainties using histograms. The cumulative probability curve is also plotted, summing the individual probabilities (frequencies) for each value. The cumulative probability curve represents the probability that a variable is less than or equal to a specified value, being more useful to compare the derived results.

2.4. Sensitivity Analysis

The sensitivity analysis was used to quantify the impact of each parameter on the output results, considering the parameter mean value and uncertainty. This study used the Importance Factor [35], which defines a dimensionless metric to rank the importance and uncertainty of input parameters.

The Importance Factor (IF) for each parameter i was calculated as:

$$IF_i = \frac{1}{u_{input}^2}\left(\frac{\partial S}{\partial X_i}u_{X_i}\right)^2 \tag{4}$$

where u_{X_i} is the uncertainty of the input parameter X_i, $\partial S/\partial X_i$ is the sensitivity coefficient and u_{input} is the uncertainty in output S. The sensitivity coefficient was defined as the derivative of the output S and parameter input X_i and was calculated using the second-order finite difference according to the following equation:

$$\frac{\partial S}{\partial X_i} = \frac{S(X_1, X_2, \ldots, X_i + \Delta X_i, \ \ldots, \ X_{np}) - S(X_1, X_2, \ldots, X_i - \Delta X_i, \ \ldots, \ X_{np})}{2\Delta X_i} + O\left(\Delta X_i^2\right) \tag{5}$$

where ΔX_i is the perturbation in parameter X_i for evaluating the derivative.

The parameter uncertainty, u_{input}, was calculated as the summation of the variance for all np parameters in the analysis:

$$u_{input}^2 = \sum_{i=1}^{np}\left(\frac{\partial S}{\partial X_i}u_{X_i}\right)^2 \tag{6}$$

The results from the sensitivity analysis are presented in a tabular format with the Importance Factors for each parameter considered in the uncertainty analysis, shown in Appendix A, corresponding to the CII and NPV for the four investigated cases.

3. Results

This section presents the derived results for the carbon intensity indicators (CIIs) and the net present values (NPVs) for the investigated cases. Figures 4 and 5 compare the derived distributions of the CIIs and NPVs, respectively, in each case, and include the cumulative probability curve (sum of probabilities) for a quantitative comparison. Table 6 provides the average and the standard deviation CII and NPV values for the investigated cases. These values were used as a baseline for further uncertainty and sensitivity analyses.

Table 6. Derived CIIs and NPVs for the investigated cases.

Cases	Indicators	
	CII (kg CO_2/t·nm)	**NPV (Million EUR)**
1	0.138 ± 0.004 (±2.67%)	4.86 ± 0.24 (±4.91%)
2	0.123 ± 0.004 (±3.32%)	5.24 ± 0.31 (±5.90%)
3	0.069 ± 0.002 (±2.67%)	7.96 ± 0.34 (±4.29%)
4	0.062 ± 0.002 (±3.32%)	8.03 ± 0.39 (±4.86%)

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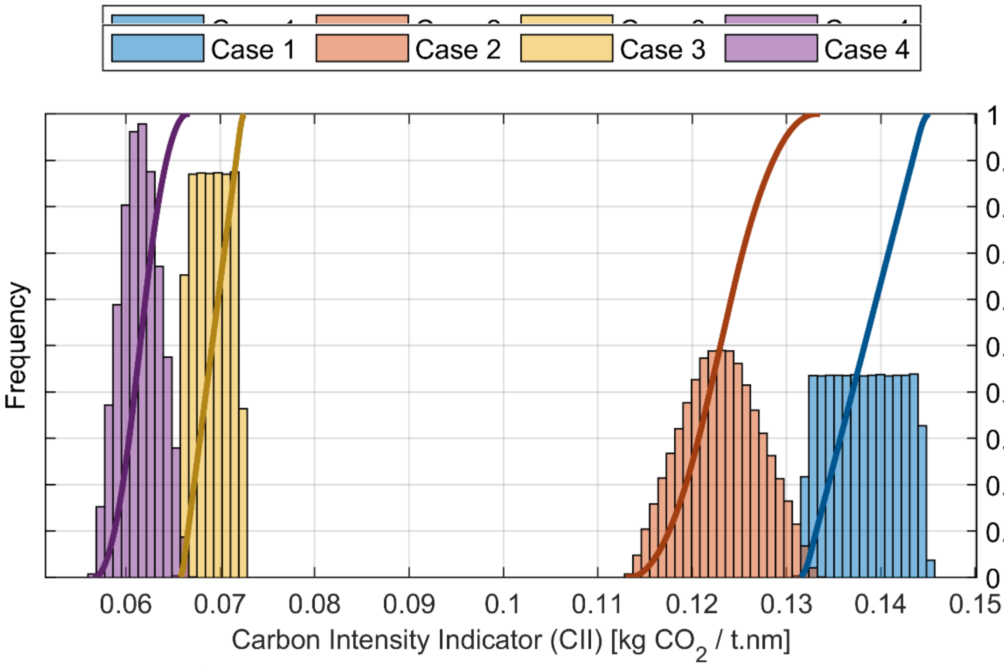

Figure 4. Uncertainty analysis results: CII probability distribution (left axis) and cumulative probability (right axis) for the investigated cases.

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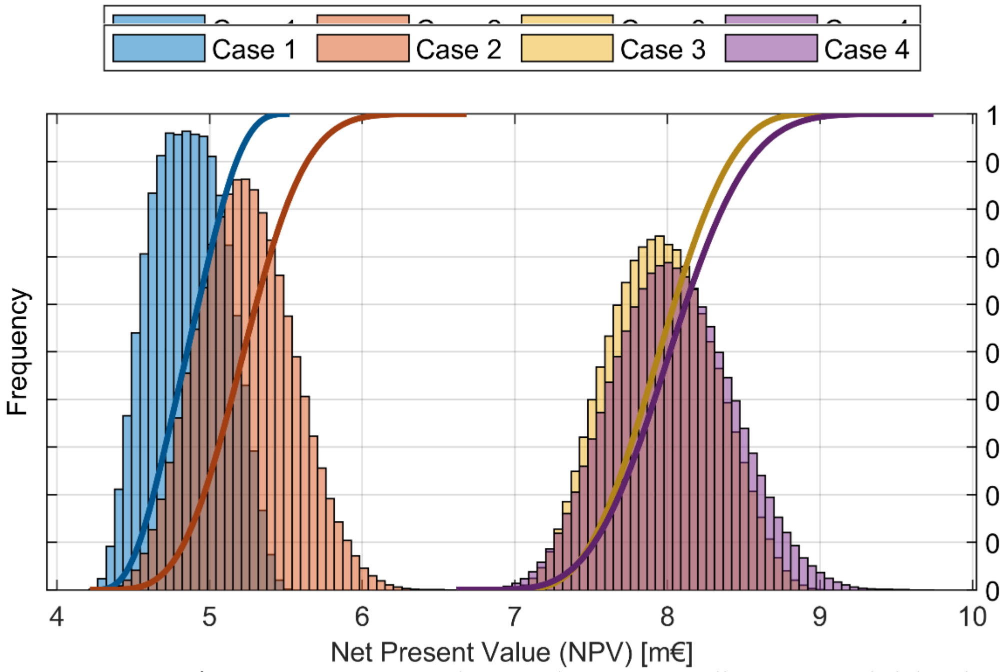

Figure 5. Uncertainty analysis results: NPV (in million EUR) probability distribution (left axis) and cumulative probability curve (right axis) for the investigated cases.

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The CII was selected in this study as a metric to represent the lifetime environmental performance of the investigated case studies. It is observed from Figure 4 that the hybrid power system with 50% energy-wise ammonia fuel contribution (Case 4) provided the lowest CII values, thus the most environmentally friendly performance (in terms of CO_2 emissions). This was attributed to the combination of ammonia fuel carbon neutrality and fuel consumption savings achieved via power plant hybridisation. In Case 2, the exhibited slight reduction in the CII (compared with Case 1) was aligned with the MGO fuel savings associated with the hybrid power plant. Case 3 (conventional power plant with 50% MGO fuel substitution with ammonia fuel) exhibited a remarkable reduction in the CII, with the derived CII values being closer to the ones for Case 4. This was attributed to the significant contribution of carbon-neutral fuel compared with power plant hybridisation. These results were derived under the assumption of constant transported cargo, as its variation was expected to influence the CII values. The derived CII distributions demonstrated that the CII was affected by the uncertainties in main and auxiliary engine fuel consumption. The latter was subject to the ship voyage characteristics and varying weather conditions; however, these were not considered herein.

Figure 5 presents the NPV results for the different cases. Due to the increased CAPEX and OPEX (apart from Case 2, which had lower OPEX but higher CAPEX than the baseline), all cases performed worse than baseline Case 1 in terms of economic evaluation. Case 2 presented an NPV median about 7% higher than Case 1, but the overlap of their probability curves indicated that this difference could change depending on the combination of uncertainties. Case 4 and Case 3 had statistically the same NPVs, i.e., similar distribution, which were about 59% higher than that for Case 1, requiring a greater investment. It could be deduced from the NPV distributions that the NPV was affected by the uncertainties in the fuel prices, as well as uncertainties in the power plant component CAPEX (Table A1, Appendix A).

Carbon taxation is considered a policy measure to incentivise the use of technologies and fuels for maritime transportation decarbonisation. This study calculated the minimum carbon tax required to be applied to conventional power plants and fuels (Case 1) for achieving equal economic outputs (NPVs) between Case 1 and Cases 2, 3 and 4. The derived results for Case 2 demonstrate that the minimum carbon tax of 200 EUR/t is required to incentivise the transition towards economically sustainable hybrid power plants. It must be noted that the batteries charging with renewable energy at ports could provide additional incentives, reducing or even nullifying the carbon tax need, as the emissions could be reduced significantly. The investigation of this case was considered to be outside of the scope of this study. For Cases 3 and 4, the adaptation of ammonia fuel required increased incentives, with the carbon tax levels being at 349 EUR/t and 324 EUR/t, respectively. Comparing these values with the currently employed ones in Norway and in the European Union (for other industries), 50 EUR/ton and 70 EUR/ton respectively [36,37], it is inferred that further uptake in carbon taxation and/or technologies advancement are required to achieve the targeted carbon emission reductions.

The results of the sensitivity analysis are presented in Table 7, using the Importance Factors (Section 2.3) of the parameters listed in Appendix A, for the selected indicators (CII, NPV). The presented values indicate the normalised influence of each parameter and its uncertainty on the investigated indicators. Higher values correspond to a greater influence on the indicators for the considered uncertainty.

Table 7. Sensitivity analysis results: Importance Factors (IF) calculated by Equation (4) for the considered input parameters; zeros indicate non-sensitive parameters.

Parameter		IF-CII (%)				IF-NPV (%)			
		Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
Fuel	MGO price	0	0	0	0	77	37	9.4	5.8
	Ammonia price	0	0	0	0	0	0	60	37
Voyage	ME [1] energy	99	65	99	65	17	7.8	25	14
	AE [2] energy	0.7	0.5	0.7	0.5	0.1	0.1	0.2	0.1
	Voyage efficiency	0	35	0	35	0	4.7	0	8.8
Battery	Size	0	0	0	0	0	23	0	15
CAPEX	Engine	0	0	0	0	6.2	3.8	5.3	4.1
	AT [3] unit	0	0	0	0	0	0	0	0
	Battery systems	0	0	0	0	0	14	0	8.9
	Electric machine	0	0	0	0	0	0	0	0
	Battery	0	0	0	0	0	1.1	0	0.7
OPEX	Engine maintenance	0	0	0	0	0	0	0	0
	Battery system maintenance	0	0	0	0	0	2.0	0	1.2
	Battery maintenance frequency	0	0	0	0	0	5.9	0	3.7

[1] ME, main engine; [2] AE, auxiliary engine; [3] AT, after-treatment.

Considering the environmental indicator (CII), the most influential parameter in the four cases analysed was the ship main engine energy supply (ME). In Cases 1 and 3, which considered a conventional power plant, the major contribution (about 99%) was due to the ship ME. However, in Cases 2 and 4, the ME influence was reduced, as the fuel savings from the hybrid power plant were of significant importance.

For the economic indicator (NPV) in Case 1, the MGO price was the most influential parameter. In Case 2, the ammonia price became the most influential parameter, as ammonia is more expensive than MGO. For the hybrid power plants (Case 2 and 4), the adopted model showed a dispersed influence of the considered parameters, without pointing out a major contribution from a single parameter.

4. Discussion

This study calculated the CIIs and NPVs for the considered power plants and fuels, revealing that decarbonisation strategies for short-sea shipping cargo ships were plausible under the adequate policy measures. This generalisation was made possible considering ships with similar power plant and voyage characteristics. Case 2 demonstrated the worst economic but the best environmental performance compared with Case 1 (baseline). This was due to the battery usage that allowed fuel consumption to be reduced. According to Figure 4, the CII followed a bell-shaped distribution, meaning that the factors affecting it were more than one (main and auxiliary engine fuel consumption in this case), with a median CII of around $0.123\frac{kg\ CO_2}{t\ nm}$ in Case 2, not enough to reach the IMO 2050 target. This was already 11% lower than the baseline and aligned with the expected fuel consumption savings in Case 2. Economically, the NPV calculated in Case 2 was around 8% higher than the baseline (Figure 5) due to the increased CAPEX of the hybrid system, requiring a carbon tax in the range of 200 EUR/t to equalise the NPVs in Cases 1 and 2 (Table 8).

Table 8. Minimum carbon tax (applied to Case 1) for achieving equal NPVs between Case 1 and Cases 2, 3 and 4.

Cases	Carbon Tax (EUR/t)
Case 2	200
Case 3	349
Case 4	324

In Case 3, which considered partial MGO fuel substitution with ammonia, the CII distribution followed a linear cumulative probability, as it was only based on emission-free ammonia combustion in the engines. The CII median was close to $0.069\frac{kg\ CO_2}{t\ NM}$ or 50% lower than the baseline. This demonstrated the direct impact of ammonia fuel usage on the carbon environmental footprint. On the other hand, the NPV followed the normal distribution, as there was a high dependency on several factors, such as the CAPEX of the engine and the after treatment (AT) unit, plant component maintenance and fuel prices, which were characterised by high uncertainty factors (as seen in Table 7). To equalise the NPVs in Cases 1 and 3, a carbon tax of 349 EUR/t, i.e., 43 % higher than that in Case 2, was needed.

Case 4 combined both the decarbonisation strategies (hybrid plant and ammonia fuel) and exhibited a 66% CII reduction compared with Case 1, which enabled the alignment with the IMO 2050 targets of 50% CO_2 reduction. The NPV increased by 40% compared with the baseline and was influenced by uncertainties in multiple parameters, the most important of which were (according to Table 7): fuel price, battery cost and engine cost. However, to equalise the NPVs in Case 4 and in the baseline, a carbon tax of around 325 EUR/t was required, which was lower than that in Case 3.

By elaborating the above results, the economic–environmental performance of different pathways to reduce the carbon footprint of vessel power plants in the short-sea shipping could be evaluated. Considering the target of the highest environmental benefit, the adoption of ammonia fuel seemed to be an effective solution. However, a CO_2 emission taxation policy may be required to accelerate the transition towards short-sea shipping sector decarbonisation.

It must be noted that the employed methodology and the derived results pertain to the specific vessel type and voyage characteristics. Recommendations for further developments include studies of the battery size effects on the energy conversion efficiency and thus the profitability of the hybrid propulsion system, as well as comparative assessments of several alternative fuels that could include, but not be limited to, methanol, LNG and hydrogen. Additionally, a focused safety analysis including reliability and maintainability for vessel operation considering hybrid power plants and alternative fuels should be considered.

5. Conclusions

This study examined different power plant configurations for a short-sea cargo vessel. The baseline operation of the conventional propulsion system operating with marine gas oil fuel was benchmarked against hybrid propulsion and the use of ammonia. The model developed for estimating two major indicators, the NPV and the CII. Uncertainty and sensitivity analyses were conducted to determine the influence of externalities and to identify the most sensitive parameters influencing the investigated cases economic and environmental performance. The following findings were reported:

- Significant environmental benefit was achieved by combining a hybrid propulsion system with alternative fuels such as ammonia, as the CII was reduced by 66%;
- Such power plants achieving reduced environmental footprint could be financially sustainable with the application of a carbon tax of 324 EUR/t;
- Among the most influential parameters on the NPV were found to be MGO and ammonia fuel prices, which were characterised by increased uncertainty;
- The uncertainty of the battery system capital expenditure amounted to 14% and 8.9% of the total expenditure in Cases 2 and 4, respectively, whilst uncertainties regarding engine fuel consumption severely influenced the final engine output, with smaller dependencies for the cases of hybrid plants.

The outcome of this study provides a clear pathway for power plant decarbonisation of short-sea shipping vessels. By analysing the dependencies of the considered parameters on the financial performance, directions are provided for future research and policy incentives. Carbon emission taxation is expected to accelerate the adoption of decarbonisation technologies, including the hybridisation of ship power plants and use of alternative fuels. Future studies could focus on in-depth investigation of battery system usage, as well as, ammonia combustion in marine engines addressing issues of efficiency and safety. Other alternative fuels, such as hydrogen and methanol, are important for shipping operation decarbonisation and need to be examined for identifying and addressing potential challenges in their use. In this way, the shipping sector can achieve the much-needed decarbonisation and participate in the global effort to mitigate climate change implications in the short–medium-term future.

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Appendix A

The uncertainty percentages of the considered parameters are listed in Table 7.

Table A1. Uncertainty percentages of the considered parameters.

Parameter		Uncertainty (%)
Fuel	Price of MGO	10
	Price of ammonia	10
Voyage	ME energy consumed	5
	AE energy consumed	5
	Voyage efficiency	30
CAPEX	Battery size	33
	Engine cost	10
	AT unit cost	10
	Battery system cost	50
	Electric machine cost	50
	Battery cost	25
OPEX	Engine maintenance	25
	Battery system maintenance	50
	Battery replacement frequency	33

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