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Life Cycle Analysis of Hydrogen Powered Marine Vessels—Case Ship Comparison Study with Conventional Power System

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Abstract: The latest International Maritime Organization strategies aim to reduce 70% of the CO_2 emissions and 50% of the Greenhouse Gas (GHG) emissions from maritime activities by 2050, compared to 2008 levels. The EU has set up goals to reduce GHG emissions by at least 55% by 2030, compared to 1990, and achieve net-zero GHG emissions by 2050. The UK aims to achieve more than 68% GHG emission reduction by 2030 and net-zero GHG emissions by 2050. There are many solutions under development to tackle the challenge of meeting the latest decarbonization strategies from the IMO, EU, and UK, among which are hydrogen powered marine vessels. This paper presents a life cycle analysis study for hydrogen fuelled vessels by evaluating their performance in terms of environmental friendliness and economic feasibility. The LCA study will consider the gas emissions and costs during the life stages of the ships, including the construction, operation, maintenance, and recycling phases of the selected vessels. The results of the comparisons with the conventional version of the ships (driven by diesel generators) demonstrate the benefits of using hydrogen for marine transportation: over 80% emission reduction and around 60% life cycle cost savings. A sensitivity analysis shows that the prices of fuels and carbon credits can affect the life cycle cost, and recommendations for low H2 price and high carbon credit in the future are provided to attract the industry to adopt the new fuel.

Keywords: hydrogen; life cycle analysis; life cycle cost analysis; ships; decarbonization

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1. Introduction

International shipping enables 80–90% of global trade and comprises about 70% of global shipping energy emissions [1]. The UK domestic maritime vessels represented around 5% of the UK's domestic transport GHG emissions in 2020, which was more than the domestic rail and bus emissions combined [2]. According to the IMO strategy of 2018, the United Nation (UN) is expected to reduce CO_2 from international ships by at least 40% by 2030, compared with 2008 levels, and work towards reductions of at least 70% by 2050 [3]. One of the solutions is to use hydrogen, with heat and water as by-products, to replace the current marine diesel oil (MDO), which is critical for the decarbonisation of both international shipping and the UK Clean Maritime Plan [4]. If used as a replacement fuel, it will need five times the volume of liquefied hydrogen to provide the same energy as HFO, or ten to fifteen times the volume if stored as compressed gas [5]. The current cost for green hydrogen production is around $66–154/MWh, which is predicted to drop to around $32–100/MWh in 2050 with the reduction in prices for both electrolysers and renewable energies [1]. In the medium to long term, green hydrogen will be the foundation of a decarbonised international shipping industry [6]. However, due to the natural property of hydrogen, there are still a few aspects that need to be studied before safe commercial application can be achieved, such as leakage [7] as well as its production, transport, and storage [8]. Nevertheless, researchers have carried out a series of studies to investigate hydrogen applications in shipping transportation. Taccani, Malabotti [9] carried out a case study of a small roll-on/roll-off passenger ferry retrofit with hydrogen fuel cells. This study introduced gaseous hydrogen as fuel and was focused on the hydrogen storage onboard, which showed that the filling process is very critical to maximizing the stored hydrogen mass. Aarskog, Danebergs [10] conducted a study to analyse the energy and cost of a high-speed passenger ferry driven by hydrogen, which showed that the OPEX could be 12% to 28% higher when using the on-board hydrogen fuel cell than when using biodiesel or diesel, in the current scenario. But with moderate technology improvements and cost development, the technology could be competitive from 2025 to 2030.

Life cycle assessment (LCA) has also been carried out by researchers to investigate the application of hydrogen in the shipping industry. Trillos, Wilken [11] have conducted the LCA for a green hydrogen (i.e., H_2 produced using renewable energy) fuel cell-powered ferry compared with a conventional diesel ferry, which showed up to 89% reduction in GHG in a 30-year life. Hydrogen fuel cells also have advantages compared to batteries, especially when large on-board energy storage is required [12]. Ling-Chin and Roskilly [13] conducted an LCA study to verify the retrofit engine technologies compared with a conventional power system and showed that less fuel was consumed and less emissions released. Gilbert, Walsh [14] conducted the LCA for air emissions of alternative shipping fuels, and green hydrogen was one of the most promising candidates in regards to carbon reduction. Ling-Chin and Roskilly [15] conducted the LCA to assess the impact of a new-build hybrid system designed for roll-on/roll-off cargo ships on the environment, human health, and natural reserves. To achieve the zero GHG emission goal, Kanchiralla, Brynolf [16] conducted the LCA for potential decarbonisation solutions, such as electrolytic hydrogen, electro-ammonia, electro-methanol, and electricity, in different propulsion systems such as engines, fuel cells, and carbon capture technologies, in terms of environmental impact and costs. This study gave a detailed assessment of different decarbonisation pathways from a life cycle perspective, and the largest part of the cost was associated with the fuel, except for the battery-electric case. Wang etc. [17] developed a comprehensive life cycle assessment framework for hydrogen fuelled ships. The type of ship under evaluation was a small passenger and cargo ship operated and served in the seas around China. Jang etc. [18] applied a parametric trend lifecycle assessment (PT-LCA) for thousands of ships using hydrogen fuel cells. The relationships between emissions and ship characteristics were presented with the lifecycle benefits/harms of hydrogen and recommendations on the proper use of hydrogen as marine fuel. Wang etc. [19] evaluated the environmental impact of various alternative low-emission fuels for a super yacht using life cycle analysis. The study analysed marine gas oil (MGO), liquefied natural gas (LNG), methanol, biodiesel, and hydrogen and recommended hydrogen from renewable production as a decarbonisation solution for this particular ship type.

For all these studies, their methodology involved applying life cycle analysis and life cycle cost analysis to evaluating the performances of their research or study targets. However, among these studies, none focused on the performance evaluation of small vessels retrofitted with hydrogen fuelled engines. As an important solution for decarbonisation of the maritime industry, it is of interest to the participants in the maritime sector to understand the performances of hydrogen fuelled engines for maritime transportation, especially for the case study vessels in this article, which serve and operate in the waters around Scotland, UK.

2. Materials and Methods

2.1. Life Cycle Analysis

The LCA has been widely applied in the maritime sector, according to the ISO standards, and the following four procedures are fundamentally included for an LCA study:

1. Definition of research/analysis objectives and boundaries;
2. Life cycle inventory analysis (LCI);

3. Life cycle impact analysis (LCIA);
4. Life cycle interpretation [20,21].

Figure 1 presents the flowchart and interactions between these procedures.

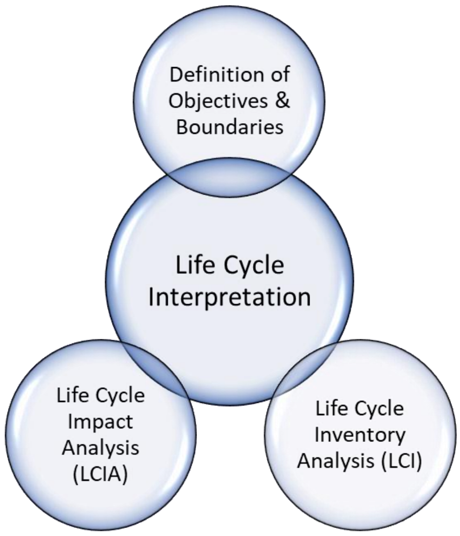

Figure 1. The life cycle assessment procedures.

To define the objectives and scope of a research study, it is customary to establish specific performance or cost criteria for the system or product under investigation, with a focus on environmental and cost impacts. These environmental impacts are typically classified into various groups, including global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP). Therefore, before delving into a comprehensive analysis, the first crucial step involves setting clear study goals to understand the intended outcomes.

Once the study goals are defined, it becomes essential to establish the scope and boundaries of the analysis, as life cycle assessment (LCA) allows for a comprehensive examination of the target. By defining the scope and boundaries, the analysis avoids becoming overly extensive and time-consuming. Additionally, it enables the identification and prioritization of emissions and pollutants that significantly influence the study outcomes, while disregarding less impactful ones.

Typically, the life stages considered in the LCA are divided into four phases: construction, operation, maintenance, and scrapping. These stages provide a structured approach to evaluating the entire life cycle of the system or product in question.

Setting the scope and boundaries is a critical aspect of simplifying the study, ensuring that the results are credible, and making reasonable assumptions. By doing so, the study becomes more manageable and trustworthy, providing valuable insights into the environmental and cost implications of the researched system or product. Once the scope and boundaries of the study are established, the next step involves selecting a functional unit as a standard or scale for evaluation. This functional unit serves as a reference point that allows for meaningful comparisons between different scenarios.

To facilitate these comparisons effectively, a normalization process is applied. This process involves converting the quantities of selected emissions into various indicative emissions specific to different environmental impacts. By doing so, the data can be standardized and made comparable across diverse environmental contexts. Based on the CML database [22], the emissions contributing to global warming will be normalized by converting into an equivalent quantity of CO_2, and the unit is kg CO_2 equivalent. Similarly, for AP and EP, the fundamental pollutants are sulphur dioxide and phosphate (SO_2 and PO_4^{3-}). Usually, a functional unit could be the quantified ship performance during its service (such as cargo transport per km), but it can also be set up based on the preferences of the end-users and their objectives.

Following the goal and scope definition, the life cycle inventory analysis can be conducted as shown in the schematic diagram in Figure 2.

Figure 2. Schematic chart of life cycle inventory analysis.

The process begins with the establishment of defined goals and scope from the previous step, where an initial LCA plan has been selected and defined. With this plan in place, data relevant to the LCA can be collected, normalized, and aggregated to derive preliminary results. However, the scope of the LCA analysis may be adjusted depending on the availability of pertinent data.

Following the refinement of the scope based on data availability, similar processes of data collection, normalization, and aggregation are carried out. This ensures that a modified, yet comprehensive inventory is obtained for the LCA analysis. By iteratively updating and refining the scope and data, a more accurate and complete picture of the LCA results can be achieved.

The life cycle inventory will be used as a fundamental basis for the life cycle impact analysis, which consists of three steps:

a. Impact categories selection, including indicators and characterization models;
b. Emissions classification to assign LCI results to the selected impact categories;
c. Characterization to calculate the LCI results as a base and apply characterization models to quantify the impacts based on category indicator.

During the final phase of life cycle interpretation, a sensitivity analysis is performed to assess the influence of selected inputs on the established LCA processes and outcomes, including both mid-term and end-term results. The inputs chosen for this analysis are carefully selected based on their importance, accessibility, and uncertainty. By scrutinizing these key factors, the sensitivity analysis helps to understand the robustness and reliability of the LCA results, offering valuable insights into the overall study. For the sensitivity assessment, key parameters will be selected and addressed to understand their impact on the final outcomes of the LCA. It is conducted by varying the collected/assumed value of a parameter, such as 50%, 150%, or 200% of the used value. The trends or the pattern of changing or impacting the final LCA results will be observed to indicate the significance of the key parameters to the LCA outcomes. In the meantime, an uncertainty treatment will be conducted to analyse the confidence levels of the key parameters and data. The selection approaches of data/parameters in sensitivity assessment and uncertainty treatment are different: (1) in sensitivity assessment they are selected based on the data importance to the study; (2) in the uncertainty treatment the selection is according to the data availability. The levels of confidence will be categorized into three levels: low, medium, and high. The higher category means the data, or the values, are more trustworthy. The consequence level is also defined by three levels: severe, intermedium, and slight. The categorisation in this uncertainty treatment is conducted by the project team in which they apply their experience and judgement to provide a level for each parameter and data point. The product of the confidence and consequence levels will present the impacts of the parameters on the LCA outcomes (Table 1).

Table 1. Impact matrix: confidence and consequence levels.

		Consequence		
		Slight	**Intermedium**	**Severe**
Confidence	Low	3	6	9
	Medium	2	4	6
	High	1	2	3

The outcomes of the LCIA analysis will highlight the notable advantages of using a hydrogen fuelled engine. These results typically yield recommendations for end-users regarding the selection of various alternatives. Additionally, during the interpretation process, the conclusions, limitations, and recommendations of the LCA analysis are presented. This presentation not only elucidates the decisions made but also outlines the constraints inherent in the analysis. By providing this comprehensive interpretation, stakeholders gain a clear understanding of the benefits and considerations associated with the implementation of hydrogen fuelled engines.

2.2. Governing Formula

The analysis approach will follow the LCA guidelines and will be customised with the study. A system breakdown in which the ship is divided into two entities with a consideration of four life stages is shown in Figure 3. The two partial entities are ship hull and machinery while the four stages are construction, operation, maintenance, and scrapping. Figure 3 presents what main activities will be considered under different life stages. As this study investigates the life cycle performances of the hydrogen and HFO powered marine vessel, the main focus is on the main and auxiliary engines. The software ShipLCA v1.4, developed in EU H2020 project—SHIPLYS, has been deployed to ensure the same ship construction, maintenance, and dismantling data are applied. The additional equations will be necessary to estimate the fuel consumption for the hydrogen version of the case ships. The estimation is conducted using the following steps:

A. Theoretical energy provided from main engine to shaft:

$$E_{provide} = m_{fuel} \times LHV_{MDO} \times \eta$$

where,

$E_{provide}$ is the energy provided from the engine to the shaft during operation (kWh),
m_{fuel} is the mass quantity of the fuel oil consumption (kg),
LHV_{MDO} represents the lower hearing value of the MDO (kWh/kg),
and η is the estimated energy efficiency of the original power plant.

B. Hydrogen fuel required to provide equivalent energy:

$$m_{H2} = E_{provide}/(\eta_{H2} \times LHV_{H2})$$

where,

$E_{provide}$ is the energy provided from the engine to the shaft during operation (kWh),
m_{H2} is the mass quantity of the hydrogen consumption (kg),
LHV_{H2} represents the lower hearing value of the hydrogen (kWh/kg),
and η_{H2} is the estimated energy efficiency of the hydrogen power plant.

To clarify the usage of these two equations, the masses of two fuels are estimated following the engine project guide and ship operational data.

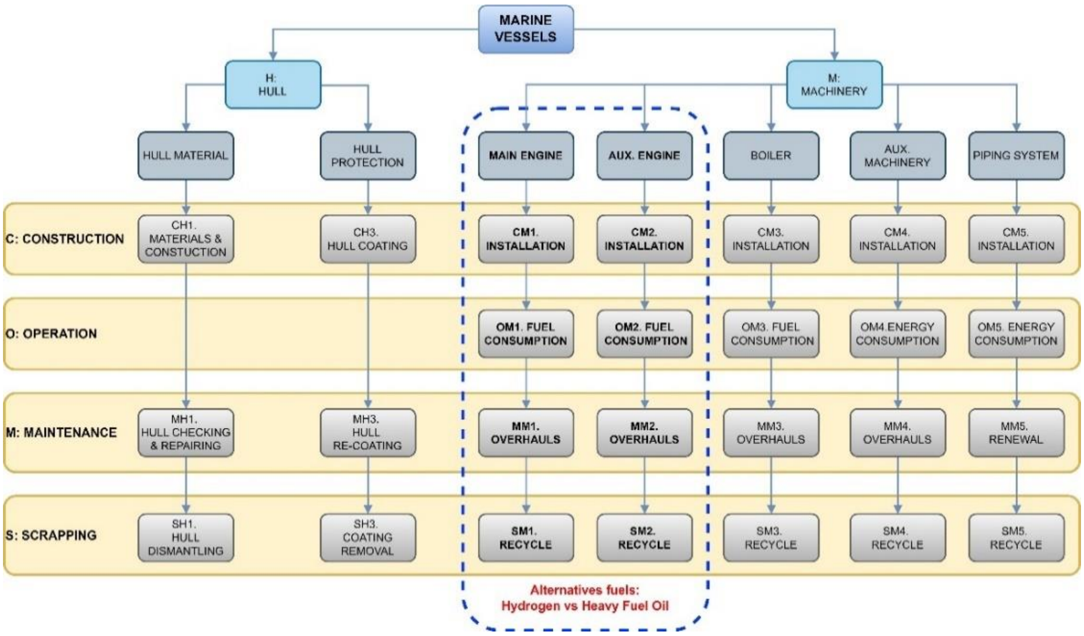

Figure 3. Overall study scope and system.

2.3. Data Collection and Assumption

Data for four case ships, including a mainland ferry, a pelagic trawler, a large tug ship, and an interisland ferry, were collected. The case specific details for the four ships are shown in Table 2.

Table 2. Data collection for the case study ships.

Life Stages	Parameters	Mainland Ferry	Pelagic Trawler	Large Tug	Interisland Ferry	Units
Design	Length overall	125	69.9	38.4	65.4	m
	Length between perpendiculars	119	61.8	35	58.4	m
	Breadth	19.5	15.6	13.4	13.8	m
	Depth	8	9.5	7.9	5.6	m
	Draught	5.3	7.9	6.0	3.6	m
	Block Coefficient	0.59	0.55	0.65	0.49	-
	Service speed	24	15.2	13.5	11	kn
	Number of crew	33	12	5	6	
	Engine Power	4 × 5400	5400	2 × 2150	2 × 1200	kW
	Ship total price	35	28	8	4.5	million €
Construction	Number of Engines	4	1	2	2	
	Engine weight	207 × 4	63.2	15.6 × 2	10.7 × 2	tonne
	Maximum engine output	5400	5400	2150	1200	kW
Operation	Annual working hours	1200	1200	1200	1200	
	Number of engines running	4	1	2	2	(@85% MCR)
	Actual working power per engine	4590	4590	1828	1020	kW (85% MCR)
	Actual specific fuel oil consumption	175	175	202	188	g/kWh
	Actual specific lubricating oil consumption	0.6	0.5	-	-	g/kWh

To proceed with the LCA analysis, the following assumptions have been applied to the case ship study and inputted into the ShipLCA software:

1. The carbon credit is around 70 € per tonne CO_2 based on the study from [23]. The sulphur credit is 7788 € per tonne according to the study from [24].
2. Two types of fuels are under consideration and comparison: hydrogen and marine diesel oil (MDO); the hydrogen fuel in the UK is about 2500 € per tonne [25]; and the MDO price is according to the data found in [26].
3. As the database from ShipLCA has been used, these data include the specification of hull and outfitting processing, transportation means, electricity types, maintenance strategies, and end-of-life scenarios.
4. The operational phase considers the fuel production processes for MDO, hydrogen, and lubricant oils.
5. The drydocking schedule varies. Usually, a drydocking survey is conducted every 2.5 years, and, in some cases, every 5 years for large commercial vessels. In this study, a drydocking is assumed to be conducted every 2.5 years for the purpose of surveying, cleaning, and repairing.
6. For the end-of-life scenarios, the costs of the scrapping are based on the material quantities to be treated from both the ship hull and machineries.
7. Four different categories of the environmental impacts are taken into account: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and photochemical ozone creation potential (POCP). The indicative emissions for normalisation and impact evaluation are CO_2, SO_2, PO_4, and C_2H_6, respectively.
8. The study will consider a 30-year operation for all the case study ships.

The following are the limitations of the study due to data availability and will be further discussed in the next section:

1. The hull structure remains unchanged while considering different versions of the case study vessels.
2. The hydrogen engine, and therefore the price quotation, are not yet available, so the work has a limitation regarding the engine investment because it applies the same engine price for different versions of the case study vessels.
3. The cost of the construction phase in the LCCA is mainly estimating the cost of materials based on empirical equations, the supply chain of the engines, and the construction and installation activities (e.g., cutting, bending, welding, blasting, and coating), which might not be sufficiently reflecting the real-world costs; although, the outcomes of the comparison studies will not be significantly affected.

3. Results

3.1. Life Cycle Assessment (Environmental Impact)

This section presents the evaluation results for four case study ships in terms of environmental impacts. The figures below show the results for four case vessels, i.e., mainland ferry, pelagic trawler, large tug ship, and interisland ferry (Figures 4–7).

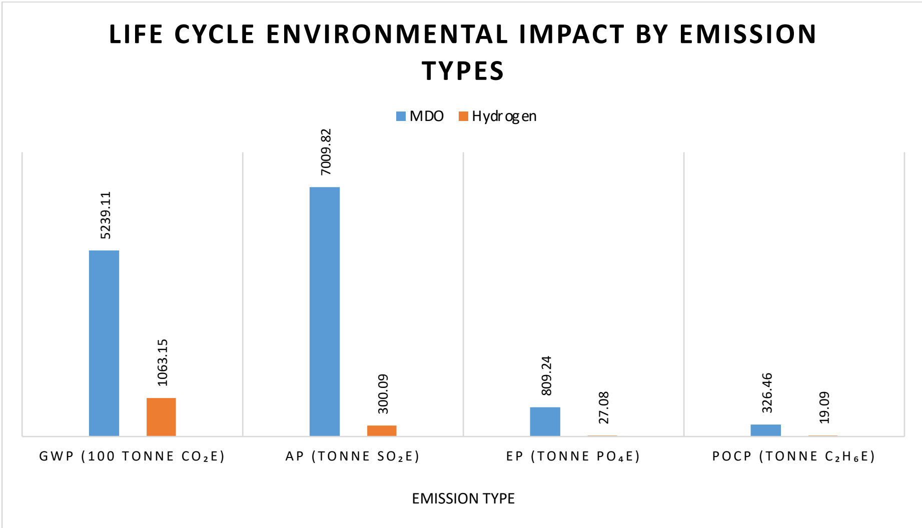

Figure 4. Mainland Ferry—Life Cycle Environmental Impacts.

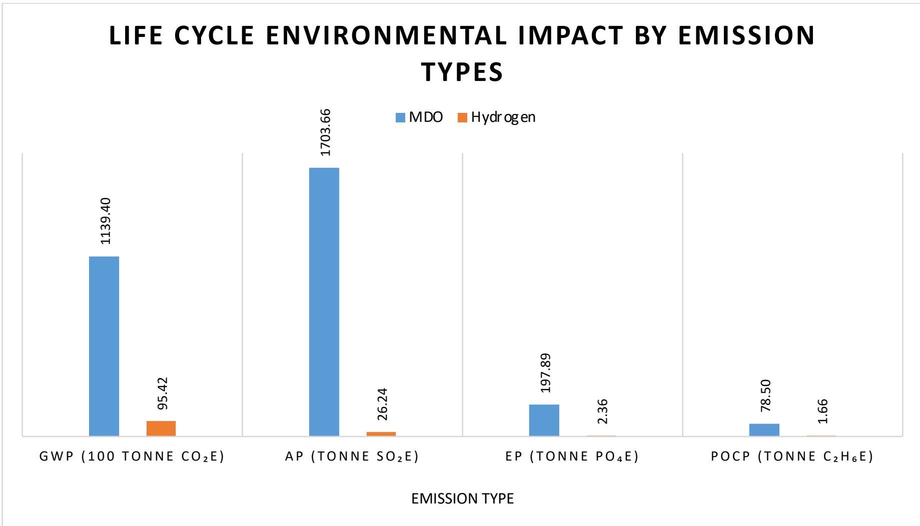

Figure 5. Pelagic Trawler—Life Cycle Environmental Impacts.

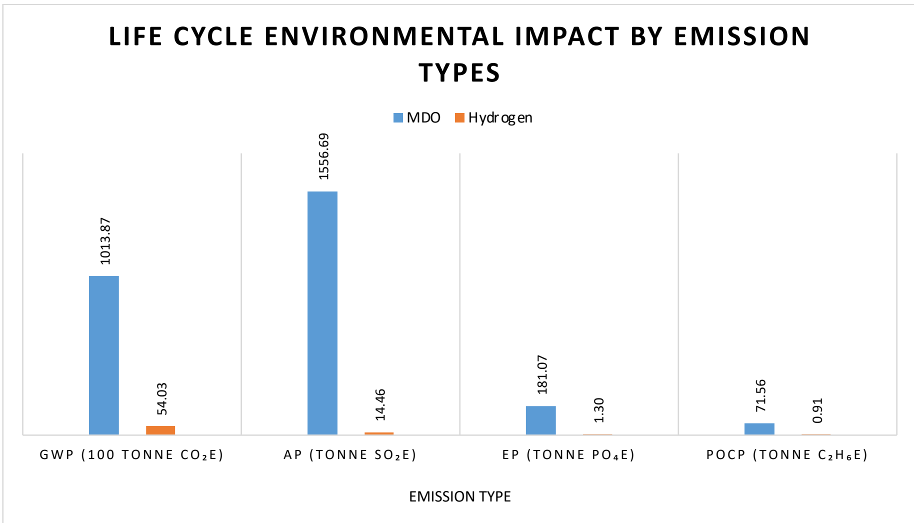

Figure 6. Large Tug Ship—Life Cycle Environmental Impacts.

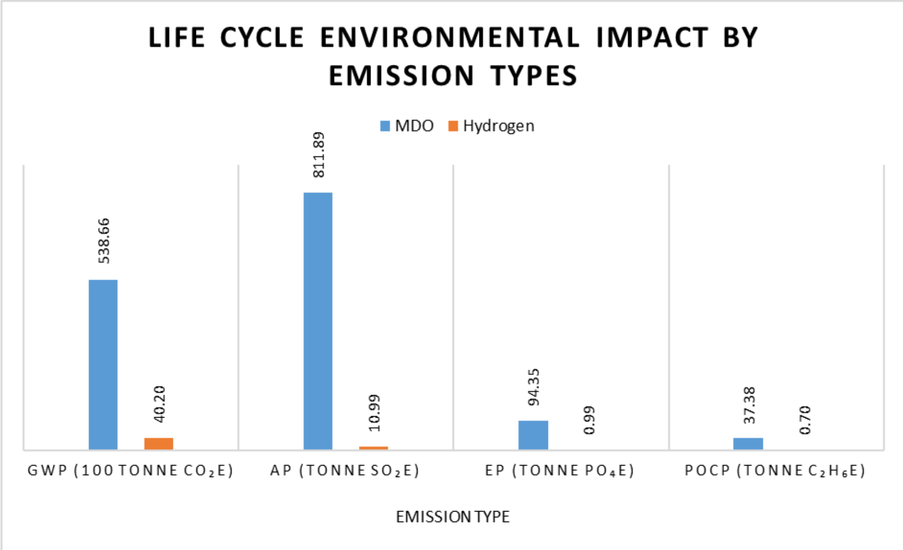

Figure 7. Interisland Ferry—Life Cycle Environmental Impacts.

From the LCA results, it can be seen that the emissions from the MDO version of the ship were much greater than those from the H_2 version for the global warming potential (GWP), to which CO_2 is one of the main contributors. With the replacement of MDO by H_2, the CO_2 emissions from ship operation were significantly reduced because the combustion of H_2 releases no CO_2. For the mainland ferry, the GWP reduction was about 79.71%, which was the lowest reduction among all the case ship vessels. This is because the construction phase contributes a large amount of GHGs, resulting a lower GWP reduction. For the other three vessels, with the replacement of MDO with H_2, a GWP reduction of over 91% was achieved.

In terms of AP, EP, and POCP results for all four ships, the reductions reached over 98% as H2 is a green fuel contributing to none of these environmental potentials.

3.2. Life Cycle Cost Assessment (Economy Impact)

In the meantime, the LCCA estimated and investigated the cost of the two versions of the case ships to compare how the total cost/investment varied while applying H_2 as fuel instead of MDO. The same activities were under consideration as the LCA analysis and the focus was the cost from capital investment, energy cost, fuel cost, etc. For the case ships, the results are shown in Figures 8–11.

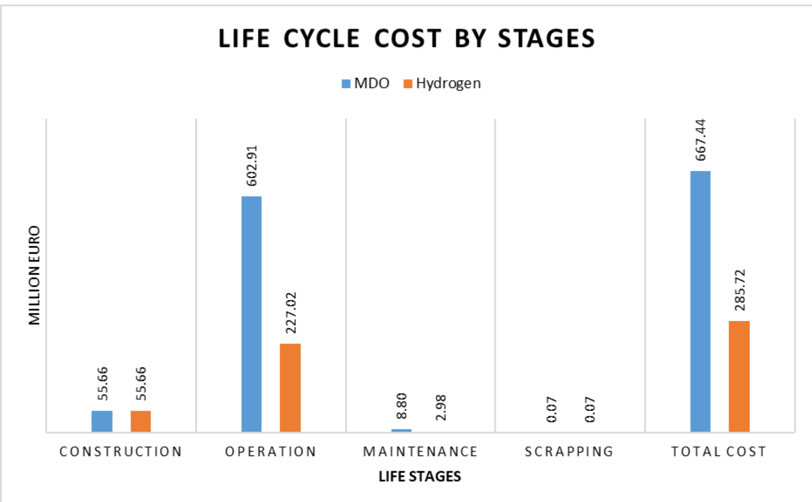

Figure 8. Mainland Ferry—Life Cycle Cost Impacts.

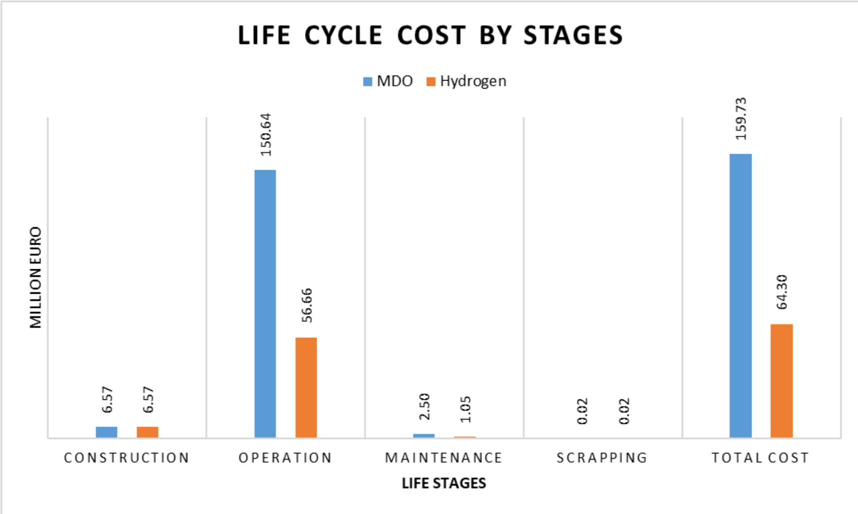

Figure 9. Pelagic Trawler—Life Cycle Cost Impacts.

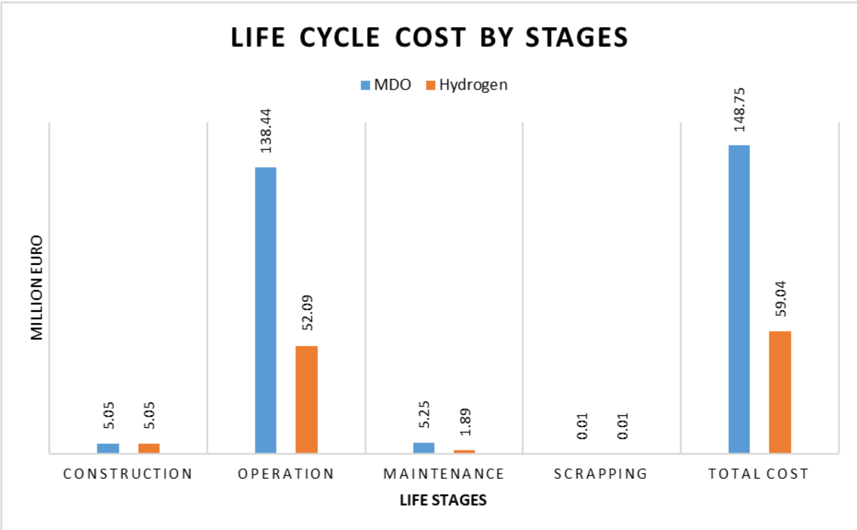

Figure 10. Large Tug Ship—Life Cycle Cost Impacts.

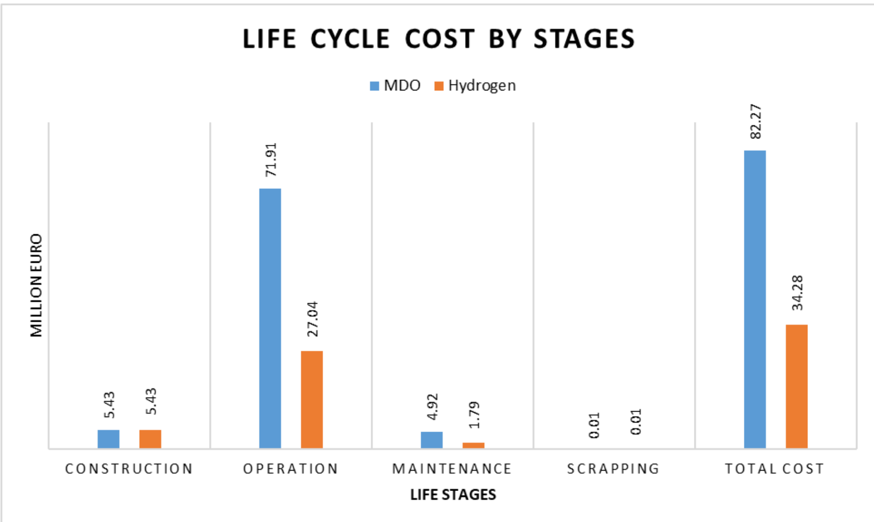

Figure 11. Interisland Ferry—Life Cycle Cost Impacts.

With the LCCA analysis, the most important phase was the operation phase, which occupied the largest portion of the total cost since the fuel cost accumulated over the operation stage. This represented about 88% and 80% of the total cost for MDO and H_2 version ships, respectively. The two limitations described in the previous section are not considered to have significantly affected the outcomes of this work. This is because the cost is accumulating from the cradle to the grave of the selected ships and most of the costs are from the operational phase.

Additionally, with the consideration of carbon credits, the more carbon emission released, the more carbon credits need to be purchased. This will provide ship operators an option to optimise the cost and policy makers can moderate the carbon credits rate to accelerate the adoption of green fuels in the maritime industry.

Therefore, the prices of the fuels and the carbon credit play vital roles in this cost evaluation. In the next section, a further evaluation will be conducted to illustrate how these two parameters can impact the LCCA results.

3.3. Sensitivity Assessment

From the study, assumptions were made due to the lack of data to determine comparable results from different scenarios. To test the impact of the assumed parameters, further analysis will be conducted by repeating the LCA analysis with varied assumed values in this section. As not only an assessment of individual parameters, but also a generalised approach for any further investment on parameter sensitivities, this section describes how the sensitivity assessment works and what the results looks like.

The main assumption that may affect the results is the price of hydrogen fuel, which fluctuates for different regions and industries. From the additional run of the LCA and with the hydrogen price ranging from 1500 Euro/ton to 3500 Euro/ton, it was found that the life cycle total cost increased linearly, as shown in Figure 12, which was within expectations. It will be recommended to limit the price of hydrogen fuel to encourage its application by reducing the life cycle expenditures. Another factor assessed was the carbon credit price and the original input was 70 Euro/ton CO_2. The situations of 35, 140, 210, and 280 Euro/ton CO_2 were evaluated and compared. The effect on the life cycle cost was also linear, but due to the usage of green hydrogen, the increment of cost mainly resulted from the construction phase (Figure 13). The fact is that even though the credit was increasing it was still lower than the traditional version of the ship because the carbon credit for the traditional ship will be even larger due to the large quantity of CO_2 emissions from fossil fuels.

3.4. Uncertainty Treatment

The LCA analysis uses data collected from the Neptune project and is also based on data from the literature and assumptions. Therefore, an uncertainty treatment should be included to evaluate the confidence of the parameters/data used in the LCA so that the LCA is trustworthy. The method to conduct the uncertainty treatment is to identify the key parameters/data and use experts' judgement to categorise the confidence level of each parameter and data point. For this study, the experts among the project team were consulted for their opinions on the key parameters/data selection and their confidence levels.

Ten parameters/data were eventually selected based on the approach of the LCA to estimate the environmental impacts. The confidence levels of all these parameters and data were judged and commented on by the partners and finally summarised and averaged, as listed in Table 3.

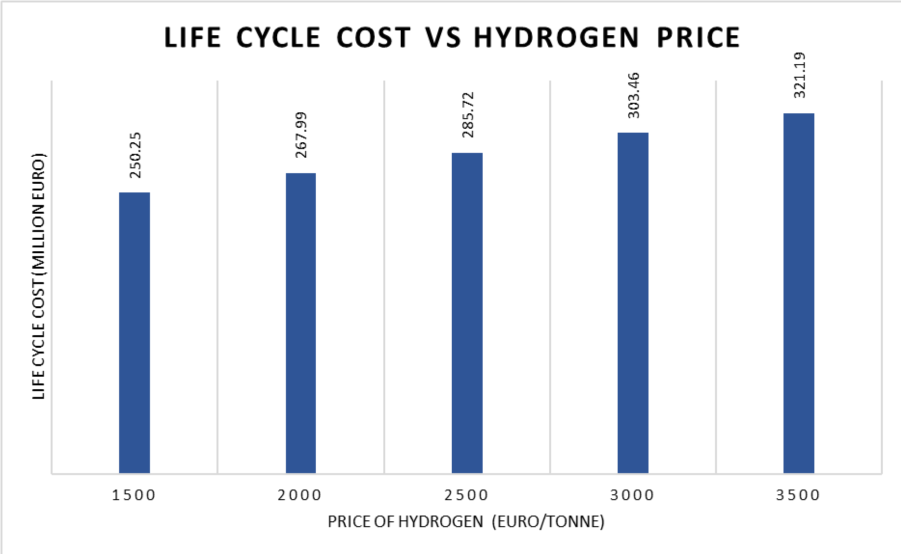

Figure 12. Total life cycle cost vs. hydrogen price.

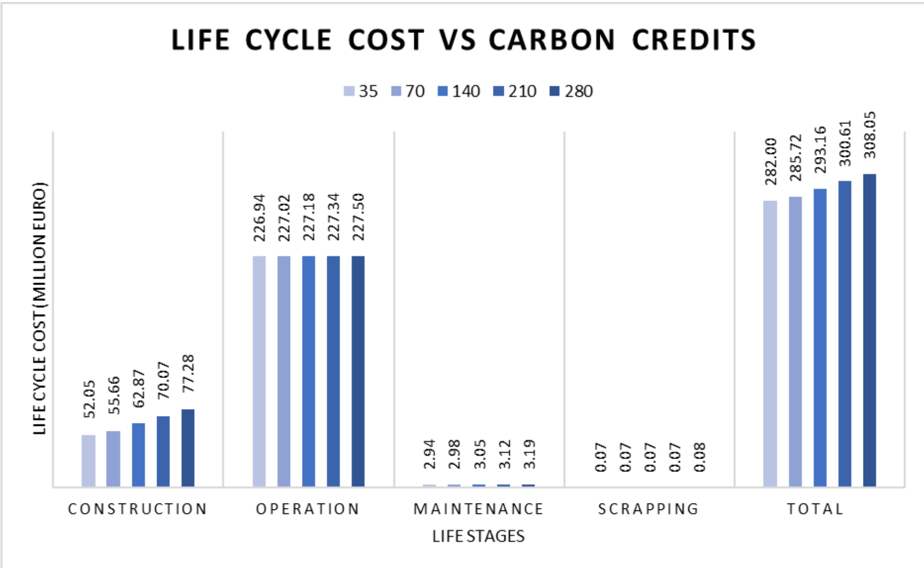

Figure 13. Total life cycle cost vs. carbon credits (phase view).

Table 3. Uncertainty treatment: parameters/data and their impacts.

No.	Parameter/Data	Confidence	Consequence	Final Impact
1	Carbon credit	Medium	Intermedium	Medium
2	MDO price	High	Severe	Low
3	Hydrogen price	Medium	Severe	Medium
4	Drydocking interval	Medium	Slight	Low
5	Scrapping cost	Low	Slight	Low
6	Engine efficiency	Medium	Severe	Medium
7	Electricity type	High	Intermedium	Low
8	Operational years	Low	Severe	High
9	SFOC	High	Severe	Low
10	Transportation means	Low	Slight	Low

4. Conclusions

To follow the IMO's maritime emission control strategy of reducing 70% of the CO_2 emissions and 50% of the GHG by 2050, a range of technologies has emerged, including the usage of hydrogen as a marine fuel for transportation. The application of hydrogen is challenging and one of the purposes of this article was to evaluate the life cycle performance of vessels with hydrogen fuel replacing traditional fuels from the perspective of environmental protection (emissions) and economic feasibility (cost). The following findings were concluded with the support of in-house software SHIPLCA:

1. This paper first provided a generalised LCA approach to evaluate the applications of new alternative green fuels to assess and compare the environmental and economy impacts.
2. Four vessels were investigated, and as expected, hydrogen brought significant improvement by lowering emissions and cost due to the facts of fuel price and carbon credits.
3. The most significant phase of the ship's life on the environment and economy was the operational phase due to the high fuel consumption and long operational years.
4. A sensitivity analysis was conducted to test how these two parameters, H_2 price and carbon credits, can affect the life cycle performance results. It was observed that the lower H_2 price will be more attractive; however, a higher carbon credit increased the cost but the overall cost (3.08×10^8 Euro) was still lower than the traditional vessel with MDO (6.67×10^8 Euro).
5. For the uncertainty treatment, the assumptions in this study were evaluated considering their confidence and consequence levels and their impacts on the LCA outcomes were determined.

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