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Life Cycle Cost Analysis for Scotland Short-Sea Ferries

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Abstract: The pathway to zero carbon emissions passing through carbon emissions reduction is mandatory in the shipping industry. Regarding the various methodologies and technologies reviewed for this purpose, Life Cycle Cost Analysis (LCCA) has been used as an excellent tool to determine economic feasibility and sustainability and to present directions. However, insufficient commercial applications cause a conflict of opinion on which fuel is the key to decarbonisation. Many LCCA comparison studies about eco-friendly ship propulsion claim different results. In order to overcome this and discover the key factors that affect the overall comparative analysis and results in the maritime field, it is necessary to conduct the comparative analysis considering more diverse case ships, case routes, and various types that combine each system. This study aims to analyse which greener fuels are most economically beneficial for the shipping sector and prove the factors influencing different results in LCCA. This study was conducted on hydrogen, ammonia, and electric energy, which are carbon-free fuels among various alternative fuels that are currently in the limelight. As the power source, a PEMFC and battery were used as the main power source, and a solar PV system was installed as an auxiliary power source to compare economic feasibility. Several cost data for LCCA were selected from various feasible case studies. As the difficulty caused by the storage and transportation of hydrogen and ammonia should not be underestimated, in this study, the LCCA considers not only the CapEx and OpEx but also fuel transport costs. As a result, fuel cell propulsion systems with hydrogen as fuel proved financial effectiveness for short-distance ferries as they are more inexpensive than ammonia-fuelled PEMFCs and batteries. The fuel cost takes around half of the total life-cycle cost during the life span.

Keywords: life cycle cost analysis; carbon-free fuel; electric propulsion ship; greener shipping; solar PV

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1. Introduction

1.1. Background

Since the First Industrial Revolution occurred around the middle of 18 century in the United Kingdom, fossil fuel consumption was accelerated until the Fourth Industrial Revolution, and it has caused severe environmental pollution [1]. As global warming and climate change are major worldwide concerns, reducing greenhouse gas (GHG) emissions is becoming a priority in every business sector. The marine sector, which takes charge of 80% of volumetric world trade [2], is not an exception. Waterborne transportation requires relatively less energy than road and air transportation for shipping goods of the same weight and distance, but still, marine vehicles consume around 300 million tonnes per annum [3]. The massive quantity of fuel consumed by ships emits enormous GHG emissions. From 2007 to 2012, GHG emissions by ships contributed 13.0% of sulphur oxides (SO_x), 15.0% of nitrogen oxides (NO_x), and 3.1% of carbon dioxide (CO_2) of total global artificial emissions [4]. Methane (CH_4) emissions increased by 87% from 2012 to 2018, and SO_X and particulate matter (PM) emissions increased as well [5].

The International Maritime Organization (IMO) set several regulations to control and mitigate air pollution from ships, represented as the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) [6]. They have continuously been strengthening the regulations, and as part of this, the Energy Efficiency eXisting ship Index (EEXI) and Carbon Intensity Indicator (CII), which are scheduled to come into force in 2023, were stipulated. Some technical and operational methods focus on optimising and improving ship energy consumption. However, as long as fossil fuels are used as the main source of producing energy for ships, there is a limitation to reducing emissions to some extent.

Alternative energy sources have emerged as more eco-friendly substitutes for world widely spread marine fuels, such as heavy fuel oil (HFO), marine diesel oil (MDO), and liquefied natural gas (LNG). Eco-friendly fuels such as hydrogen, ammonia, and electrical energy are being studied as alternatives and are expected to reduce GHG emissions and eliminate them eventually. Even though the next-generation fuel has not yet been confirmed due to many challenges such as technical issues, supply chain, cost, and so on, hydrogen, ammonia, and electricity, which are zero-carbon emissions, are considered feasible next-generation fuels/energy.

1.1.1. Fuel Cells

Among various technologies using alternative fuel sources, fuel cells are one of the most feasible advanced technology with low environmental impact [7]. A single conversion process of fuel cells generates electricity from energy sources [8]. As the fuel cells do not require a combustion process which is needed for internal combustion engines (ICEs), the energy efficiency of fuel cells is higher than ICEs. The typical energy efficiency of ICEs is 30 to 45%, whereas fuel cells are 40% to 60% and even up to 80% with a waste heat recovery system [9,10]. The fuel cell propulsion system has been adopted for submarines, autonomous underwater vehicles, commercial yachts, small ferries, and auxiliary power units for Ro-Pax and car carriers with the benefit of continuous electricity supply without recharging while the energy sources are provided [11]. The proton-exchange membrane fuel cell (PEMFC) is the most common type of fuel cell in the marine sector with a technical readiness level [12]. Various realistic projects verify the feasibility of the application of fuel cells, as shown in Table 1, though the application of fuel cells to large merchant cargo ships faces limitations due to insufficient power generation.

Table 1. Projects to apply fuel cells into the marine sector.

Title	Year	Reference
Fuel Cells for Low-Emissions ships—Viking Lady	2015	[13]
Viking Energy	2020	[14]
MF Hydra	2021	[15]
Sea change	2021	[16]
HyDroMer	2022	[17]
Elektra	2023	[18]

While PEMFCs are widely applied in the marine sector, the source of energy generation is one of the challenges to using PEMFCs in the commercial market. Due to its characteristics, high purity of hydrogen is needed as the source for PEMFCs. Moreover, hydrogen requires special handling in storage and transport because it is a highly flammable gas with oxygen [19]. Many studies and research have been conducted to find the proper technique for safe hydrogen storage. One of the feasible ways to store hydrogen is hydrogen-enriched compounds. The most reliable compound is ammonia. Ammonia has more profit in storage than hydrogen in terms of availability and restricts flammability limits. Liquefied ammonia contains much more hydrogen than liquefied hydrogen in the same volume [20]. Additionally, ammonia synthesis has 75% energy conversion efficiency, which is the most effective commercial process [21]. As the direct usage of ammonia in the PEMFC causes damage to the fuel cells, the process which decomposes ammonia into hydrogen is needed.

1.1.2. Plug-in Battery Ship

The plug-in battery technology is broadly adapted to eliminate emissions of both on-shore and off-shore vehicles. Due to all the necessary power coming from the charged batteries, any emissions do not occur. However, some challenges are the obstacle to battery propulsion ships becoming dominant in next-generation large merchant ships. Nevertheless, electricity propulsion ships are still an attractive option in the marine sector. Significantly, the electric propulsion system has a relatively more extended period of technical development than other ways in various transport sectors. This technology is a prospective option for achieving zero emissions in waterborne transportation. According to the European Maritime Safety Agency (EMSA), the lithium-ion battery is considered the key to the marine sector to open the door to non-fuel consumption vessels. However, even how much power the lithium-ion batteries produce is not enough to run large marine vehicles [22]. The high cost of batteries and insufficient energy density for a large ship are still challenges for a fully battery ship. On the other hand, applying an electric-battery propulsion system for short-distance ships is more reasonable and feasible. Table 2 shows the cases of application of battery propulsion ships.

Table 2. Projects to apply batteries propulsion into the marine sector.

Title	Year	Reference
Future of the Fjords	2018	[23]
Ellen	2019	[24]
GO Vakker Elen	2019	[25]
Stena Jutlandica	2019	[26]
AIDA Perla	2020	[27]
MS Medstraum	2021	[28]
MV Yara Birkeland	2022	[29]

1.2. Research Gap

The pathway to zero carbon emissions passing through carbon emissions reduction is mandatory in the shipping industry. Various methodologies and technologies are verified and studied by Life Cycle Cost Analysis (LCCA) to determine the economic feasibility and sustainability of short-sea ferries. However, the insufficient technical maturity in commercial applications causes a conflict of opinion on which fuel and the way to consume it are the keys to decarbonisation. Among many options, fuel cells and plug-in battery propulsion systems are expected realisable propulsion systems to achieve zero-carbon ship propulsion. Nevertheless, differences in view raise questions regarding which type of fuel cell is more cost-effective and which fuel is the most beneficial power generation source. Specifically, contrast studies lack consistent results. A plug-in battery ship propulsion system is one of the high technical maturity methods like a fuel cell system. Additionally, there are many opinions comparing fuel cell propulsion ships and plug-in battery ships with the ununiformed result. The current LCCA studies about eco-friendly fuels are arranged in Table 3 with the selected case ships and scenarios and the study result.

Table 3. Comparison between performed LCCA studies.

Total Number of Case Ships	Type of Case Ships	Comparison Methods	Cost-Effective Methods	Reference
2	Water taxi, 2500TEU container ship.	Liquefied ammonia Fuel cell Gaseous hydrogen Fuel cell Liquefied hydrogen Fuel cell	Gaseous hydrogen Fuel cell	[30]

Table 3. *Cont.*

Total Number of Case Ships	Type of Case Ships	Comparison Methods	Cost-Effective Methods	Reference
3	Ferries in Croatia	Grey Hydrogen Fuel cell Blue Hydrogen Fuel cell Green Hydrogen Fuel cell Grey Ammonia Fuel cell Blue Ammonia Fuel cell Green Ammonia Fuel cell	Grey ammonia Fuel cell	[31]
1	Ro-Ro passenger ship	Diesel engine-powered ship Battery-powered ship PV cells battery-powered ship	Battery-powered ship	[32]
3	Cargo ship	Diesel-powered ship Hydrogen-powered ship	Diesel-powered ship	[33]
1	ASPEN HYSYS simulation	22 cases of simulation	Install Carbon Capture System with HFO	[34]
1	Inland ferry	Marine diesel engine Battery powered system	Battery powered system	[35]

In many LCCA studies, the conclusions have shown different results. Some research claims that hydrogen is a better source for PEMFCs in terms of cost savings than ammonia, and others believe ammonia is an economical power source for PEMFCs [30,31]. In contrast, someone insists the plug-in battery propulsion system is more commercially effective than the fuel cell propulsion system [36].

However, each study had some limitations in representing the LCCA for eco-friendly fuels. As seen in Table 3, most of the studies considered the maximum of three case ships, which are too small to gain varying results. Additionally, there are no-studied including fuel transport costs in its research. Zero-carbon fuels, such as hydrogen and ammonia, require much energy and cost in their transportation [20,37]. The fuel transport cost was not a huge concern for HFO and MGO. However, emissions caused by the storage and transportation of hydrogen and ammonia are absolutely not negligible. Hydrogen and ammonia fuels, unlike HFO and MGO, require special handling for storage and transport and limited production facilities. The consideration of solar panels can be another option for LCCA studies. Solar photovoltaic (PV) panels are a valuable energy source for sustainable electricity generation, so they can reduce the total cost [38]. Therefore, the method of applying the solar PV system to ships needs to be studied and analysed.

This study began with the question of which factors lead to such different LCCA results. Various life cycle cost assessments were carried out for short-sea ferries in Scotland to solve this question. A comprehensive comparison of life cycle cost assessments, considering different methods for the same vessel, will indicate the core factors that affect the results. Three primary systems (hydrogen fuel cell system, ammonia-cracking fuel cell system, and battery propulsion system) and one auxiliary system (solar PV panel) are selected for comparison. At the end of the study, it will be proven which factors contributing significantly to LCCA will be demonstrated and how they affect it. Thus, it is strongly asserted that this study is valuable in the cost-benefit analysis of zero-carbon fuels dealing with many alternative energy sources and case ships. In addition, it provides the exact payback period of the solar PV system considering the environmental condition based on the actual sailing route of case ships, which is a step further from current LCCA studies. It is expected to contribute to the maritime sector by confirming core factors of the economic feasibility of zero-carbon fuel and the technical feasibility of sailing to a zero-emission vessel.

1.3. Aim and Object

This study aims to prove the factors influencing different results from similar studies in Life Cycle Cost Analysis (LCCA) for different types of zero-carbon fuels and to suggest the best way to build greener ships in terms of cost, which is one of the sustainability factors. Using eco-friendly fuels is an irresistible global trend irrelevant to the economic benefit of fossil fuel usage. The technical availability of eco-friendly energy is visible and feasible. The next step to apply in the marine sector is a financial analysis that covers a broad scope of sustainable technology. Various technologies are increasing their maturity to dominate a ship propulsion system. However, the argument of which method has economic effectiveness is still ongoing. Under the present circumstances, more broadly applicable LCCA studies are essential. The forcing regulations to reduce emissions approach whether the shipping enterprises are prepared or not. When the time has come, shipping companies have to select the method to apply their ships. Moreover, once a method is applied to a ship, it is used for at least 25 years until the ship's retirement. Without considering the LCCA, it is possible that the accumulating opportunity cost is enormous by choosing a high-cost method. LCCA that can be applied to a wider range rather than a limited case is necessary, and it is also essential to study which factors influence the results the most. The goal of this research is automatically achieved by accomplishing several objectives.

To achieve the final goal, the following objectives were set and proposed:

- Conducting extensive research considering feasible technologies with investigating the existing research;
- Identifying the possible propulsion scenario and collecting data;
- Support for research in terms of cost to contribute to the sustainability of ships.

Based on the limitations and gaps, the need for the next step to bridge them was clearly identified. To this end, an appropriate methodology was presented, and case studies to which the methodology is applied were performed. Based on the case study results, interpretation and analysis were carried out. Through it, this paper reveals the factors that have the most significant impact on the application of eco-friendly fuels. In addition, it clearly identifies factors that lead to different LCCA results, a research gap identified in the literature review.

Through this process, this study can help investors in terms of cost when introducing greener fuels into ships. In addition, it can contribute to lowering the price of equipment that is necessary but currently expensive for the application of zero-carbon fuels through additional investment for items. In terms of policy, the results of this study can be used as basic data to support these new applications for environmental protection to be settled in the market.

2. Methodology

The methodology aims to reach the concluding aim by suggesting solutions for each object. It covered the primary design stage of this project to the final result analysis stage. The specific process to accomplish each step is described in Figure 1.

2.1. Step 1: Goal and Scope

The first step of this project is setting the goal and scope. In this step, two main tasks were planned. The first one is vessel specification and confirming case route details. The other one is developing scenarios. In terms of vessel specification and confirming case route details, ships and routes are selected to apply to the cases. A large number of case ships will be selected to achieve a more broadly applicable result. Furthermore, for more realistic output, it is going to consider the detailed ship specification and operation data, including but not limited to ship operation time, distance, and required power capacity. The ideal result is to reduce assumptions as much as possible and use real data to obtain more realistic results.

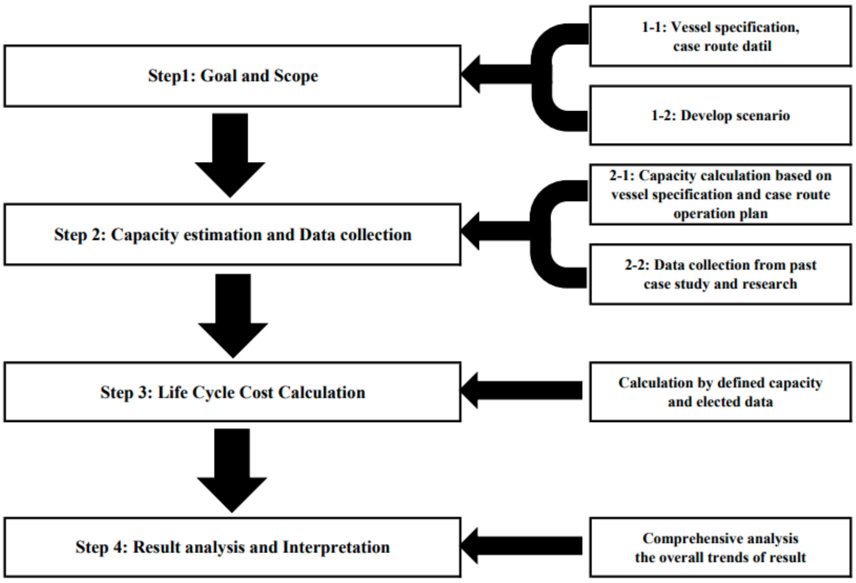

Figure 1. Flowchart of methodology.

For the second part, it was determined that different percentages of energy sources are applied in each case for the selected case vessel and case route. In the case of an electric propulsion system, the combination of different methods can be more effective and stable than using a single method. Fuel cells, ammonia-cracking fuel cells, and the battery-electricity system are selected as primary zero-carbon systems to apply in this study. The solar PV panel power system has limitations in being the main power source of ship propulsion due to the inconstant and insufficient electricity supply. As an auxiliary power source, however, it is able to take on a sufficient role. Each primary type combines varying types as a single power source, a main power source, an auxiliary power source, and a dual power source.

2.2. Step 2: Capacity Estimation and Data Collection

According to considering scenarios, detailed distinct power capacity is calculated. The fuel used for each scenario and the components required for system configuration according to the fuel are different. Taking this into account, setting an appropriate capacity for each component is the first task of Step 2.

After estimating the capacity of each scenario, vast data is collected. For each scenario, equipment is selected according to the power source, and for scenarios where carbon-free fuels are applied, appropriate equipment and additional devices are identified. In this step, not only the power source but also the fuel storage and power transmission facilities are included, and parameter factors are selected that comprehensively consider them.

The former stage of LCCA is setting standard parameter factors and data. Setting reliable standard components for LCCA is a vital process because it solidifies the foundation of LCCA research. Extensive data collection leads to a more reliable standard factor selection. The first step is gathering a wide range of case studies for each piece of equipment. In order to increase the credibility of the research, particular case studies are chosen as prime data sources. Afterwards, it is followed by electing standard data collection by cross-checking each other.

2.3. Step 3: Life-Cycle Cost Calculation

Based on selected case types and standard data, cost calculation is implemented from the perspective of the life cycle. It demonstrates the total cost of adapting new technologies during the life span of the ship. In this step, it is considered not only the capital expenditure (CapEx) and operational expenditure (OpEx) but also the transportation cost for each fuel. The CapEx contains device installation cost, regular replacement cost according to the expiry date, and fuel tank installation cost for hydrogen and ammonia. At the same time, OpEx is basically the operation and maintenance cost of each piece of equipment and fuel cost. The fuel transport cost is also an option to consider. In this project, both analyses with and without consideration of hydrogen and ammonia transport costs were conducted.

2.4. Step 4: Result Analysis and Interpretation

The calculation result derived through Step 3 displayed the quantitative value for each type. Additionally, the individual estimates for each case vessel are independent. Although the LCCA performed for each ship is a valuable result in itself, Step 4 was performed to enable the novelty of the research and general application of the research results.

At this stage, based on the calculation results, trends were identified through comparison/analysis, and future directions were presented to stakeholders. In addition, the cause of the result that occurred was identified, and the research results were summarised and provided as a whole. In addition, a comprehensive perspective was presented on the cost, payback period, and factors that affected the installation of additional auxiliary power sources such as solar panels.

Through this analysis, it was illustrated what factors commonly affect the results in the application of each type of alternative zero-carbon fuel, which is the goal of the study. It also showed how much the factor affects each type.

3. Case Study

3.1. Step 1-1: Case Ships and Routes

Among the vessels operating by Caledonian Maritime Assets Ltd. (CMAL) (Port Glasgow, UK), 27 ships with 26 routes were chosen to conduct case studies by applying specific eco-friendly fuels. The concept of the case study is to change all the propulsion systems of the selected case ships to the electric propulsion system and to check the cost difference that occurs when various electric energy supply methods are adopted. Depending on the case, ships were assigned case routes of various distances, both short and long, respectively. Figure 2 shows the perspective pictures of twenty-seven case ships and twenty-six case route configurations. Each voyage has different operating times and distances per day. Table 4 and Supplementary materials describes the specifications and case routes.

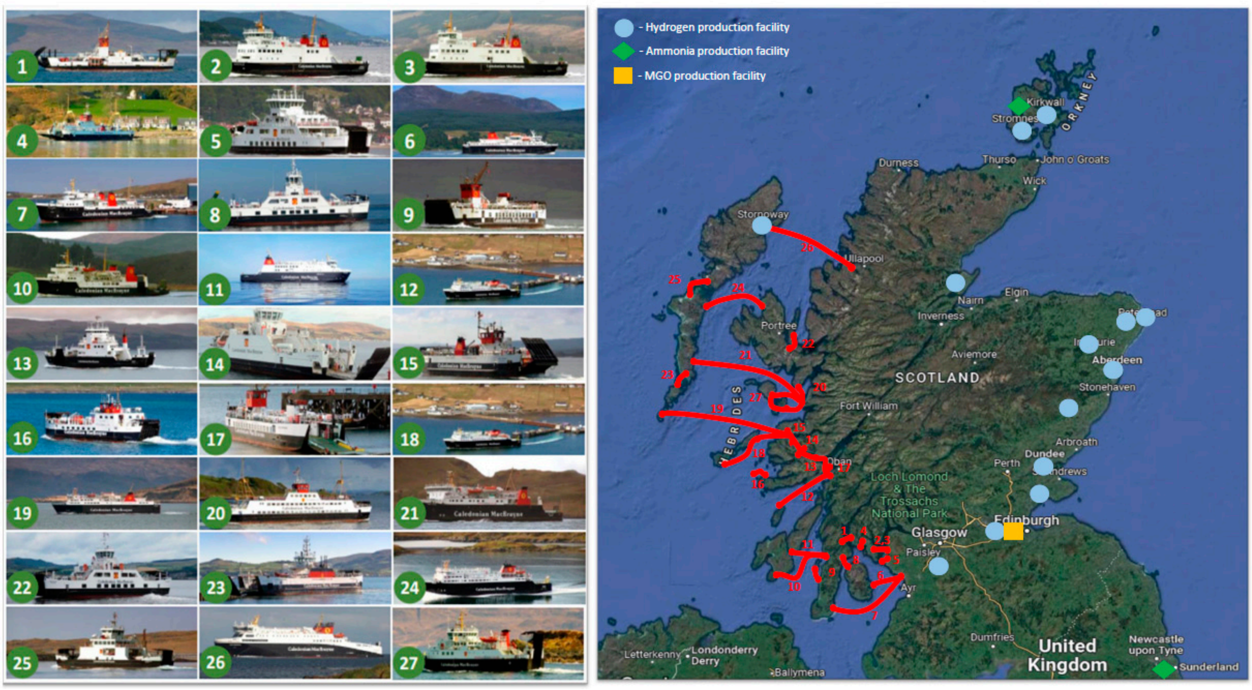

Figure 2. Perspective picture of case ships and diagram of case routes (red line) with fuel production locations in Scotland.

Table 4. Detailed ship specifications and routes.

Ship No.	Name	Voyage Time	Daily Round Trip	Route Distance (km)	Propulsion Power (kW)	Ship Length (m)	Ship Breadth (m)
1	MV Isle of Cumbrae	0.42	12	5.6	380	32.0	10
2	MV Argyle	0.58	8	11.4	2696	72.0	15
3	MV Bute	0.58	8	11.4	2696	72.0	15
4	MV Loch Dunvegan	0.08	32	0.45	659	54.2	13
5	MV Loch Shira	0.17	28	1.9	1100	53.9	13.9
6	MV Caledonian Isles	0.92	5	21.1	4320	94.0	15.8
7	MV Isle of Arran	2.67	1	66.6	3450	84.92	16
8	MV Catriona	1.90	4	20.6	750	43.5	12.2
9	MV Loch Ranza	0.33	11	4.5	540	30.2	10
10	MV Hebridean Isles	2.33	2	56.0	3450	85.15	15.8
11	MV Finlaggan	2.08	2	47.3	8000	89.8	16.3
12	MV Clansman	2.33	1	61.5	7680	99.0	15.8
13	MV Coruisk	0.77	10	16.4	2280	65.0	14
14	MV Lochinvar	0.25	14	3.5	750	43.5	12.2
15	MV Loch Tarbert	0.58	13	7.9	540	30.0	10
16	MV Loch Buie	0.17	48	1.4	540	30.2	10
17	MV Loch Striven	0.83	9	11.7	540	30.2	10
18	MV Clansman	3.33	2	98.8	7680	99.0	15.8
19	MV Isle of Lewis	5.00	1	141.0	6520	101.3	18.52
20	MV Loch Fyne	0.42	5	8.4	659	54.2	13.2
21	MV Lord of the Isles	3.25	2	93.7	5320	84.6	15.8
22	MV Hallaig	0.25	32	5.1	750	43.5	12.2
23	MV Loch Alainn	0.67	12	9.5	970	41.0	13.4
24	MV Hebrides	1.75	4	47.8	7680	99.0	15.8
25	MV Loch Portain	1.00	8	16.3	2120	49.0	14.4
26	MV Loch Seaforth	2.75	2	82.6	8000	117.9	18.4
27	MV Loch Nevis	4.08	1	70.5	2266	49.0	11.4

3.2. *Step 1-2: Energy Supply Scenarios*

The propulsion scenarios are decided by considering sufficient technology maturity. The three primary technologies that acknowledged the feasibility are plug-in batteries, hydrogen PEMFCs, and PEMFCs with ammonia and a cracking system. These three methods generate electricity individually or incorporated. In addition, solar PV panels produce electric power as an auxiliary method to give a variety of types applied to the vessel. Direct current (DC), as the main power system of the ship, has several advantages compared to alternating current (AC), and the power sources set in this study produce DC, except for the diesel generator [39]. Therefore, the power system of the case ships is set to DC as the default. Each primary method produces power as a combination of the main, combined, and auxiliary methods. The combination of types and the required fuel sources are described in Table A1 with an example of a No. 1 case ship.

3.2.1. Type 1: Diesel Generator Engine (ICE)

A diesel generator engine is widely spread machinery for generating electricity in the marine sector. The MGO with less than 0.1% sulphur content is selected to use to achieve the emission regulation of IMO. The electricity that comes from the diesel generator is AC, so the present power distribution system requires a few changes for the DC power system, such as additional converters. The fuel consumption quantity was calculated based on the specific fuel consumption of the selected generator model, which is 205 g/kWh.

3.2.2. Type 2: Hybrid Ship (Diesel Engine + Battery)

The diesel generator or batteries produce the required electricity for hotel load and propulsion. The onboard batteries are charged from the shore connection while berthing.

Depending on the capacity of the generator, that of the batteries is changed. Types 2-1 to 2-3 show the distribution of power demand for generators and batteries, as shown in Table 5. Based on the power demand of the case ship, the capacity of diesel generators, batteries, and AC/DC and DC/AC converters are decided.

3.2.3. Type 3: Full Battery Ship

The full battery ship satisfies all power requirements by shore plug-in batteries. The capacity of batteries and AC/DC and DC/AC converters are decided by the propulsion and accommodation power demand. In this study, a lithium-ion (Li-ion) battery, which is the most popularly used, was adopted.

3.2.4. Type 4: Battery + Solar PV System

The batteries and solar PV panels provide electricity to this type of case ship. Solar PV panels produce limited electricity depending on the weather and sunshine. The inconstant electricity generation from the solar PV panel leads to the same capacity of batteries as a full battery ship (Type 3). The batteries are charged by the solar PV system and shore power because the charging capacity from solar panels is insufficient to cover the whole battery capacity.

3.2.5. Type 5: Fuel Cell

The fuel cells, PEMFCs, are an adequate way to generate electricity by using hydrogen. In this type, a PEMFC was chosen as a power source. PEMFC is currently known to be the most suitable for use as a power source in ships among various fuel cell types. The reason is due to the various characteristics of PEMFCs, such as fast operating time, low operating temperature, high power density, and compact structure [40]. However, there is a disadvantage in that only high-purity hydrogen of more than 99% can be used as fuel due to the performance and durability of the fuel cell [41]. The power demand of case ships decides the capacity of fuel cells and the size of a hydrogen storage tank.

3.2.6. Type 6: Fuel Cell + Battery

The combination of PEMFCs and batteries provides proper electricity for propulsion and other requirements of vessels. The fuel cell and battery capacity would be determined by the power demand and power supply plan. Based on this, subtypes are explained below:

1. Fuel cells take charge of the main propulsion power, and the batteries take charge of the other loads.
2. Fuel cells and batteries serve 50% of total power demands, respectively.
3. Fuel cells contribute to minor power demand. Batteries provide propulsion power opposite the first subtype.

3.2.7. Type 7: Fuel Cell + Battery + Solar PV System

The solar PV panels contribute to the battery charging of a hybrid fuel cell and battery ship power system. Solar-produced electricity has a limitation in fully charging installed batteries depending on weather conditions. Accordingly, the capacity of batteries was set the same as the non-installation of solar panel type.

3.2.8. Type 8: Ammonia-Fuelled Fuel Cell

It is a similar fuel cell power system to PEMFC that generates electricity. The difference in this system is the fuel source compared to Type 5. It consumes ammonia as a power source instead of hydrogen. As the fuel cell requires pure hydrogen, an ammonia cracker splits ammonia into hydrogen and nitrogen. The benefit of using ammonia is that storage of it is easier than that of hydrogen. One ammonia cracker handle from 5 m^3/h to 250 m^3/h of ammonia [42].

3.2.9. Type 9: Ammonia-Fuelled Fuel Cell + Battery

The power system of this type is the battery system with the previous ammonia-fuelled fuel cell. The power distribution depends on the ratios of fuel cells and batteries. Three sub-different types are considered below:

1. Fuel cells in charge of main propulsion + batteries in charge of hotel load.
2. Fuel cells and batteries simultaneously serve the total power demand.
3. Fuel cells contribute to the hotel load, and batteries contribute to the main propulsion.

The ammonia cracker capacity is the same as Type 8.

3.2.10. Type 10: Ammonia-Fuelled Fuel Cell + Battery + Solar PV System

Additional solar PV panels were installed on the former type. Solar panels have the ability to charge batteries even if it is not enough to fully charge as well. The same capacities of the battery and ammonia cracker were considered as the previous type.

3.3. Step 2: Capacity Estimation and Data Collection

This section focused on the capacity calculation of each component and the collection of cost data for each type. Capacity calculation of each scenario and type was conducted based on the formula which is described in Table A2.

The early data was collected from a wide range of feasible case studies, with at least a few data per each required equipment. Among the collected data, reliable data was selected for LCCA. In this project, the lifespan of the case ships was set as 25 years. The life-cycle cost evaluation consists of capital expenditure (CapEx) and operational expenditure (OpEx). Therefore, the sum of CapEx and OpEx for a 25-year period was considered to compare which type would be an optimised type in economic feasibility.

The RETScreen Clean Energy Management Software, which is developed by the Canadian government, offers continuous energy performance analysing for practical energy feasibility and renewable energy. Information about solar PV panels in this paper was collected from this software. The data of this software is reliable enough to report emissions to all federal departments and agencies [43].

Cost data were used as input parameters for life-cycle calculation for the case ships. All currencies were converted to USD with the exchange rates as EUR 1 = USD 1.13, GBP 1 = USD 1.35, and AUD 1 = USD 0.75. The CapEx considers the initial installation cost for each system and replacement costs for fuel cells and batteries when they reach the end of their lifetime. The lifetime of the fuel cells was considered six years [44] and 35,000 h by industry findings, and ten years for batteries [45]. The components of CapEx are an Internal Combustion Engine (ICE), Lithium-ion battery with additional two times of replacement, PEMFC with additional three times of replacement, hydrogen tank, ammonia tank, ammonia cracker, and converter. The amounts of hydrogen and ammonia fuel tank consider 15% of the sea margin and 15% of the safety margin from daily consumption quantity. From several data sources [42,43,46–55], the CapEx data was collected, and the standard parameters for each component were listed in Table 5.

Table 5. List of capital expenditures.

Equipment	CapEx Min.	CapEx Average	CapEx Max.	Unit	References
ICE	1000	1150	1300	USD/kW	[46]
Battery	-	791	-	USD/kWh	[50]
Fuel Cell	-	2260	-	USD/kW	[51]
Hydrogen Tank	-	1130	-	USD/kg	[51]
Ammonia Tank	-	1.06	-	USD/kg	[54]
Ammonia Cracker	-	2,690,000	-	USD/unit	[42]
Converter	-	40	-	USD/kW	[53,55]

The OpEx represents operational and maintenance costs for each component and consumption of energy sources such as MGO, blue and green hydrogen, ammonia, and UK business electricity over the ship's lifespan. OpEx displays two main components: Operation and maintenance cost and fuel cost. From various data sources [42,43,46,48–63], the OpEx data was gathered, and the reliable parameters for conducting LCCA were chosen and listed in Table 6.

Table 6. List of operational expenditures.

Equipment	OpEx Min.	OpEx Average	OpEx Max.	Unit per Year	References
ICE-Fixed	2%	3%	4%	%/CapEx	[46]
ICE-variable non-fuel	0.014	0.021	0.028	USD/kWh	[46]
Battery	-	0.07503	-	USD/kWh	[50]
Fuel Cell	-	0.09763	-	USD/kW	[51]
Cracker	-	1%	-	%/CapEx	[42]
Ammonia fuel tank	-	3%	-	%/CapEx	[54]
Converter	-	10	-	USD/kW	[53,55]
Blue Hydrogen	1.5	2.2	2.9	USD/kg	[61]
Green Hydrogen	3	5.25	7.5	USD/kg	[61]
Blue Ammonia	0.3	0.4	0.5	USD/kg	[61]
Green Ammonia	0.1	0.65	1.2	USD/kg	[61]
MGO 0.1%	-	0.627	-	USD/kg	[63]
UK Electricity	0.09530	0.2353	0.2565	USD/kWh	[58,64,65]

3.4. Steps 3 and 4: Calculation/Result Analysis and Interpretation

The zero-carbon fuel sector is engaged with complex value chains that can replace existing energy activities or create new avenues for value. With all credible scenarios defined in Section 3.2 Step 1–2 and the data library developed in Section 3.3 Step 2, the LCCA was undertaken to forecast the overall economic benefits/costs and the indicative cashflows.

The life-cycle costs for all proposed scenarios were calculated as illustrated in Figure 3.

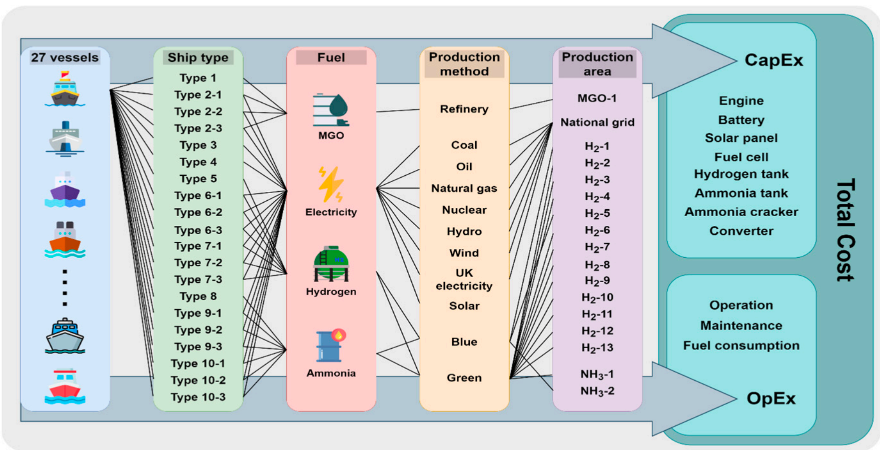

Figure 3. Outline of the proposed LCCA.

Figure 3 represents a summary of the LCCA results where thousands of cost assessment results were condensed into the average. It shows the life-cycle costs for the 27 case ships with twenty different system types. With the selected factors, cost analyses were carried out, and the result based on green fuel (green hydrogen and ammonia) for the No. 1 case ship is shown in Figure 4, with red cost gap marks for blue fuels. As a result, it can be observed that the overall costs of blue energy production are relatively lower than those of green energy production.

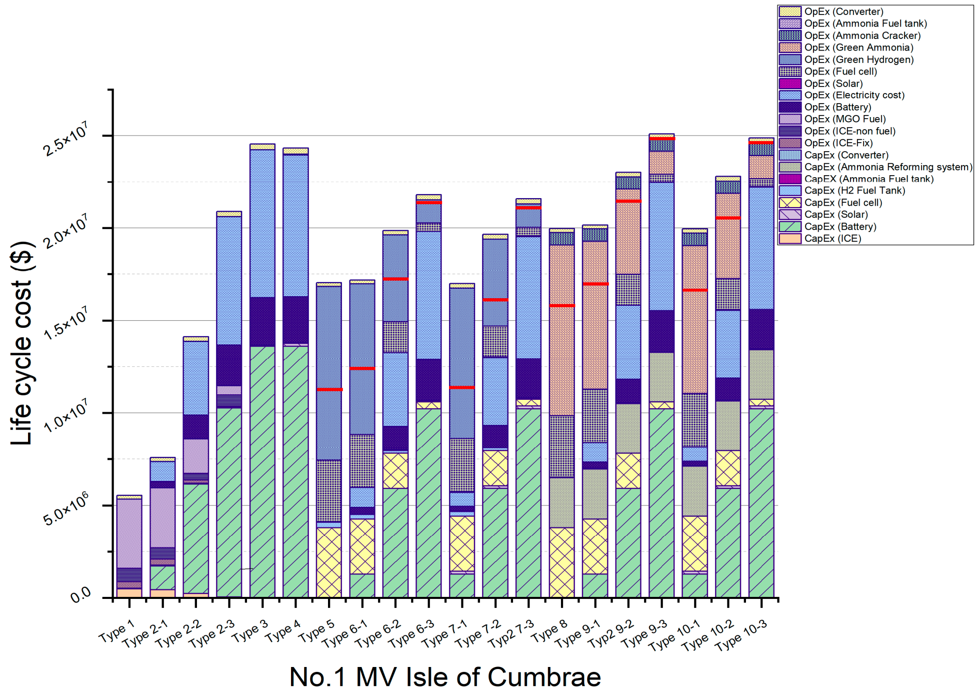

Figure 4. Result of LCCA for No. 1 case ship with the proposed types.

Meanwhile, most case ships have similar trends in that the most economical type that uses zero-carbon fuels is Type 7-1. In general, it is shown that the systems, which mainly use fuel cells as their propulsion, were cost-saving types.

The ammonia fuel cells have some cost benefits in OpEx by relatively lower fuel costs than hydrogen. However, the energy loss due to the transformation of ammonia to hydrogen causes high energy consumption and leads to a higher cost. It was also observed that the cost of ammonia crackers is too high for financial gain. On the other hand, relatively high figures were found in all power system types with batteries due to high CapEx and OpEx. There is little cost for maintenance and operation, but the retail electricity price is quite high even though considered a business electricity price.

More details description of Figure 4 based on the No. 1 case ship, MV Isle of Cumbrae. For types 2-1, 2-2, and 2-3, which are a hybrid of ICEs and batteries, CapEx ranged from USD 1,754,020 to USD 10,316,830, with the range of OpEx from USD 5,824,191 to USD 10,571,592. Type 3, which uses batteries as the main power source, required a high price of USD 24,543,260 with the highest CapEx of USD 13,670,620 in all types, though OpEx was estimated at USD 10,872,640. If the solar electronic system was added to Type 3, the CapEx increased to USD 13,822,060, but the OpEx decreased to USD 10,505,252, so the total cost was estimated to be USD 24,327,312. The fuel cell (Type 6-1) was the most economically effective means with USD 4,551,637 of CapEx and USD 12,627,127.99 of OpEx. On the other hand, the power ratio of batteries increased, and the CapEx increased dramatically to USD 7,993,093 (for Type 6-2) and to USD 10,671,659 (for Type 6-3), although the OpEx decreased slightly to USD 11,800,920.07 (for Type 6-2) and to USD 12,283,353.59 (Type 6-3). Those costs could be further reduced by around UDS 200,000 with additional solar systems (indicating Types 7-1, 7-2, and 7-3).

The high capital cost of an ammonia cracker and the great quantity of ammonia demand led to the rise of CapEx to USD 6,990,111 and of OpEx to USD 13,177,743.32 for Type 9-1. The power demand for batteries grew at Types 9-2 and 9-3, CapEx and OpEx were further increased than Type 9-1; for Type 9-2, CapEx was USD 10,537,862, and OpEx was USD 12,483,043.94; for Type 9-3, CapEx was USD 13,322,723, and OpEx was USD 11,773,344.55. Types 10-1, 10-2, and 10-3, where solar systems were applied to Types 9-1, 9-2, and 9-3, were found to save USD 200,000 or more from Type 9.

For the other case ships, the financial figures have differences due to the ship's power demand and running hours by operational routes. Nevertheless, the general trend of LCCA was shown to be greatly similar to the results obtained from the No. 1 case ship. The rest of the results of LCCA for other case ships are attached in the appendix with three different values: the minimum, average, and maximum values.

Based on the cost data from 27 ships, the levelised cost of energy (LCOE) was determined in Table 7 as "Cost per kWh of electricity", with a total average of each type with the minimum, average, and maximum costs. Figure 5 illustrates the proportion comparison of capital and operating expenditure of average cost.

Table 7. Levelised cost of each type for ships excluding fuel transport.

Type		CapEx (USD/kWh)	OpEx (USD/kWh)		Total (USD/kWh)		Total Cost Ratio	
			Blue	Green	Blue	Green	Blue	Green
	Min	0.016	0.138		0.154		100%	
1	Avg	0.018	0.151		0.168		100%	
	Max	0.020	0.164		0.184		100%	
	Min	0.053	0.141		0.193		125%	
2-1	Avg	0.055	0.160		0.214		127%	
	Max	0.057	0.173		0.230		125%	
	Min	0.182	0.159		0.341		222%	
2-2	Avg	0.183	0.235		0.419		249%	
	Max	0.184	0.253		0.437		238%	
	Min	0.331	0.191		0.522		339%	
2-3	Avg	0.331	0.330		0.662		393%	
	Max	0.331	0.358		0.689		375%	
	Min	0.406	0.181		0.588		382%	
3	Avg	0.406	0.321		0.728		432%	
	Max	0.406	0.343		0.749		407%	
	Min	0.409	0.178		0.587		381%	
4	Avg	0.409	0.314		0.723		429%	
	Max	0.409	0.335		0.744		404%	
	Min	0.141	0.184	0.262	0.324	0.403	211%	262%
5	Avg	0.141	0.220	0.380	0.361	0.521	214%	309%
	Max	0.141	0.257	0.499	0.398	0.639	216%	348%
	Min	0.149	0.183	0.258	0.332	0.407	216%	264%
6-1	Avg	0.149	0.226	0.377	0.375	0.526	223%	312%
	Max	0.149	0.261	0.490	0.411	0.639	223%	347%
	Min	0.245	0.182	0.221	0.427	0.466	277%	303%
6-2	Avg	0.245	0.270	0.350	0.515	0.595	306%	353%
	Max	0.245	0.299	0.420	0.544	0.665	296%	361%
	Min	0.342	0.181	0.185	0.523	0.527	339%	342%
6-3	Avg	0.342	0.315	0.324	0.657	0.666	390%	395%
	Max	0.342	0.337	0.350	0.679	0.692	369%	376%
	Min	0.152	0.180	0.254	0.332	0.406	215%	264%
7-1	Avg	0.152	0.218	0.370	0.370	0.522	220%	310%
	Max	0.152	0.254	0.482	0.406	0.634	221%	344%
	Min	0.247	0.178	0.218	0.426	0.465	276%	302%
7-2	Avg	0.247	0.263	0.343	0.510	0.590	303%	350%
	Max	0.247	0.291	0.412	0.539	0.659	293%	358%
	Min	0.345	0.177	0.181	0.522	0.526	339%	342%
7-3	Avg	0.345	0.308	0.316	0.652	0.661	387%	393%
	Max	0.345	0.329	0.342	0.674	0.687	366%	373%
	Min	0.197	0.246	0.163	0.443	0.360	288%	234%
8	Avg	0.197	0.288	0.393	0.485	0.590	288%	350%
	Max	0.197	0.330	0.622	0.527	0.819	287%	445%
	Min	0.205	0.243	0.164	0.448	0.369	291%	240%
9-1	Avg	0.205	0.290	0.389	0.495	0.594	294%	352%
	Max	0.205	0.331	0.607	0.536	0.812	291%	442%

Table 7. *Cont.*

Type	CapEx (USD/kWh)		OpEx (USD/kWh)		Total (USD/kWh)		Total Cost Ratio	
			Blue	Green	Blue	Green	Blue	Green
9-2	Min	0.283	0.216	0.174	0.499	0.457	324%	297%
	Avg	0.283	0.307	0.359	0.589	0.642	350%	381%
	Max	0.283	0.338	0.484	0.621	0.767	338%	417%
9-3	Min	0.371	0.190	0.186	0.561	0.557	364%	361%
	Avg	0.371	0.325	0.331	0.696	0.701	413%	416%
	Max	0.371	0.347	0.363	0.718	0.734	390%	399%
10-1	Min	0.207	0.240	0.161	0.447	0.368	290%	239%
	Avg	0.207	0.283	0.382	0.490	0.589	291%	350%
	Max	0.207	0.323	0.599	0.531	0.806	288%	438%
10-2	Min	0.285	0.212	0.170	0.498	0.456	323%	296%
	Avg	0.285	0.299	0.351	0.585	0.637	347%	378%
	Max	0.285	0.330	0.476	0.616	0.762	335%	414%
10-3	Min	0.373	0.187	0.182	0.560	0.556	364%	361%
	Avg	0.373	0.318	0.323	0.691	0.697	410%	414%
	Max	0.373	0.339	0.355	0.713	0.729	387%	396%

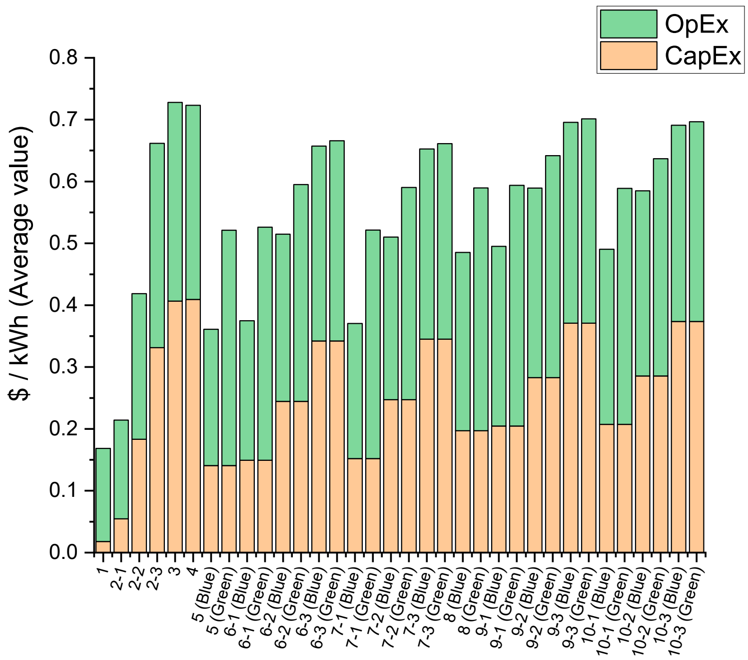

Figure 5. The proportion of capital and operating expenditure to the total cost.

From Table 7 and Figure 5, the comparison, except for ICEs (Types 1 to 2-3), was performed to figure out the characteristics of different types. The primary power source with the highest levelised cost for CapEx was identified as the battery. It was estimated in Types 3 and 4 at 0.41 USD/kWh for CapEx. While the minimum value of OpEX for Types 3 and 4 was at 0.18 USD/kWh, it could increase to 0.34 USD/kWh in the maximum value. This result was influenced by the increment in UK electricity costs since April 2020 [64]. It is expected to increase further owing to the increase in the electricity price cap from April 2022 [66].

Meanwhile, Types 5, 6-1, and 7-1, in which the primary power source is a fuel cell, had the lower figure in CapEx and OpEx than any other type. However, the difference between the minimum and maximum levelised cost of using fuel cells with green hydrogen was higher than using blue hydrogen and even more than the types of batteries. Ammonia fuel cells such as Types 8, 9-1, and 10-1 have a great deviation between the minimum and maximum values in the total cost ratio, which is around 200%. Meanwhile, the cost gaps from minimum to maximum across the battery types were approximately 24%, and fuel cells with green hydrogen types were about 83%. High-cost gaps of green ammonia, depending on region and production method, have contributed to increasing the economic gaps.

Accordingly, the difference in fuel cost led to the greatest gaps between the lowest and highest levelised costs across the types. It is expected that the popularisation of the production and supply of ammonia and hydrogen fuel will diminish the deviation of fuel costs in the near future.

Eco-friendly fuels such as hydrogen and ammonia are produced in a few facilities. Unlike traditional fossil fuels, there is a possibility that the accessibility to alternative fuel refining facilities is insufficient. Thus, the fuel transport cost has to be considered in LCCA.

MGO used in Type 1 and Type 2 was considered to be transported by truck. Diesel fuel prices were set based on the price before the price of crude oil soared due to the Russia-Ukraine war. In the case of electric energy, a loss of about 10% occurs during transmission. Therefore, 10% of the total energy used was set as the transport cost of electricity. In the case of the transport of hydrogen and ammonia, the total transport cost was calculated by considering the liquefaction, storage, and road transfer costs together.

Based on Table 8, the following levelised cost of fuel transport table can be prepared. There was a difference in the minimum and maximum costs depending on the fuel transport distance, transport cycle, etc. The final price analysis was performed in Table 9 by applying the average value.

Table 8. Transport cost [67–69].

Transport by Truck (kWh/km)			**Electricity**	**Hydrogen**		**Ammonia**	
Load	50%	Full					
<3.5 tonnes		1.767	10% loss	Liquefaction and Storage (USD/kg)	0.975	Liquefaction and Storage (USD/kg)	0.1575
3.5–7.5 tonnes	1.921	2.075					
7.5–17 tonnes	2.425	2.728		Road transfer (USD/t kg)	0.69	Road transfer (USD/t kg)	0.2475
>17 tonnes	3.699	4.365					
Diesel = 11.904 (kWh/kg) Diesel = 2.387 (USD/kg)				t kg = tonne-kilometre means transport of one tonne of goods by a given transport mode over a distance of one kilometre			

Table 9. Levelised cost (USD/kWh) of fuel transport.

Type	**Levelised Cost (USD/kWh)**		
	Min	**Average**	**Max**
Type 1	0.0001955	0.004438	0.03443
Type 2-1	0.0005505	0.00569	0.03636
Type 2-2	0.01196	0.01604	0.0462
Type 2-3	0.0223	0.02642	0.05604
Type 3	0.02353	0.02353	0.02353
Type 4	0.02088	0.02288	0.02335
Type 5	0.05151	0.06265	0.07184
Type 6-1	0.0511	0.06052	0.06989
Type 6-2	0.03752	0.04309	0.04768
Type 6-3	0.02394	0.02565	0.02988
Type 7-1	0.05041	0.05979	0.06941
Type 7-2	0.03722	0.04244	0.04693
Type 7-3	0.02355	0.02501	0.02894
Type 8	0.09316	0.1223	0.1594
Type 9-1	0.09215	0.117	0.1523
Type 9-2	0.05835	0.07292	0.09147
Type 9-3	0.02454	0.02888	0.03712
Type 10-1	0.09185	0.1161	0.152
Type 10-2	0.05805	0.07228	0.09122
Type 10-3	0.02424	0.02824	0.03618

The functional unit of the cost that comprehensively considers capital expenditures (CapEx), operating expenses (OpEx), and fuel transport costs are as follows in Table 10.

Table 10. Levelised cost for the shipping operated in the UK, including fuel transport.

Type		Total (USD/kWh)		Total Cost Ratio	
		Blue	Green	Blue	Green
1	Minimum	0.1542		100%	
	Average	0.1729		100%	
	Maximum	0.2184		100%	
2-1	Minimum	0.1938		126%	
	Average	0.2198		127%	
	Maximum	0.266		122%	
2-2	Minimum	0.3534		229%	
	Average	0.4347		251%	
	Maximum	0.4832		221%	
2-3	Minimum	0.5443		353%	
	Average	0.6881		398%	
	Maximum	0.7452		341%	
3	Minimum	0.6114		396%	
	Average	0.7514		435%	
	Maximum	0.7726		354%	
4	Minimum	0.6079		394%	
	Average	0.746		432%	
	Maximum	0.7671		351%	
5	Minimum	0.3758	0.4545	244%	295%
	Average	0.4237	0.5838	245%	338%
	Maximum	0.4696	0.7111	215%	326%
6-1	Minimum	0.3836	0.4581	249%	297%
	Average	0.4353	0.5868	252%	339%
	Maximum	0.4806	0.709	220%	325%
6-2	Minimum	0.4641	0.5035	301%	326%
	Average	0.558	0.6381	323%	369%
	Maximum	0.5916	0.7123	271%	326%
6-3	Minimum	0.5467	0.551	355%	357%
	Average	0.6829	0.6915	395%	400%
	Maximum	0.7091	0.7222	325%	331%
7-1	Minimum	0.3821	0.4564	248%	296%
	Average	0.4302	0.5813	249%	336%
	Maximum	0.4751	0.703	218%	322%
7-2	Minimum	0.4629	0.5023	300%	326%
	Average	0.5527	0.6327	320%	366%
	Maximum	0.5855	0.7063	268%	323%
7-3	Minimum	0.5455	0.5497	354%	356%
	Average	0.6775	0.6862	392%	397%
	Maximum	0.7029	0.7159	322%	328%
8	Minimum	0.5367	0.4531	348%	294%
	Average	0.6076	0.712	351%	412%
	Maximum	0.6864	0.9787	314%	448%
9-1	Minimum	0.5401	0.4611	350%	299%
	Average	0.6119	0.7107	354%	411%
	Maximum	0.6879	0.9644	315%	442%
9-2	Minimum	0.5569	0.5152	361%	334%
	Average	0.6624	0.7146	383%	413%
	Maximum	0.7124	0.8586	326%	393%
9-3	Minimum	0.5856	0.5811	380%	377%
	Average	0.7247	0.7303	419%	422%
	Maximum	0.7552	0.771	346%	353%

Table 10. *Cont.*

Type		Total (USD/kWh)		Total Cost Ratio	
		Blue	Green	Blue	Green
10-1	Minimum	0.5389	0.4601	349%	298%
	Average	0.6066	0.7051	351%	408%
	Maximum	0.6825	0.9584	313%	439%
10-2	Minimum	0.5557	0.514	360%	333%
	Average	0.657	0.7092	380%	410%
	Maximum	0.7068	0.853	324%	391%
10-3	Minimum	0.5844	0.5799	379%	376%
	Average	0.7193	0.7249	416%	419%
	Maximum	0.749	0.7647	343%	350%

The figure shows levelised cost (USD/kWh) considering CapEx, OpEx, and fuel transport costs in the UK. Electricity has a substantial profit in levelised fuel transport cost. Though, there is still a limitation to being an economic propulsion system due to the high cost of CapEx and OpEx. Compared with Type 1, the total cost ratio is still high at around 430%. Ammonia requires only 16% of liquefaction and storage cost and 25% of road transport cost compared with hydrogen, as seen in Tables 9 and 10. However, the required budget for the ammonia power system overwhelms these benefits. Hydrogen fuel, even with the highest cost for liquefaction, storage, and road transport cost, still have financial strength compared with electricity and ammonia types at 340% of the total cost ratio, as shown in Figure 6.

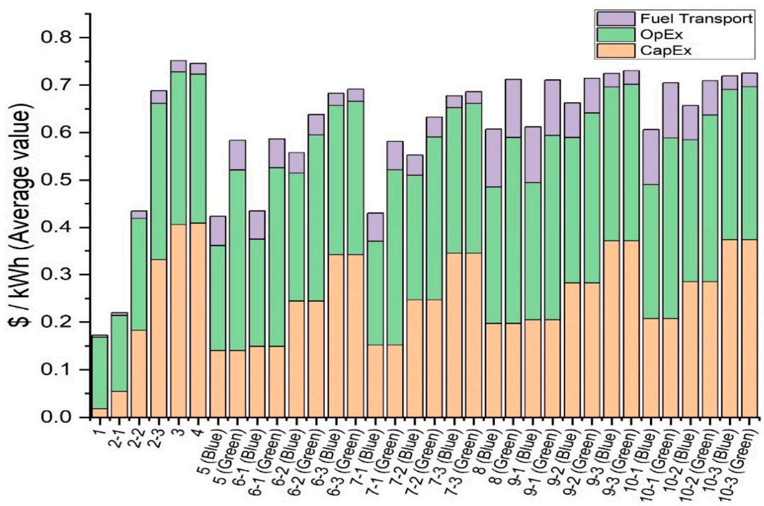

Figure 6. Levelised value of total cost, including CapEx, OpEx, and fuel transport.

The solar PV system was considered as an auxiliary system to produce electricity in this study. Given this, in order to demystify the economic benefits and costs of this system, a payback period analysis has been conducted. In this analysis, the future value of cost was considered with 0.5% standard interest of the Bank of England [70]. Figure 7 shows the differences in a payback period for each case ship with an average value. The compound investment return and benefit were considered to evaluate the solar system's feasibility. While a cash outflow indicates a negative value, cost benefits are revealed as positive as it brings in revenue to the company. The annual savings were assumed to be used to settle the investment cost under some interest rates.

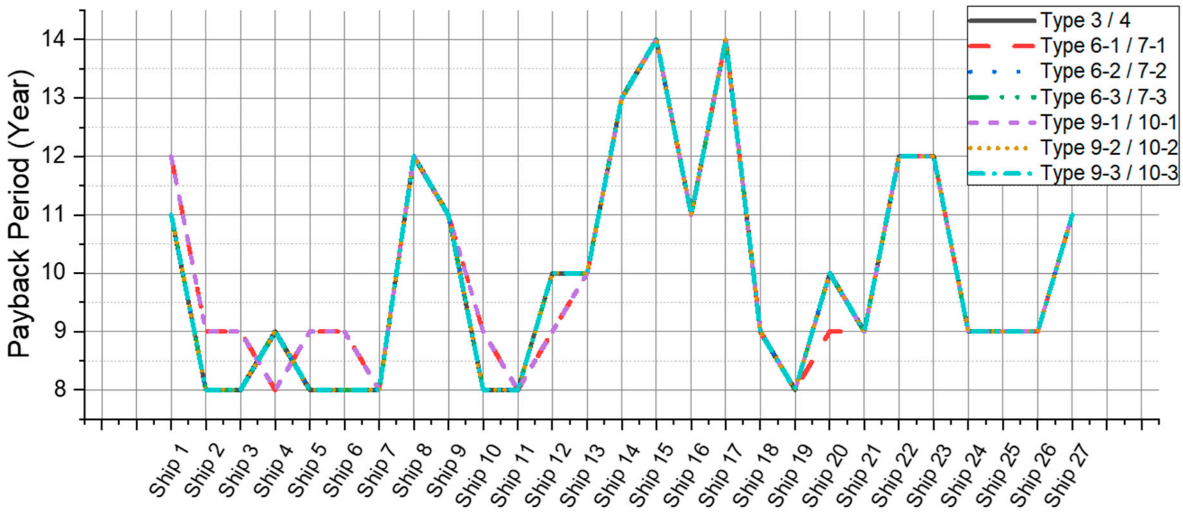

Figure 7. Payback period of solar PV system.

To the cost of power sources and the operation situation of case ships, the payback period of the solar PV system was shown up to 14 years. Each ship has different solar power generation based on its operating route and the size of solar panels onboard. For example, case ships such as 14, 15, and 17 have relatively low figures for solar power generation, and it causes some delays in reaching the payback period than the other case ships. The savings from operation costs are significantly influenced by the cost of power sources such as hydrogen, ammonia, and UK business electricity. Accordingly, any price change in each power source will result in different payback periods in the future.

4. Discussion

4.1. Research Findings

This research demonstrated that hydrogen fuel cell has the financial effectiveness than ammonia-fuelled hydrogen fuel cell and plug-in battery. In terms of using fuel cells, this study causes a paradigm change, which is widely known in the marine sector. It was known that ammonia is an effective source of hydrogen transfer for two reasons. One is relatively high in hydrogen density, and the other one is storage convenience. This well-known fact leads to an unconfirmed opinion that ammonia is a more economically adequate fuel than hydrogen, without taking into account that the system is dependent on the power source. However, when the PEMFC, which is most suitable for use on ships, is applied, the process of additionally converting ammonia into hydrogen results in a loss of efficiency and cost. As a result, when fuel cells are applied as a power source, hydrogen has been confirmed to be a more economical alternative fuel than ammonia for short-distance ferries.

The solar panels support a sustainable ship propulsion system as an auxiliary generation with different payback periods. Even though fuel transport costs showed different figures, it was shown that they did not dramatically affect total LCCA results.

The price of fuel cells and lithium-ion batteries significantly contributed to CapEx. The commercial market for non-fossil fuel power systems is still increasing. With the rising commercial market, it is expected that the decrease in retail cost of fuel cells and batteries. Such a price drop causes economic profit for the application of eco-friendly fuels, especially the battery propulsion system, in which the cost of the battery takes to charge a high proportion of the total cost.

In the case of OpEx, the fuel cost is the factor that affects most of it. With the passing of time, the fossil fuel price is expected to increase while the cost of hydrogen and ammonia decreases [71]. It is still unknown about the commercial retail price of hydrogen and ammonia when they are spread worldwide, but they are expected to decrease in price than the current study time or not increase at least.

The payback period of solar PV panels is affected by the fluctuation of CapEx and OpEx. Even though it has limitations in providing a clear answer about the payback period of the solar system, the key factor is that the application of the solar PV system brings financial benefits during the lifespan of ships.

Pieced all together, eco-friendly fuel price is the core factor affecting total life-cycle cost in most cases, which is the answer to the fundamental question, "which factors lead to such different LCCA results". According to the findings identified in this study, regardless of the type of green-produced fuel (ammonia, hydrogen, and in-land electricity), the green fuel price takes around half of the total life-cycle cost during the life span. The only exception is battery installation and replacement costs if the battery becomes a main power supply system. In this case, those can take a similar or more proportion as fuel cost.

In addition, at present, it is not economically feasible to install ammonia cracking facilities on small ships, and it is true that the cost of batteries is also unrealistic for ships.

Based on the results of this paper, it is particularly noteworthy that 20 types of cases applied to 27 small ferries show similar trends for each vessel. It means the finding of this study can be adopted widely in coastal ferries even outside of Scotland and has a great impact in that the results of the study can be generalised.

4.2. Research Novelty

The bulk of existing LCCA studies provided only narrow results due to the derivation of results through a single or a few methods for a small number of case ships. However, this paper implemented a large number of scenarios with twenty cases for twenty-seven case ships. Therefore, a comprehensive understanding can be provided based on the results obtained. In addition, this study has great novelty in terms of generalisation that the results confirmed in this study can be applied to ships other than the case vessels used in the study.

The LCCA performed on the basis of this large amount of data provides reliable and practical results in finding the optimal power system for short-distance ferries. Therefore, the future direction can be presented to stakeholders, and it serves as a guide for future LCCA research.

Finally, this study identified the most contributing factors in terms of the cost of applying zero-carbon fuels, which could not be performed in previous studies, based on the study conducted through various factors. Therefore, it can serve as a basis for devising activities for cost reduction and ways to strengthen economic benefits.

4.3. Future Study and Limitations

The actual application of technology requires a comprehensive evaluation covering various views. This study assessed only the economic view of the alternative propulsion methods. Therefore, for the next step, a more practical analysis will be followed up with a Life Cycle Cost Analysis as a view of multicriteria considering safety, risk, the convenience of storage and usage, technical maturity, and effective emissions reduction.

Additionally, in this study, only carbon-free fuels were studied, but various carbon-neutral fuels are also being considered in the current industry. Extended studies including these fuels are planned, and it is expected that further expanded results and impact will be achieved by covering the fuels applicable to ships as a whole.

This study aims for a feasible and realistic study, but still, there are some limitations to overcome for actual adoption as the components are not specified as certain products. Furthermore, the fuel price of hydrogen and ammonia are not introduced in the commercial market. The market price of hydrogen and ammonia is based on market-based or academic-based studies. It causes some gaps in the case of the actual application for a real ship.

5. Conclusions

This paper suggests economic guidelines for applying zero-carbon fuels with power systems. At the end of this research, some key findings are summarized:

- The result of this research proves the abstract view is not true, which is that ammonia is more financially effective than hydrogen in the shipping sector. When a PEMFC is applied for the power system, the hydrogen-fuelled system is more economically beneficial than the ammonia-fuelled system. When blue hydrogen is used as fuel, the life-cycle cost is 69.7% compared to the blue ammonia-fuelled system, and it is possible to operate ships at a cost of 81.9% if green hydrogen is used rather than green ammonia.
- Based on numerous cases and scenarios, it was confirmed that fuel prices accounted for the largest proportion of total expenditure in ships that applied alternative fuel, regardless of the system, from a life-cycle perspective.
- Although the degree of benefit varies depending on the operating course and hours of ships, as a result, the solar PV system has been proven to be economically useful as an auxiliary power generation system from the point of view of the life cycle of the vessels.
- Compared with the MGO-fuelled type, the system with the smallest budget required is the hydrogen fuel cell system, which is from 336% to 400%, depending on the ratio of battery power generation and the presence of solar PV panels. It is followed by the ammonia-fuelled fuel cell system, which is around 410% depending on support systems. The battery-powered system, however, indicates relatively high figures than other systems, at more than 430%.
- Lastly, this paper derived cost results for the shipping sector using alternative energy sources based on extensive data, and it is significant that the results can be generalised and can provide direction in terms of price to many stakeholders.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/jmse11020424/s1.

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Appendix A

Table A1. Energy system scenario for ship propulsion and capacities and factors of No. 1 case ship.

Type	Energy System	Fuel Type	Capacities and Factors of No. 1 Case Ship (Power Consumption: 1,361,450 kWh/Year) Components					Consumption				
			ICE (kW)	Battery (kWh)	Fuel Cell (kW)	Solar Panel (ea)	Converters (kW)	MGO (kg)	Battery (kWh)	Solar Power Generation (kWh)	H_2 (kg)	NH_3 (kg)
1	Diesel generator engine (ICE)	Diesel (MGO)	420	-	-	-	840	238,628	-	-	-	-
2-1	Hybrid ship (Diesel engine (main) + Battery (sub))	Diesel (MGO) + Electricity	380	540	-	-	890	206,640	182,500	-	-	-
2-2	Hybrid ship (Diesel engine (50%) + Battery (50%))	Diesel (MGO) + Electricity	210	2490	-	-	990	119,314	680,725	-	-	-

Table A1. *Cont.*

Type	Energy System	Fuel Type	Capacities and Factors of No. 1 Case Ship (Power Consumption: 1,361,450 kWh/Year) Components					Consumption				
			ICE (kW)	Battery (kWh)	Fuel Cell (kW)	Solar Panel (ea)	Converters (kW)	MGO (kg)	Battery (kWh)	Solar Power Generation (kWh)	H_2 (kg)	NH_3 (kg)
2-3	Hybrid ship (Diesel engine (sub) + Battery (main))	Diesel (MGO) + Electricity	40	4310	-	-	1080	31,988	1,178,950	-	-	-
3	Full battery ship	Electricity	-	5740	-	-	1240	-	1,361,450	-	-	-
4	Battery + Solar PV system	Electricity	-	5740	-	160	1300	-	1,307,036	54,414	-	-
5	Fuel cell	Hydrogen	-	-	420	-	840	-	-	-	71,476	-
6-1	Fuel cell (main) + Battery (sub)	Hydrogen + Electricity	-	540	330	-	840	-	182,500	-	61,895	-
6-2	Fuel cell (50%) + Battery (50%)	Hydrogen + Electricity	-	2490	210	-	990	-	680,725	-	35,738	-
6-3	Fuel cell (sub) + Battery (main)	Hydrogen + Electricity	-	4310	40	-	1080	-	1,178,950	-	9581	-
7-1	Fuel cell (main) + Battery (sub) + Solar PV system	Hydrogen + Electricity	-	540	330	160	950	-	128,086	54,414	61,895	-
7-2	Fuel cell (50%) + Battery (50%) + Solar PV system	Hydrogen + Electricity	-	2490	210	160	1050	-	626,311	54,414	35,738	-
7-3	Fuel cell (sub) + Battery (main) + Solar PV system	Hydrogen + Electricity	-	4310	40	160	1140	-	1,124,536	54,414	9581	-
8	Ammonia-fuelled fuel cell	Ammonia	-	-	420	-	840	-	-	-	-	568,545
9-1	Ammonia-fuelled fuel cell (main) + Battery (sub)	Ammonia + Electricity	-	540	330	-	840	-	182,500	-	-	492,332
9-2	Ammonia-fuelled fuel cell (50%) + Battery (50%)	Ammonia + Electricity	-	2490	210	-	990	-	680,725	-	-	284,272
9-3	Ammonia-fuelled fuel cell (sub) + Battery (main)	Ammonia + Electricity	-	4310	40	-	1080	-	1,178,950	-	-	76,212
10-1	Ammonia-fuelled fuel cell (main) + Battery (sub) + Solar PV system	Ammonia + Electricity	-	540	330	160	950	-	128,086	54,414	-	492,332

Table A1. *Cont.*

Type	Energy System	Fuel Type	Capacities and Factors of No. 1 Case Ship (Power Consumption: 1,361,450 kWh/Year) Components					Consumption				
			ICE (kW)	Battery (kWh)	Fuel Cell (kW)	Solar Panel (ea)	Converters (kW)	MGO (kg)	Battery (kWh)	Solar Power Generation (kWh)	H_2 (kg)	NH_3 (kg)
10-2	Ammonia-fuelled fuel cell (50%) + Battery (50%) + Solar PV system	Ammonia + Electricity	-	2490	210	160	1050	-	626,311	54,414	-	284,272
10-3	Ammonia-fuelled fuel cell (sub) + Battery (main) + Solar PV system	Ammonia + Electricity	-	4310	40	160	1140	-	112,4536	54,414	-	76,212

Table A2. Calculations for each component in this study.

No.	Component	Formula	Remarks
1	ICE capacity (kW)	Required power	
2	Fuel cell capacity (kW)	Required power	
3	Battery capacity (kWh)	Required power/0.75	Considering the calendar lifetime of the battery [45], it was set that state of charge (SOC) of batteries is 25~100% based on battery characteristics, i.e., 75% of battery capacity is used [72]
4	Solar panels (ea)	Solar collector area × 0.8	It is assumed that solar panels are installed on 80% of the total area of the ship deck.
5	AC/DC converter (kW)	Required power source per hour	Calculated as (Battery capacity/night hour) × 1.1 (margin) by considering required battery charging hours.
6	DC/AC converter	Required power source per hour	
7	DC/DC converter	Required power source per hour	Calculated as (Battery capacity/voyage time) × 1.1 (margin) by considering the power load of the battery and peak load.
8	Converter for battery (kW)	(Battery capacity (kWh) × 0.75)/(24 − nighttime) × 1.1 + (Battery capacity (kWh) × 0.75)/(nighttime) × 1.1	Considering nighttime as charging time and adding 10% of the margin.
9	Converter for solar panel (kW)	Solar panels (ea) × 0.345	
10	Power consumption per day (kWh)	Propulsion power (kW) × 0.85 × Voyage time (hours) × daily round trip × 2 (Propulsion motors)	
11	Yearly power consumption (kWh)	Power consumption per day (kWh) × 2	
12	Main power consumption per year (kWh)	Propulsion power × 0.85 × Voyage time (hours) × Daily round trip × 2 (Propulsion motors) × 365	

Table A2. *Cont.*

No.	Component	Formula	Remarks
13	Sub-power consumption per year (kWh)	Yearly power consumption (kWh)—Main power consumption per year (kWh)	
14	Yearly MGO consumption (kg)	Yearly ICE consumption × 0.205 × 0.855	
14	Yearly Battery power consumption (kWh)	Yearly power consumption (kWh)—Fuel cell capacity—Solar power generation	
15	Yearly hydrogen consumption (kg)	Fuel cell capacity (kW) × 1000 × $1.05/10^8/0.72$ × 3600 × 365	
16	Yearly ammonia consumption (kg)	((Yearly hydrogen consumption (kg)/0.178) × 1.41 × 1000 × $1.05/10^8/0.72$ × 3600)/0.178 + 5)/0.178	

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