Journal of
Marine Science and Engineering

MDPI

Article

Selecting Appropriate Energy Source Options for an Arctic Research Ship

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Abstract: Interest in more sustainable energy sources has increased rapidly in the maritime industry, and ambitious goals have been set for decreasing ship emissions. All industry stakeholders have reacted to this with different approaches including the optimisation of ship power plants, the development of new energy-improving sub-systems for existing solutions, or the design of entirely novel power plant concepts employing alternative fuels. This paper assesses the feasibility of different ship energy sources for an icebreaking Arctic research ship. To that end, possible energy sources are assessed based on fuel, infrastructure availability and operational endurance criteria in the operational area of interest. Promising alternatives are analysed further using the evidence-based Strengths, Weaknesses, Opportunities, and Threats (SWOT) method. Then, a more thorough investigation with respect to the required fuel tank space, life cycle cost, and CO_2 emissions is implemented. The results demonstrate that marine diesel oil (MDO) is currently still the most convenient solution due to the space, operational range, and endurance limitations, although it is possible to use liquefied natural gas (LNG) and methanol if the ship's arrangement is radically redesigned, which will also lead to reduced emissions and life cycle costs. The use of liquefied hydrogen as the only energy solution for the considered vessel was excluded from the potential options due to low volumetric energy density, and high life cycle and capital costs. Even if it is used with MDO for the investigated ship, the reduction in CO_2 emissions will not be as significant as for LNG and methanol, at a much higher capital and lifecycle cost. The advantage of the proposed approach is that unrealistic alternatives are eliminated in a systematic manner before proceeding to detailed techno-economic analysis, facilitating the decision-making and investigation of various options in a more holistic manner.

Keywords: energy sources; arctic research ship; strengths, weaknesses, opportunities, and threats; greenhouse emissions

Citation: Palmén, M.; Lotrič, A.; Laakso, A.; Bolbot, V.; Elg, M.; Valdez Banda, O.A. Selecting Appropriate Energy Source Options for an Arctic Research Ship. *J. Mar. Sci. Eng.* **2023**, *11*, 2337. https://doi.org/10.3390/jmse11122337

Academic Editor: Diego Villa

Received: 30 October 2023
Revised: 29 November 2023
Accepted: 1 December 2023
Published: 11 December 2023

1. Introduction

Climate change, mainly caused by global warming, has become one of the main concerns for humankind in recent years, and all possible means for tackling this phenomenon are explored to moderate the inevitable impacts. Among the main contributors to global warming are greenhouse gases (GHG), mainly carbon dioxide (CO_2), emitted during the transformation of fossil fuels' chemical energy into other forms [1]. In the Fourth Greenhouse Gas Study by the International Maritime Organization (IMO), it was estimated that total shipping emissions accounted for 1056 million tonnes of CO_2 in 2018, which is around 2.9% of the global anthropogenic GHG emissions [2]. To decrease the GHG impact caused by the maritime industry, the IMO has set ambitious goals to reduce the emissions per transport work by 40% by 2030 and 70% by 2050, compared to the 2008 figures [3]. The first mandatory regulations were introduced by the IMO in 2011 when the Energy

Efficiency Design Index (EEDI) was proposed. EEDI came into force in 2013, promoting energy-efficient equipment and engines in newly built ships [4]. Simultaneously, other regulations targeting the reduction of maritime emissions have been introduced. One of the most impactful is Regulation 13 under Annex VI restricting ship engine nitrogen oxide (NO_x) emissions [5].

Yet, the main focus of the present discussion in the industry aims at a well-to-wake reduction in GHG emissions, capturing the problem in a more holistic fashion, as demonstrated by the reviewed literature below. Many recent studies have employed different approaches to identifying more energy-efficient, cleaner, and less harmful energy source options for the shipping industry. Barreiro et al. [6] and Jimenez et al. [7] reviewed the energy efficiency factors in the maritime industry by analysing decarbonization and emission reduction measures, policies, and regulations, economic factors, and alternative energy sources, proposing high-level strategies to reduce emissions such as improving ship designs, considering metrics other than EEDI, optimizing ships' operational speed, and employing more digital solutions. Foretich et al. [8] conducted a scoping study aiming to outline the barriers, possibilities, and uncertainties of multiple alternative fuels such as liquified natural gas (LNG), biofuels, methanol, and ammonia, with LNG being considered the most promising alternative. Al-Enazi et al. [9] presented a review of LNG, hydrogen, and ammonia as alternative shipping fuel options, assessing them from the environmental, overall feasibility, operational viability, and supply chain aspects, and concluding that the demand for alternative fuels will increase in the next years. Law et al. [10] presented a study of 22 potential pathways for transitioning to low- or zero-carbon marine fuels by including parameters such as fuel mass, fuel volume, energy intensity, cost, and GHG emissions amongst others, concluding that the carbon capture technologies are the most cost-efficient solution towards decarbonisation due to less volume required and reduced need for infrastructure modifications, followed by biodiesel. Gilbert et al. [11] assessed the life cycle emissions of different shipping fuel options, including both conventional and alternative fuels. In their study, LNG was considered a promising option for ship decarbonisation at the stage of technology in 2018. Deniz and Zincir [12] conducted an environmental and economic assessment of methanol, ethanol, LNG, and hydrogen fuels and concluding hydrogen the most promising solution. Hansson et al. [13] assessed the prospects of ammonia as a marine fuel of the future through energy system modelling and multi-criteria decision analysis and concluded that hydrogen is still a better option for shipping than ammonia. Atilhan et al. [14] investigated aspects related to hydrogen application as an alternative fuel for the shipping industry, by evaluating production routes, techno-economic performance, storage, and safety, concluding that the safety and supply chain aspects need to be properly resolved before hydrogen can be widely introduced into maritime. Bilgili [15] compared the different aspects of alternative fuels for decarbonisation in shipping. In this study, the use of ammonia was ruled out, hydrogen was considered an option for ships operating on short voyages, and LNG was highlighted as a promising transitional fuel. Methanol was considered an important promising future fuel as well. Fan et al. [16] conducted a literature review on current research related to ship energy management. The results emphasized the importance of a multi-objective optimisation approach to the ship energy system and management problem, where all the design variables have to be accounted for. Despite their obvious utility, these studies concentrated on ship fleets and not specific ships.

In addition to broader review studies, many articles have assessed the feasibility and application of alternative fuels to specific ships. Jafarzddeh and Schjølberg [17] presented an overview of hydrogen fuel cells' current ship applications, future potential, and emission reduction possibilities, concluding that hydrogen with fuel cells can be effectively used in conventional power systems running on diesel to reduce emissions in a research vessel. Fan et al. [18] proposed alternative fuels replacing diesel in inland waterway shipping based on ship tonnage, voyage distance, and navigational conditions. The abilities of the different fuels to meet the new emission standards and the effect of a possible carbon tax were considered. Radonja et al. [19] investigated the potential of methanol and ethanol as alternative fuels in ferries, chemical tankers, and cruise ships, presenting ethanol as the most cost-efficient option in three cases. Rivarolo et al. [20] conducted a case study, in which proton-exchange membrane (PEM) fuel cells were applied to a passenger ferry with a capacity of 200 people by analysing costs, emissions, and operative strategies in comparison to state-of-the-art fuel oil-based solutions. They concluded that hydrogen is the best in terms of emissions, whilst the diesel option remains the optimal solution in terms of space, volume, and economics. Other research studies on ship power plants [21–24] focused on the design of technical specifications of power plants or optimization in terms of cost, emissions, and potentially other characteristics. For instance, Bolbot et al. [21] proposed the use of LNG in cruise ships as the optimal solution in terms of safety, CO_2 emissions, and cost for a cruise ship when compared to methanol, carbon capture with diesel, and diesel. Dotto et al. [22] found that LNG and hydrogen blends are better in terms of environmental performance than methanol in a cruise ship.

However, such approaches are usually very distant from the holistic approach required in the design and can result only in suboptimal solutions [25]. This is due to the fact that it is important to consider multiple parameters during the design of a power plant in addition to the previously mentioned, such as safety, space, and weight limitations, maintainability, fuel availability, impact on manoeuvrability, vibrations, and many others [26,27]. It is also crucial to consider these factors as early as possible during the design process, in the feasibility and concept or preliminary design stages [26,28], to avoid costly mistakes. To that end, the use of simple methods based on rules of thumb and heuristics would be beneficial at the feasibility and concept design stage for the selection of alternative fuels.

Although significant research activity has focused on the reduction in maritime emissions at the fleet and ship level through alternative fuel use, only a few studies have considered these topics in the context of Arctic shipping, in which the requirements for the energy source are more demanding due to remoteness, long distances, and environmental aspects. The Arctic is an environmentally and ecologically sensitive area [29], and therefore additional regulations, such as the Polar Code, have been created to preserve and protect the Arctic. DNV [30] published a report in which a variety of alternative fuels were assessed in an Arctic shipping scenario and ranked based on environmental performance, costs and scalability. Based on this assessment, the report concluded that LNG is currently the most feasible solution to be used for Arctic shipping, followed by biodiesel, Marine Diesel Oil (MDO) and methanol burnt in fuel cells. Joseph et al. [31] developed a model combining policies, alternative fuels, emissions, and microeconomic theory for Arctic shipping economic feasibility assessment. By simulating the model, green ammonia was found to be the most appropriate fuel for a Handymax bulker compared to LNG, hydrogen, and methanol. Theocharis et al. [32] assessed the feasibility of alternative fuel types in the Northern Sea Route (NSR) for seasonal operations for oil tankers and concluded that the combination of LNG and low-sulphur heavy fuel oil can be a feasible solution compared to the conventional operations running on diesel and heavy fuel. In a study conducted by Lindstad et al. [33], a holistic assessment of costs, emissions, and climate impact of Arctic freight shipping concluded that switching to LNG from diesel will result in reduced environmental impact. Kodratentko et al. [34] presented a holistic multi-objective design approach for the optimization of an Arctic offshore supply vessel (OSV), but this study concentrated on conventional fuels. In follow-up, Kodratenko [35] reviewed the challenges related to the development of sustainable shipping in the Arctic and investigated the potential for batteries application. Xu et al. [36] analysed the economic feasibility and emission reductions associated with using LNG as the energy source in the NSR, indicating its potential as a promising fuel type.

The lack of more environmentally friendly alternative fuel applications in the considered context can be attributed to multiple factors. Hydrogen or batteries require significant space to achieve sufficient autonomy of the vessel. Biofuels such as biodiesel are relatively sparsely available in northern European ports. Ammonia is a toxic fuel which can cause harm in the very volatile Arctic area. With LNG, sufficient autonomy can also be difficult to achieve, and the bunkering possibilities are more limited compared to traditional fuels.

None of the studies presented investigated fuel alternatives for a specific Arctic operating vessel. Furthermore, none of the studies used the SWOT method for an Arctic ship, which is a method suitable for use at the concept and feasibility design stage of the fuel selection problem since techno-economic analyses, as previously mentioned, can lead to narrow focus and omitting important parameters in the analysis and fuel selection process. To fill this research gap, this study aimed to assess and compare the most relevant energy source options for an Arctic operating vessel from a wider perspective, including more generic technical, economic, and carbon neutrality aspects related to the potential alternative fuels. The novelty of this study stems from the assessment of various energy source options in a case study, where the different options are compared in a ship concept design E3RV Tangaroa, a research and resupply vessel designed to operate in the northern polar areas. The novelty also stems from the use of SWOT and an approach that gradually converges into a set of preliminary solutions.

This study does not focus on well-to-wake emissions but rather on emissions emitted during ship operations. Furthermore, we exclude the application of such technologies as carbon capture due to significant space and weight limitations associated with carbon capture. Additionally, the conducted analysis focuses on alternative fuels, rather than the associated machinery, which can be addressed in the next stage of the ship design spiral.

The remainder of this paper is organised as follows: Section 2 describes the ship case study concept. Section 3 describes the methodology used in the assessment, Section 4 presents the results and discussion, and, finally, Section 5 provides the study conclusions and main findings.

2. The Considered Ship

The ship considered in this study is an Arctic research and resupply vessel non-existing concept named E3RV Tangaroa. The E3RV Tangaroa design is mainly based on two reference ships, the Australian Research and Supply Vessel RSV Nuyina, launched in 2021, and the Royal Research Ship RRS Sir David Attenborough, launched in 2020. Both vessels are new and feature state-of-the-art technology and design for vessels operating in the Arctic and Antarctic areas. These vessels were chosen as the reference ships since the RSV Nuyina focuses more on resupply and cargo-carrying capabilities, whereas the RRS Sir David Attenborough emphasises Arctic research capabilities. Thus, the features of these vessels were combined to end up with a genuine multipurpose research and resupply vessel.

2.1. Ship Characteristics and Operational Profile

The main dimensions of E3RV Tangaroa were chosen through an iterative process, using a statistical method based on data from similar ships and Normand's number method [37] with the initial goal of 5000 DWT. The resulting main dimensions can be observed in Table 1. The parent ships considered had similar numbers of passengers, crew, and dimensions and implemented similar research activities.

Table 1. Main dimensions of E3RV Tangaroa.

Item	Ship Data
Length (m)	142
Breadth (m)	31
Draft (m)	8
C_B	0.52
Δ (tonnes)	18,896
Deadweight (tonnes)	5000
Passengers (incl. crew)	130
Operational area	Baltic Sea, North Sea, Norwegian Sea, Greenland Sea, Barents Sea, Svalbard Archipelago

The general arrangement of the E3RV Tangaroa derived during the design process emphasises the multipurpose function of the ship, with most of the cargo spaces being modular to house more research facilities if needed. The general arrangement of E3RV Tangaroa can be observed in Figure 1.

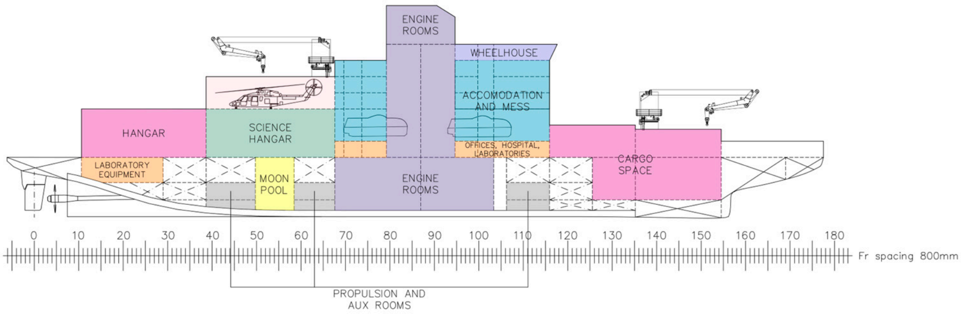

Figure 1. General arrangement of E3RV Tangaroa.

The operational area of the ship is the northern Arctic area (Table 1), where the ship is due to perform oceanic research missions and resupply the research stations in areas with limited infrastructure facilities. The vessel's home port is in Helsinki, and thus the transit to the Arctic areas through the Baltic is also included in the operational profile. This implies that the vessel needs to comply with stringent IMO Tier III emission rules on NO_x emissions [38]. The operational profile was created by simulating a typical mission of the E3RV Tangaroa, starting from Helsinki, transiting to the AWIPEV research station on Svalbard, and conducting research in the area. It is assumed that during the voyage, the vessel would perform three shorter research trips from the AWIPEV research station to remote research areas, always returning to AWIPEV in between the trips. The planned transit speed is 13 knots, while in ice conditions, the speed decreases to 3 knots. The approximated operational profile for one round trip can be observed in Figure 2. An estimated round-trip duration for the vessel is 50 days or 1200 h.

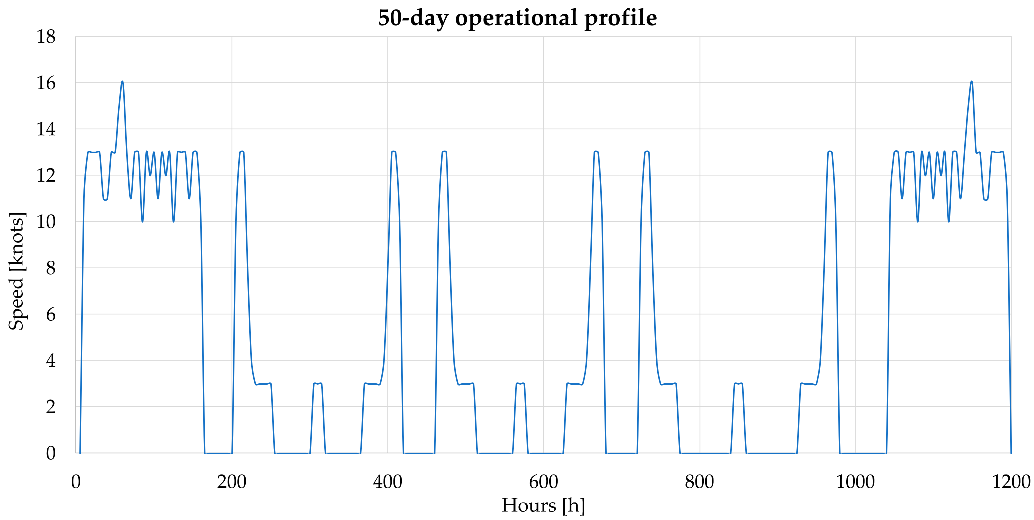

Figure 2. Operational profile of E3RV Tangaroa.

2.2. Considered Propulsion Options and Power Flow

The preliminary propulsion setup for the E3RV Tangaroa was chosen mainly by studying the solutions in the two reference ships. Thus, the E3RV Tangaroa features an electric propulsion system which is advantageous from the icebreaking perspective. Firstly, substantial improvements can be achieved in the vessel's manoeuvrability when an electric propulsion system is used in contrast to a traditional, mechanical propulsion system [39], which is important when navigating in ice. Furthermore, electric propulsion offers more control and torque than traditional mechanical propulsion since it is possible to adjust the speed of the propeller independently of the main engine's rpm. This optimises fuel consumption and allows higher torque at low speeds, which is very important during icebreaking. Furthermore, the maintenance costs of electric propulsion systems are considerably lower than those of mechanical ones [39]. The use of electric propulsion also allows for greater flexibility in terms of the selection of energy sources, as multiple energy sources can be used, for instance, batteries and hydrogen fuel cells [40], as long as the final form of the energy fed to the propulsion system is electricity. On the other hand, the use of more eco-friendly fuels is anticipated in the Arctic area along with better safety and route operability [41], which is why electric propulsion was preferred.

Two main shafts drive the ship with controllable pitch propellers (CPP) powered by electric motors. Additionally, one transversal propulsor is in the bow to aid in manoeuvring operations (bow thruster). A maximum power output of 23,600 kW needs to be produced to cover the maximum propulsion, hotel load, and electrical losses. It must be noted that the propulsion and hotel power estimation described here is preliminary, determined in the earlier phase of the iterative ship design process. As the ice conditions may vary significantly, the power consumption calculations have been performed conservatively. There is also a small thermal load which is connected to the operation of the water boiler (required for heating in the cold area). Its influence on the energy source is considered very small as irrespective of the fuel cells or engines used, this energy can be retrieved from the wasted heat. A preliminary energy flow chart for the considered ship is presented in Figure 3.

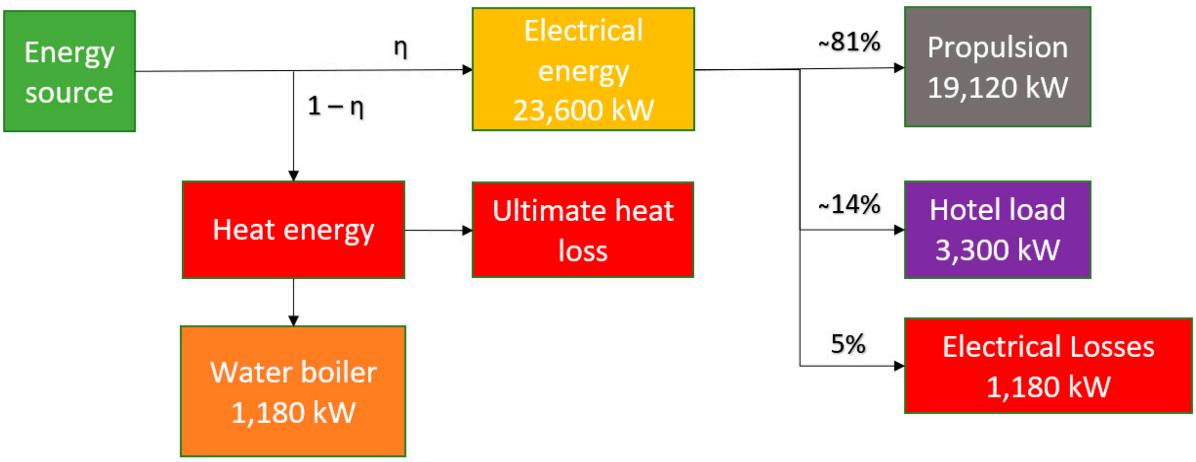

Figure 3. Energy flow chart of the E3RV Tangaroa when the energy transformer is an internal combustion engine. H is used to depict the efficiency of transformation.

The power distribution of the vessel is implemented through the main switchboard. The power network of an electrically driven vessel is divided into two parts to increase reliability, flexibility, and efficiency in power generation and reduce the possibility of blackout as well as to comply with the relevant regulations [42]. The power system redundancy is equivalent to the level 2 dynamic positioning system, as defined by the IACS.

3. Research Methodology

The vessel and its operational profile with required endurance together with information about the propulsors, the electrical hotel load, and the thermal load, can be considered as sufficient inputs to the power plant's initial development [26] and assessment of potential alternative energy sources during concept/preliminary design. To ensure that we address the alternative fuels selection process in a more holistic manner, we need to include the following aspects for consideration as referred to in previous publications [27,30,43]:

- Endurance and energy capacity for operations.
- The technology maturity and regulatory readiness for technology acceptance.
- Infrastructure readiness and fuel availability.
- Security of fuel supply.
- The capital, operational, and life cycle costs.
- Reliability, maintainability, availability, and safety aspects (RAMS).
- Emission of toxic and greenhouse gases.
- Potential external threats and opportunities.
- Impact on company reputation.
- Other aspects affecting wellbeing and ergonomics such as vibrations and automation.
- Weight and space limitations.
- Impact on ship stability and ship manoeuvrability.

However, it is very difficult, if not impossible to quantitatively estimate all of them. Thus, qualitative approaches can be of great use. The advantage of SWOT is that many of these aspects can be captured in a systematic manner and can support decision-making based on the evidence from available resources without going into detail. However, since some of the aspects can be easily quantified and support the decision-making, such as the impact on the space arrangement, life cycle costs, and CO_2 emissions during operations, some quantitative measures are also used.

The flowchart depicting the steps of the methodology is presented in Figure 4. The goal is to find the most suitable energy source for the described vessel by investigating and comparing different options at the preliminary/concept design stage. First, all the potential energy sources are identified, and then the energy sources that are deemed unrealistic are eliminated. The few selected options are analysed using SWOT in step 2 for the aspects that we considered with a view to application in the Arctic. Then, using simple calculations, we investigate the weight and space limitations in step 3. Having this information in mind, we calculate the life cycle costs and CO_2 emissions during operations in step 4 for feasible solutions. Finally, we discuss the alternative options to be adopted in the research vessel and the methodology limitations.

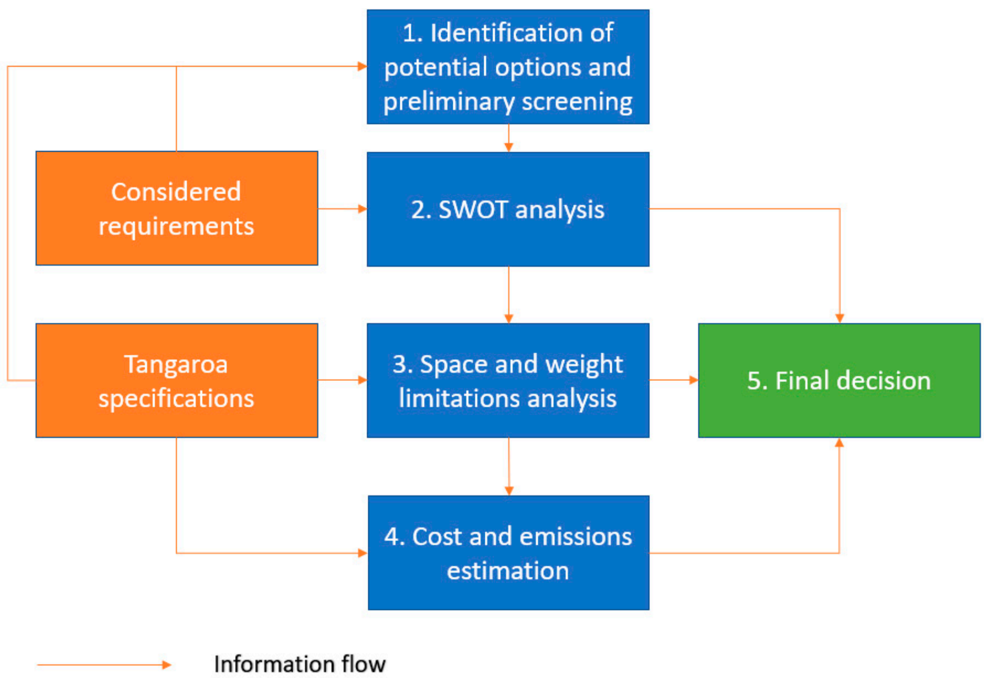

Figure 4. Methodology flow chart.

3.1. Step 1: Identification of Potential Energy Sources and Elimination of the Unrealistic Ones

First, all the potential alternative options for the main energy source are identified. Since Tangaroa is intended to operate in the Arctic region, several limitations must be considered when selecting suitable fuels. The main factors that are discussed are the technological maturity and the potential of the technology to cover all the power needs. Moreover, regulatory maturity is essential as the ship will be operating in international waters, so derogation and exception provided at the national level based on risk assessment is not an option. The operational profile of Tangaroa will also have a significant impact on the feasibility of the different energy source options. As the vessel is going to have long voyages, the endurance and power capacity of the vessel are important characteristics. Furthermore, as the fuel storage spaces onboard are limited, the energy density of the potential energy sources is an important factor when considering the feasibility of the potential fuels. Also, related to the operational area, the availability, and the existing infrastructure of the potential energy sources in the Arctic area are essential. If there is a possibility of refuelling, the vessel does not necessarily require such a large energy storage to perform the intended operations. By considering the technical maturity, regulatory maturity, energy density, security of fuel supply, and existing infrastructure in the polar region the unrealistic energy sources are discarded and the study proceeds to the next step with the identified potential energy sources. Some qualitative rankings (good, mediocre, low) are used to guide the process based on the provided evidence; wherever a solution has a low ranking it is discarded during the next steps.

3.2. Step 2: SWOT Analysis Considering Operation in the Arctic

In step 2, the most promising options are analysed further using SWOT. The SWOT analysis is a fast and efficient way to investigate the identified energy source options in a more detailed and structured manner. SWOT is a method that is very popular for decision-making support of business ideas. The advantages of using the SWOT analysis include presentability and level of detail suitable for the concept/preliminary design stage. It also allows the inclusion of concepts that are not easily quantified, such as future potential or threats. SWOT tables are focused on identifying the strengths and weaknesses of different options and their opportunities and threats, not to evaluate them, which is well aligned with the purpose of our study. Unlike other multicriteria decision methods, such as the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) or analytic hierarchy process (AHP), SWOT analysis does not include any mathematics or hierarchical levels, thus making it straightforward to implement [44]. The SWOT analysis results are used to further elaborate the characteristics of each energy source option. The SWOT analysis results are supported by references to the relevant literature, but the results are actualized for our specific case, which is also the contribution of our study. The assessment discusses the options in the context of applying them to the E3RV Tangaroa concept by primarily focusing on the operational profile and characteristics of the vessel. In SWOT, the aspects related to costs, RAMS, emissions, potential threats and opportunities, additional regulatory limitations, aspects affecting wellbeing, and the impact on company reputation are discussed on a high level.

3.3. Step 3: Energy Storage Weight and Volume Analysis

Since Tangaroa is designed to operate in remote locations with relatively long voyages, this critically emphasises the fuel storage capacity. The storage must be designed to ensure adequate fuel in any situation, even in emergency cases. Additionally, the energy storage spaces can significantly influence the vessel's overall design and stability, thus affecting the total feasibility of the energy source option.

Therefore, the selected energy source options are further compared by conducting energy storage analyses, preliminary weight and volume estimations, and discussion of the potential impact on ship stability. The challenges of each energy source are discussed in the analyses, especially considering the characteristics and the operational profile of the vessel.

The energy storage analysis is conducted by estimating the volumes of the required storage spaces and their locations on the vessel. Computer Aided Design software, such as AutoCAD 2023, can be utilised when designing the preliminary energy storage locations on the ship profile. For fuel weight and volume estimation the following formula is considered [27]:

$$Electrical\ Energy = 0.55 \times Maximumpower \times time \times Marginreserve \quad (1)$$

$$Stored\ energy = \frac{Electrical\ energy}{\eta} \quad (2)$$

$$W_{FO} = \frac{Stored\ energy}{energy\ density} \quad (3)$$

$$V_{FO} = \frac{W_{FO}}{density} \quad (4)$$

In which the maximum power is 23,600 kW from Section 2.2, time is set to 50 days, margin reserve is set to 1.3, η is used to represent the efficiency of transformation of chemical energy to electrical, and energy density and density are dependent on the fuel. A factor of 0.55 was used in contrast to the factor of 0.75 recommended in reference [45] since the vessel is not operating at the maximum power demand (icebreaking) all the time. The ship has around 400 h of transit to and from the area of operation (Figure 2) and it also might be in DP mode frequently where the power demands are significantly less. We still set the safety margin to 1.3 in line with [45], which can be considered a generous safety factor justified by the fact that this ship is expected to be operating in harsh Arctic conditions. The calculations can be used for estimation of the total power demand, ignoring for the moment the thermal load required for heating, as it can be safely assumed that exhaust gases from either fuel cells or combustion engines cover that.

During the subsequent spiral of ship design, the fuel selection as it is performed in this approach should not be separated from the choice of ship machinery, as it has a direct impact on the energy conversion efficiency and space. Furthermore, potential DF operations also influence the requirements of the main fuel storage. However, in the case of DF operation and operating with low carbon fuels, it is possible that the "main fuel" storage can be dimensioned without too big a margin, and the "pilot fuel" can be also easily allocated. Therefore, the full amount of "alternative/clean fuel" might not ever have to be dimensioned to its full maximum. Nevertheless, in this study, we consider that the final machinery or the relationship between the main and pilot fuel impact on fuel storage are outside the analysis scope. Instead, we study how large quantity of the main fuel should be taken onboard.

3.4. Step 4: Calculation of Life Cycle Costs and CO_2 Emissions

During step 4, life cycle costs and CO_2 emissions are calculated for the selected feasible options from step 3. For the estimation of operational costs (*Opex*), the fuel cost C_{FO} (EUR/ton) is used and the amount of expected fuel consumed W_{FO} (ton)/1.3 during each voyage. The division by 1.3 is performed since it is a safety margin and we do not expect to consume all the fuel under normal conditions. The maintenance cost is also included in *Opex*. If internal combustion engines (ICE) are used, then the C^M_{FO} factor (EUR/kWh) is employed to estimate the maintenance costs based on the actual power generated in Kwh (electrical energy). Then, the *Opex* per voyage is multiplied by the number of voyages per year (k) to yield annual values (Equation (5a)). In this study, the number of voyages per year (k) is considered equal to 3, so the vessel is fully operational only 150 days per year. If fuel cells are used due to the relevant data unavailability, (Equation (5b)) is employed, where the maintenance cost is set to 1.5% of the capital costs for fuel cells as the average of values present in [46,47]. The fuel cost again is normalized using the number of voyages per year (k).

The capital costs are estimated by considering the cost of the chemical to electrical energy transformation system and the storage tanks costs (Equation (6)). To estimate the cost of the transformation system, in line with [27], the C_{IP} (EUR/kW) is used, which represents the unit cost per installed power and the installed power (IP). The storage tanks and auxiliary system cost for different fuels is estimated based on the amount of stored energy from Equation (2) in Kwh and C_S factor (EUR/kWh) retrieved from the literature.

The life cycle is estimated using *Capex* and *Opex* in Equation (7a,b) with an expected service life of 25 years. In case fuel cells are used, then it is assumed that they are replaced every 5 years in line with [48–50], where it was assumed that fuel cells' life expectancy is equal to 20,000 h of operation. Considering that the vessel is voyaging only 150 days per year and the harbour's electrical needs can be covered through cold ironing, it can be easily proved that the fuel cells will need to be replaced approximately every 5 years. It is assumed that fuel cells need to be completely replaced, which can be viewed as a conservative assumption [50].

Finally, the CO_2 emissions in tons are estimated considering the annual amount of fuel consumed ($W_{FO} \times k$) and the emission factor C_F (t of CO_2/t of fuel) (Equation (8)).

$$Opex = k \times \left(W_{FO} \times C_{FO}/1.3 + C_{FO}^{M} \times Electrical\ energy\right) \quad \text{forICE} \tag{5a}$$

$$Opex = k \times W_{FO} \times C_{FO}/1.3 + 1.5\% \times C_{IP} \times IP \quad \text{forfuelcells} \tag{5b}$$

$$Capex = C_{IP} \times IP + C_S \times Stored\ energy \tag{6}$$

$$LCC = Capex + \sum_{N=1}^{N=25} \frac{Opex}{(1+r)^N} \quad \text{forICE} \tag{7a}$$

$$LCC = Capex + \sum_{N=1}^{N=25} \frac{Opex}{(1+r)^N} + \frac{C_{IP} \times IP}{(1+r)^5} + \frac{C_{IP} \times IP}{(1+r)^{10}} + \frac{C_{IP} \times IP}{(1+r)^{15}} + \frac{C_{IP} \times IP}{(1+r)^{20}} \ \text{forfuelcells} \tag{7b}$$

$$W_{CO_2} = C_F \times W_{FO} \times k \times 25/1.3 \tag{8}$$

3.5. Step 5: Selection of the Energy Source

Using the results from the previous steps, the final comparison between the selected energy sources is conducted and a choice can be made. The different alternatives which can be applied in the case of Tangaroa are discussed, based on the different incentives the ship owner and the operator can have with respect to financial cost, reputational aspects, environmental emissions, and risk appetite. To support the decisionmaker, we proceed with some semi-qualitative rankings for the different investigated criteria with Very Good = 5, Good = 4, Mediocre = 3, Bad = 2, and Very Bad = 1 based on the information identified using SWOT, techno-economic analysis, estimation of emission factors, and investigation of the potential for space allocation. The rankings are presented using a radar (spider) chart. Their average values for different criteria are used as a supportive measure.

After the alternative options are presented, it is discussed how the final choices might be altered in the future and what are the main limitations of the conducted study.

4. Results

4.1. Step 1: Identification of Potential Energy Sources and Their Properties

Currently, multiple energy sources can be theoretically utilised in day-to-day ship operations as shown in Table 2. All the presented energy sources have significant differences, resulting in varying emissions, energy density, flexibility, availability, and required infrastructure [11,13]. However, the application of multiple and novel fuels is still at the experimental and case study stage, especially when it comes to the Arctic environment [9,13].

Therefore, the energy sources whose application still lacks support from necessary infrastructure, technology, or regulations and those whose power capacity is not adequate for the ship's endurance are excluded from the analysis. If one of these criteria was not satisfactory, the energy source was excluded from further analysis.

Table 2. The investigated fuels and the rationale behind the fuels selected for SWOT.

a/a	Energy Source	Endurance and Energy Capacity for Operations	Technology Maturity and Regulatory Readiness for Technology Acceptance	Infrastructure Readiness and Fuel Availability in the Operational Area	Selection for SWOT
1	Nuclear	Very good	Mediocre, as the regulations are available and skills are present, but the skills are being degraded [51,52]	Low in Finland	No
2	Solar	Very limited	Good	Low solar power availability	No
3	Battery (electrical)	Low	Very good	Very good	No
4	Ethanol	Good	Mediocre	Low	No
5	Dimethyl ether	Good	Low	Low	No
6	CNG	Very good	Very good	Low	No
7	LNG	Very good	Very good	Very good	Yes
8	LPG	Very good	Mediocre	Low	No
9	Liquid methanol	Good	Good	Mediocre as it rapidly changing	Yes
10	Ammonia	Low	Low	Good	No
11	MDO/Biodiesel	Very good	Very good	Very good	Yes
12	Liquid hydrogen	Mediocre	Mediocre	Mediocre, but it is improving	Yes

Based on the current market trends and available technology, four types of fuels were selected and then reviewed using SWOT analysis (Table 2). The selected fuels for the energy source analysis are marine diesel oil (MDO), the most popular and established fuel choice, LNG, one of the more environmentally friendly fossil fuel options, hydrogen, and methanol, whose application is becoming more and more popular. The rationale is elaborated below and in Table 2. Some fuel properties are provided in Appendix A.

Despite the good endurance, relevant technological and regulatory maturity on a global level, and eco-friendliness in terms of greenhouse emissions [52,53], considering the limited fuel availability in Finland, gradually diminishing expertise in Finland for designing and operating nuclear power ships, high costs [52], and general public concerns associated with safety, nuclear power is discarded from the potential energy sources for Tangaroa.

In the considered operational area, the average solar energy over a year is significantly less than the average of the whole Earth and is anticipated to be insufficient as a sole energy source for the ship, resulting in its exclusion. Yet, it can be combined with other energy sources as an auxiliary means.

The energy density of the batteries is not yet sufficient to provide the range and endurance required for open-water shipping. Thus, battery power is discarded as a possible main energy source for the Tangaroa, as our vessel requires long range and endurance. Still, it can be included together with another main energy source to improve the ship's energy efficiency and environmental impact.

Although ethanol is widely used in land transportation, and it is expected that the results in marine application would lead to good performance, the lack of previous tests and conversions in the maritime context [54,55] can be seen as a major disadvantage. Due to the limited fuel supply and technical immaturity when it comes to maritime usage, ethanol is discarded from the potential energy sources for Tangaroa.

Dimethyl ether (DME) is expected to be a prominent fuel in the future, but it still requires more development [56,57]. Additionally, the regulatory framework for DME is still immature [58]. Thus, due to the limited supply as well as technical and regulatory uncertainties, DME is discarded as a potential energy source for Tangaroa.

Despite its challenges, LNG can be considered as a technically and regulatorily mature energy source [11,12,59]. LNG is also very popular. Furthermore, the existing infrastructure and supply in the operational area are sufficient for operations [60]. Therefore, LNG is chosen to be considered in the next steps and its advantages and disadvantages are elaborated further for possible application.

Due to LNG being a more feasible and mature energy source for marine applications, compressed natural gas (CNG) has not been widely used on ships. Additionally, the infrastructure for natural gas to be used for vessels is mainly built around LNG, thus limiting the availability of CNG [61]. Thus, due to the limited supply and lack of reference vessels in the same operational area as Tangaroa, CNG is discarded from the considered energy sources. For similar reasons, liquid petroleum gas (LPG) is also discarded.

Several projects have been carried out recently investigating methanol as a fuel in marine applications. In addition, it is readily available, it can be produced from a wide variety of sources, and if used, it reduces emissions during operation. There is still a need for the development of infrastructure for methanol in the considered operational area, but there are some promising developments and available regulatory frameworks [62]. For the case of Tangaroa, methanol is considered in the study due to future opportunities as a transition fuel, the low cost of the system retrofitting and installation, and opportunities as an Arctic fuel [10,63,64].

Ammonia (NH_3) is used in a wide variety of industries and has been heavily explored as a potential marine fuel [15]. However, with the energy density of ammonia being lower than that of diesel, larger fuel-storing facilities are required. Since, the regulations have not matured enough to allow wide ammonia operation despite the pressure [65], ammonia is outside the scope of our analysis, even though some promising projects investigating the infrastructure readiness in the considered operational area have recently started [66,67].

MDO is a proven and widely used marine fuel, with a high energy density, both gravimetric and volumetric [68]. In addition to the established technology, the availability of the fuel itself is also very good, making it suitable for operations in more remote areas, and thus MDO is chosen to be considered in the next steps.

Hydrogen is the most abundant element in nature with zero emissions if used in marine fuel cells. Hydrogen is categorized based on its production as grey (produced from fossil fuels), blue (captured carbon emissions from production), or green hydrogen (produced from renewable energy through electrolysis) [14]. Hydrogen as a marine fuel has a promising future, mainly due to the goals of transitioning towards zero-emissions shipping and the development of a hydrogen economy. Propulsion and power generation using hydrogen is also feasible in a maritime context and there already exist some prototype vessels utilizing hydrogen as their energy source [64]. Generally, the hydrogen refuelling infrastructure in remote regions such as the Arctic is limited [69]. However, some liquid hydrogen (LH_2) refuelling stations are in the process of construction in the Arctic region of our concern [70–73]. With the future in mind, hydrogen is considered a potential energy source for Tangaroa.

4.2. Step 2: SWOT Analysis

Detailed SWOT analysis results for the four selected fuels can be found in Appendix B, whilst only the main highlights are provided below for brevity purposes.

The advantages of MDO include its wide availability, the smaller volume required to store the fuel compared to the other three, technology maturity, well-known safety risks, lower Capex cost, and the potentially widespread availability of biodiesel. Nevertheless, the drawbacks of implementing a diesel fuel power system are higher CO_2 emissions and chances of oil spills which together with the potential carbon tax threat can lead to significant future costs and negatively impact the company's outlook. MDO is also not as good as other fuels for lower temperature operation, and it can contribute to black carbon emissions [1].

LNG, on the other hand, has lower emissions, black carbon, and seems to be a cost-efficient solution, but there are challenges with supply in more remote locations, supply chain security due to sanctions on Russia, and it also contains carbon, so depending on the carbon source it might be subject to a carbon tax. Furthermore, LNG use can lead to methane slip in internal combustion engines, which might be strictly addressed in future regulations. Like other fuels, bio or synthetic LNG can be launched in the market in the future, which will support future compliance with emission regulations.

The advantage of using hydrogen stems from its eco-friendliness and no black carbon, but it is still an expensive and challenging alternative for application in Arctic-going vessels due to significant safety risks, low hydrogen availability, low energy density, and the novelty of the concept.

Lastly, methanol can be a cost-efficient solution based on literature, with almost no black carbon, and some prototype ships are already running on methanol. If the availability of green methanol increases in the Arctic area, it can become a good option due to its easy storage requirements and low melting point. However, safety issues with respect to the application of methanol engines need to be addressed. The use of methanol can benefit from the rise of green synthetic methanol.

4.3. Step 3: Energy Storage Weight and Volume Analysis

Based on the formulas presented in Section 3.3. the required electrical power demand for a 50-day voyage is 20.25 GWh or 72.9 TJ. The total required amounts of MDO, LNG, LH_2, and methanol for a 50-day voyage can be seen in Table 3, together with their space requirements. The volume and energy calculations for the fuels were implemented using energy densities as input from Appendix A and idealised η set, in line with references [15,74–77]. For LH_2, we assumed that fuel cells would be used, and for the rest, the use of engines is anticipated. For LNG and LH_2 tanks, the required filling rates are also considered based on feedback that we received from manufacturers, whilst they are assumed for methanol.

Table 3. Estimated required volumes and weights.

	MDO	LNG	LH_2	Methanol
Energy density (MJ/kg)	42.6	48.6	120	20
η (-)	0.45	0.45	0.5	0.45
density (kg/m^3)	820	450	71	792
Weight required (t)	3790.7	3375.6	1215.0	7713.8
Filling rate	0.98	0.98	0.69	0.98
Volume required for tanks (m^3)	4717.1	7654.4	24,801	9938.4

As can be observed, the total estimated volume of LNG is around 60% more when compared to MDO, yet the total weight of the LNG is around 12% lower (however, this is true not considering the extra weight for the fuel tanks). Similarly, for LH_2, whilst the weight of hydrogen is only one-third of MDO and LNG, the required storage volume is almost five times the volume needed for MDO. That is mainly due to LH_2 low volumetric energy density and reduced filling rate. Methanol requires a double amount of volume due to lower volumetric density compared to MDO.

When comparing the fuel tanks for MDO, LNG, LH_2, and methanol, the most crucial element is the volume and location required for both energy sources, as the weight difference between the fuels is relatively small. According to MARPOL, fuel tanks located in the double hull of new-build ships have been prohibited since 2007 [78]. Therefore, the MDO tanks are on deck 1, next to the main engines inside the hull with a fireproof separation. In Figure 5, the deck plan of deck 1 is shown. The fuel tank's capacity is adequate for holding the considered MDO fuel.

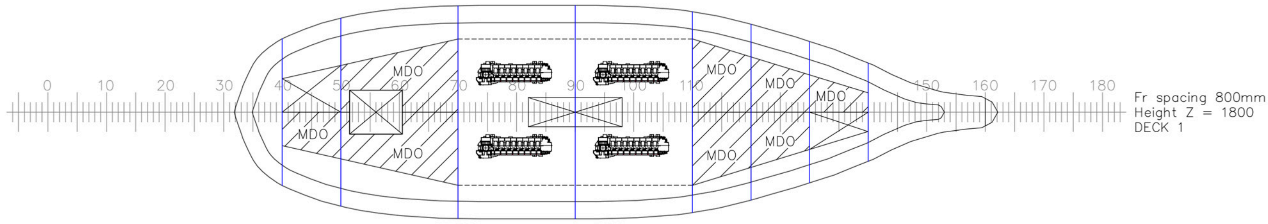

Figure 5. Deck 1 plan with MDO tanks.

For the LNG and LH_2 tanks, the biggest challenge lies in the required size and the impact this will have on the ship's stability. In addition to the actual tanks, there must be also space for all other associated systems (low or high pressure) to transfer LNG/LH_2 and render it combustible [79] as well as install the relevant energy conversion system [80]. Since LNG and H_2 are required to be kept in pressurised or liquid conditions, both fuels must be stored at very low temperatures using cryogenic equipment and relevant insulation [81,82]. The first option would be replacing the aft hangar with tank spaces as shown in Figure 6. If the aft hangar is replaced, a solid platform should be built on top of the tank to be used as a helideck. To add to the storage, an additional option is to locate the tanks forward of the superstructure, in the location of additional storage space. Consequently, this would take up some cargo space, but the released space from the MDO tank locations could be used as cargo/storage spaces. This would impact the stability as well, as we would relocate the fuel weight from deck 1 to the upper deck. As a consequence, to avoid issues with ship stability, we would need to add extra ballast and increase the ballast allocated space or redefine the ship dimensions and block coefficient.

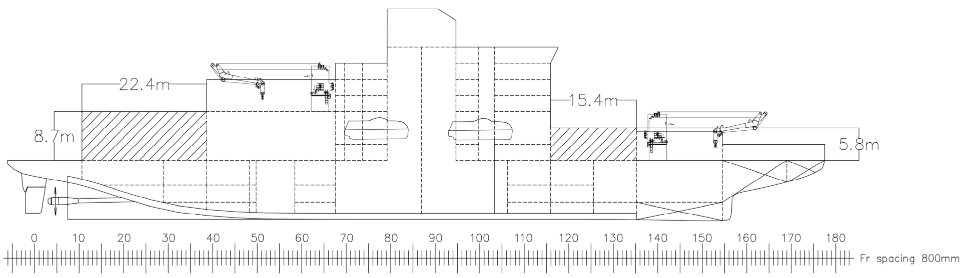

Figure 6. Potential locations for LNG and LH_2 tanks and systems.

If the tank was positioned at the main deck aft, between frames 11 and 40, where the length of the tank room would be 23 m, two LNG tanks could be placed next to the room. The required radius of one LNG tank would be up to 4.35 m for a tank volume of 1331.6 m^3. This space is calculated without any casings, additional devices, or systems taken into account. At the bow, where the allowed height is 15.4 m, the required radius would also be 4.35 m and the available volume of one tank to be installed would be 406.9 m^3. The arrangement that fits these radiuses into the ship's general arrangement can be seen in Figure 7.

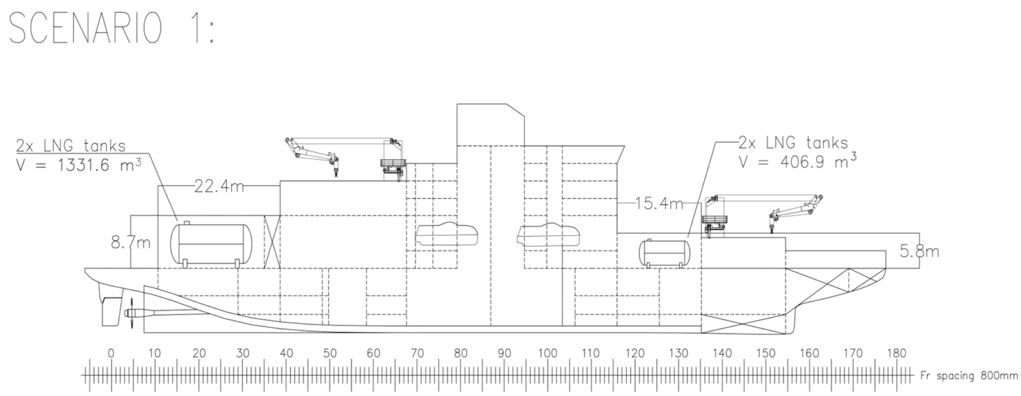

Figure 7. Tank dimensions and locations placed aft and forward of Tangaroa without any changes to dimensions.

From this preliminary check, it can be observed that in total, the volume of four installed tanks would be 3477 m^3, which does not meet the requirements as shown in Table 3. To overcome these issues, two alternative solutions were established—either through modification of tank rooms or opting for a DF system. In Figure 8, a solution where the required volume of LNG onboard would be installed results in a change in the singular tank radius of 6.2 m and a change in the height of the room.

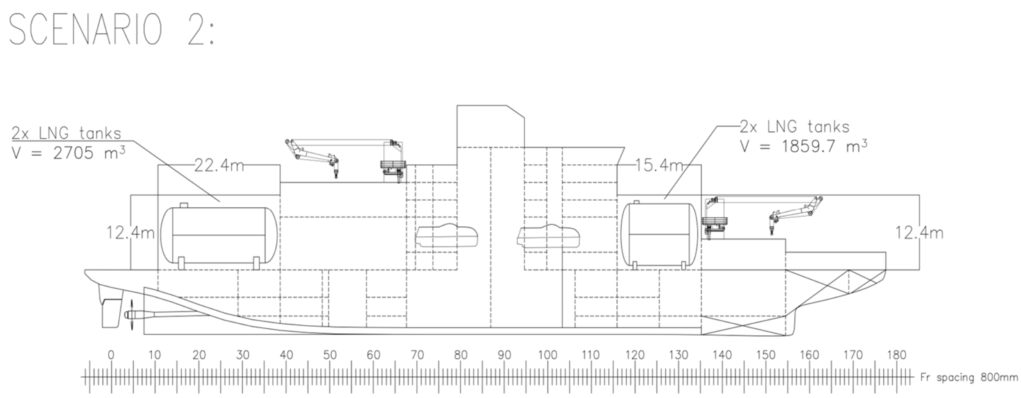

Figure 8. Tank dimensions and locations with increased radius and changes in the height of tank rooms.

With this solution, the installed volume of LNG would be 9130 m^3, which is within the requirements for the use of LNG throughout the entire 50-day operation. According to the IGF Code, the tanks should be located at a minimum distance of 2 m from the bottom shell, behind the collision bulkhead and 1.12 metres from the bottom shell at the centreline to avoid external damage (according to formulas), i.e., from collision and grounding [83]. However, fitting the tank in front of the superstructure would block the view of the whole command bridge, impairing the requirements related to the line of sight [84]. If the tank were positioned to replace the hangar, the tank would still be too large so there would be no possibility for helicopter operations.

A more realistic solution is presented in Figure 9. Two tanks with a length of 22.0 m and a radius of 6.2 m are set between deck 1 and the middle of the superstructure, allowing for space after the tank to be used either for helicopter operations or crane installation. The tanks in front of the superstructure use the space intended for cargo storage and are dimensioned at a height of 11.5 m and a radius of 6.2 m. With that, the available tank storage space is 8091 m^3.

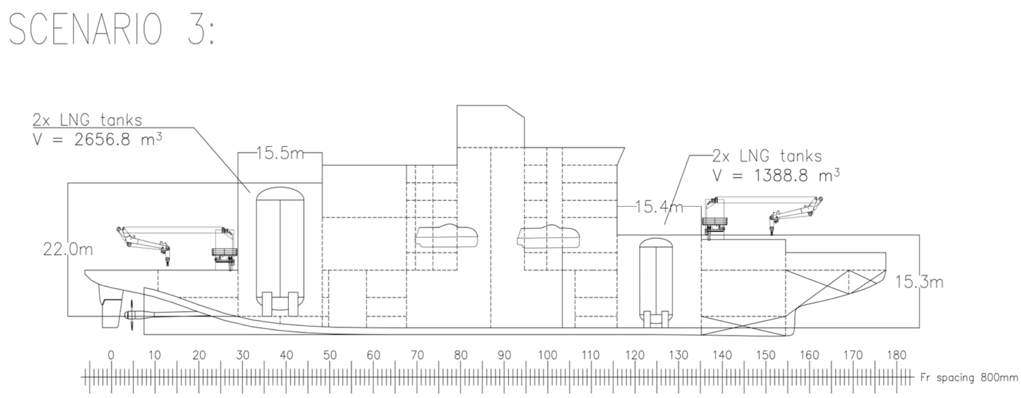

Figure 9. Tank dimensions and locations with vertical positioning and utilization of cargo and technical spaces.

Comparing the three solutions, the tank allocation in Figure 7 is most compliant with the design restrictions, but the achieved volume is less than required. This design would decrease the endurance of the vessel and thus limit the voyage length, and therefore inadequately cover the energy demands. The design in Figure 8 is able to use the space available with modifications to the tank rooms and allows for extra storage of LNG. However, it does not follow the requirements set by IMO for line of sight so it cannot be implemented. Figure 9 presents the most feasible solution for the installation of tanks with major adjustments to spaces and cargo handling facilities and operations onboard. However, both solutions in Figures 8 and 9 represent significant hazards to the crew, so they will require additional isolation and protection, similar to the design of IB Polaris. The available volume allows for the full 50-day operation solely on LNG, with an additional storage margin.

The challenge with fitting hydrogen tanks is even greater due to the larger tank size and installation of a fuel cell. The required size of tanks as presented in Table 3 is currently not applicable to Tangaroa as concluded from the LNG case (approximately 8 km^3 were required for LNG whilst LH_2 requires approximately 25 km^3 or three times more), but LH_2 could be used to cover at least some of the power requirements, reducing the operation costs and emissions if combined with DF engines. A solution using three LH_2 MANCryo vacuum-insulated tanks from MAN Energy Solutions manufactured in Gothenburg, Sweden with a volume of 335 m^3 is presented in Figure 10. In that case, a space would need to be reserved for small fuel cells on the deck, which is present in Figure 10. The selected fuel cells would act as an auxiliary power generation plant, not the main one.

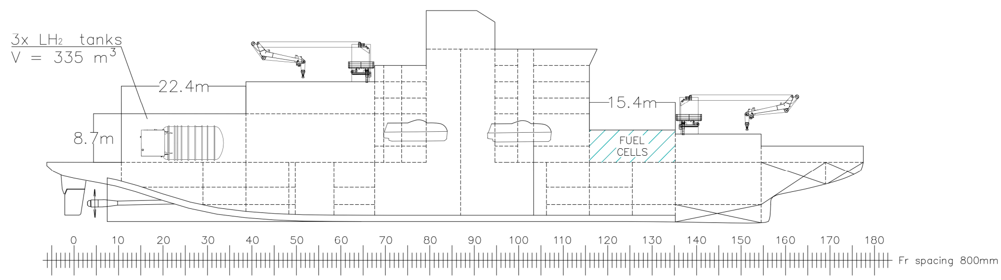

Figure 10. Design location of LH_2 tanks and fuel cells.

Since the existing fuel space reserved for MDO can be used for the storage of methanol, this greatly facilitates the use of methanol. The available volume above deck 1 where MDO is stored is around 5060 m^3 and while that is enough for covering the entire voyage with diesel, methanol requires twice as much space based on its energy density (Table 3). That means that while Figure 5 showcases a partial storage solution for methanol by replacing MDO tanks, additional space has to be found onboard to cover the required volume for a

50-day voyage (Figure 11). Based on the different ways methanol tanks can be installed, the solution has been found in sacrificing Tangaroa's cargo space and utilising provisional space, which allows for maintaining the stability of the vessel [12].

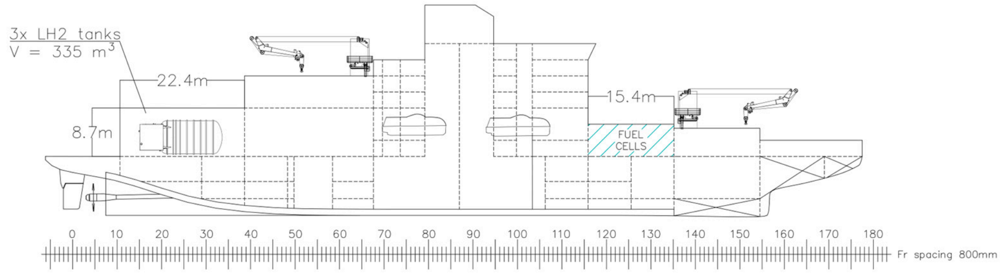

Figure 11. Modification of MDO tanks to methanol tanks on deck 1.

The total installed volume of methanol, as seen in Table 3, needs to be 9938.4 m^3. To that needs to be added spaces occupied by extra machinery, watertight bulkheads, the necessary cofferdams, and sufficient insulation. Figure 12 showcases the solution for the installation of methanol tanks between deck 1 and the main deck in place of cargo space. Alternatively, the space in the double hull can be used for methanol, as methanol is biodegradable, and its storage can be extended to the side shell. In such a case, the total volume available for methanol tanks is more than 10,000 m^3, which is sufficient for a single-fuel voyage.

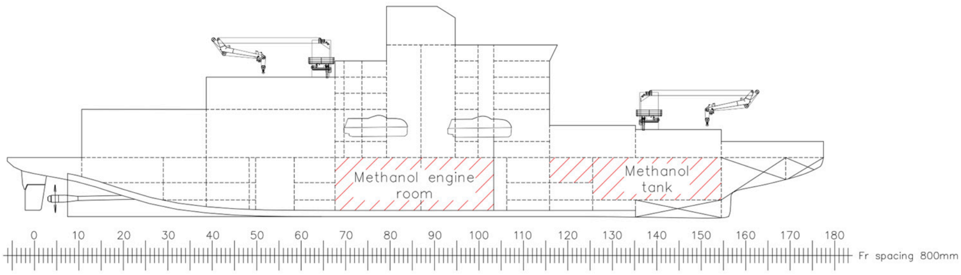

Figure 12. Design locations of methanol fuel tank and engine rooms.

In Table 4, the available dimensions and locations of fuel tanks are presented. The dimensions are based on the available space onboard the Tangaroa, as described. These results also indicate that the carbon capture use on this ship might be challenging due to the stringent space limitations.

Table 4. Tank dimensions and locations.

Fuel Type	Location	Tank Dimensions (L × r) [m]	Reserved Space	Total Fuel Volume
MDO	Deck 1	-	8 tanks with a total volume of 5065 m^3	4964 m^3 (98% allowed filling rate)
LNG (Scenario 3)	Superstructure, main deck	22.0 × 6.2 11.5 × 6.2	4 tanks with a total volume of 8091 m^3	7929 m^3 (98% allowed filling rate)
LH_2	Superstructure, main deck	18.0 × 5.3	3 tanks with a total volume of 1005 m^3	693 m^3 (69% allowed filling rate)
Methanol	Deck 1, cargo space between deck 1 and the main deck	-	8 tanks with a total volume of 5065 m^3 and 6 tanks with a volume of 5000 m^3	9859 m^3 (98% allowed filling rate)

4.4. Step 4: Calculation of Life Cycle Costs and CO_2 Emissions

For the calculation of life cycle cost and CO_2 emissions, input from Table 5 was used. The discount rate r was set to 5%. The results are presented in Table 6.

Table 5. The computational input used [15,74–77,85].

	Diesel	LNG	Methanol	H_2
C_{FO} (EUR/ton)	877	560	375	1500 (fossil-based) 5500 (green hydrogen)
C_{FO}^{M} (EUR/kwh)	0.012	0.012	0.012	Not applicable
C_F (t-CO_2/t-fuel)	3.206	2.750	1.375	0
C_S (EUR/kWh)	0.083	0.31	0.14	1.71
C_{IP} (EUR/kW)				
Four-stroke engines	240	470	265	730
(for hydrogen PEMFC is assumed)				
η [-]	0.45	0.45	0.45	0.5

Table 6. Techno-economics for different fuel options.

	Diesel	LNG	Methanol	H_2 (Fossil Hydrogen)	H_2 (Green Hydrogen)	H_2 (Green) + MDO
Capex	EUR 9.4 M	EUR 25 M	EUR 12.6 M	EUR 86.1 M	EUR 86.1 M	EUR 20.6 M (EUR 28.1 M based on industry feedback)
Annual Opex	EUR 8.2 M	EUR 4.9 M	EUR 7.2 M	EUR 4.5 M	EUR 15.7 M	EUR 8.2 M
Life cycle costs	EUR 125.4 M	EUR 94.4 M	EUR 114.5 M	EUR 187.8 M	EUR 345.9 M	EUR 153.9 M (EUR 178.4 M based on industry feedback)
Life cycle CO_2 emissions	701 kt	536 kt	612 kt	0	0	627 kt

As it can be observed, even if it was feasible to install the H_2-related storage and fuel cells, the cost would be exorbitant. The capital cost would be almost 10 times higher than the smallest of the values (for MDO) and the life cycle cost would be 3.5 higher than the smallest (running on LNG) if green H_2 is used and 2 times higher than LNG if fossil hydrogen were used. Even if a small H_2 fuel cell of 3 MW running on green hydrogen together with MDO were used, the life cycle cost would be significantly higher than that of LNG, and CO_2 emissions would still be higher. It should be noted though that the capital cost we estimated for H_2 was very optimistic, as feedback from the industry suggested a much higher value for storage tanks. So, for the hybrid case (MDO + H_2) considering the industry feedback, the capital cost would have been higher than that of LNG and the life cycle costs would also be much higher.

The methanol-fuel-based power plant seems to have a slightly higher capital cost than the MDO one but lower than for LNG and H_2. Methanol, due to its higher price and lower energy density, has higher life cycle costs than LNG. Still, it seems that methanol is a good alternative to MDO in terms of operational and life cycle costs and overall emissions, so it can be a solution worthy of consideration.

LNG seems to be the other option in terms of life cycle emissions and costs, despite its high capital cost, whilst MDO's strong point is the lowest capital cost, even if it has higher operational costs and life cycle costs due to higher fuel prices.

4.5. Step 5: Selection of the Energy Source

The Arctic region is considered an extreme environment and thus ships operating there require unique design characteristics. Four energy source options, namely MDO, LNG, hydrogen, and methanol, were chosen for a detailed assessment in this study. Although each fuel has special advantages, with methanol receiving the highest score, none can be considered the unequivocal choice for the investigated vessel. The final decision for which fuel is due for deeper consideration during the next stage of iterative power plant design depends on the goals and values of the ship owner and operator. This decision is also challenging in view of anticipated ambiguities with respect to regulatory, infrastructure, public opinion, and political and technological developments in the expected 25 years of the ship's lifetime. Yet the different advantages and disadvantages are provided in Table 7, whilst the results of evaluation criteria are provided in Figure 13. The rationale is elaborated in the following paragraphs.

Table 7. The pros and cons of different options.

Fuel	Pros	Cons
MDO	Business as usual. Good financial performance. No need for ship rearrangement. Can be an option if biodiesel becomes widely. available. Can be combined with other fuels.	No environmental emissions reduction. Risk of paying a carbon tax. Negative public company image. The ship needs to be ready for retrofit to another fuel type.
LNG	Can be combined with MDO. Reduced CO_2 emissions. Greater security against a carbon tax. Can be retrofitted to methanol. Improved public image. Proven technology. Good Life cycle cost.	A radical change in ship arrangement is required if running solely on LNG with an impact on safety, if unaddressed. Issues with security supply of LNG. Still not a complete reduction in CO_2. Methane slip needs due consideration as it might be considered in future regulations. High Capex.
LH_2 or LH_2 + MDO	Improved public image. Improved emissions if combined with MDO. High potential for innovation. Refuelling infrastructure available in Norway.	Can be applied only together with MDO due to low volumetric density, high boil-off rate, and inability to capture transients. Relatively new concept. Presently very costly solution. No security against carbon tax since MDO is still necessary.
Methanol	Easy fuel tank allocation without large modification. No frost risks. Can be combined with green methanol in the future. Achieving cost-efficient CO_2 emission reduction without methane slip Improved public image. Greater safety against a potential carbon tax. DF engines available.	Toxicity risks need to be addressed. Less CO_2 reduction than that of running on LNG.

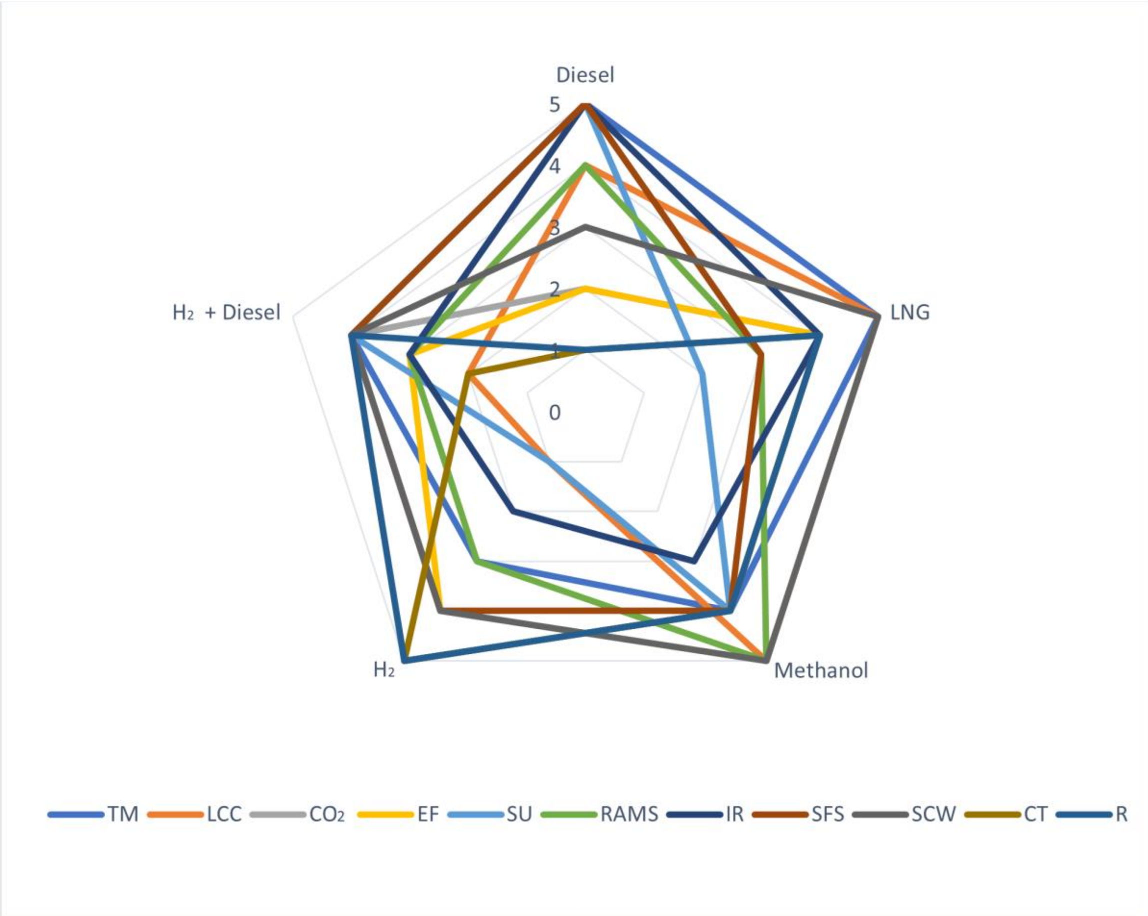

Figure 13. Radar chart for different alternatives. TM = technological maturity; LCC = life cycle cost; EF = other environmental factors; SU = space utilization; RAMS = reliability, availability, maintainability, safety; IR = infrastructure readiness; SFS = security of fuel supply; SCW = suitability for cold weather; CT = carbon tax risks; R = reputational risks.

MDO is a widely used fuel which benefits from an extensive and developed infrastructure, developed technology with a competitive market (TM = 5), and good fuel availability (SFS = 5). The bunkering of MDO is also easy in the considered area (IR = 5), and the fuel has a significantly higher volumetric energy density compared to the other fuels assessed in this study. Currently, MDO is a good cost-effective (LCC = 4) and safe solution (RAMS = 4), even if it is slightly worse than methanol and LNG in terms of life cycle cost. It must be noted that the sulphur content in the MDO used in the assessed vessel must not exceed 0,1% to meet the Annex VI MARPOL IMO guideline. Since the space on the lower decks is reserved for the fuel, there is more availability for additional equipment on the main deck and superstructure of Tangaroa (SU = 5). This is not optimal but still useful in the Arctic region (SCW = 3). However, MDO is a fossil fuel with relatively high CO_2 (CO_2 = 2), oil pollution, and black carbon emissions (EF = 2), and with the possible introduction of stringent emission rules such as a carbon tax, the economic feasibility of MDO, compared to the other less polluting fuels, will decrease (CT = 1). Furthermore, as public opinion is turning against fossil fuels and towards more sustainable solutions, the use of MDO can cause harm to the ship owner or operator (R = 1). So, if the aim of the owner and operator is to ensure reliable, cost-effective, and safe operation of the vessel in the near future, or the owner sees the availability of biodiesel in the future favourably, then the MDO can be considered as a good alternative. Yet, the owner will need to accept the potential risk of retrofits in case of a sharp increase in the carbon tax, other regulatory updates, or public and technological developments if biodiesel does not become available. In that case, it would be beneficial to prepare for such a retrofit during the design stage to manage the risks. Getting the ship ready for retrofit to methanol could be such an option, as elaborated below. So, the average score for diesel is 3.4.

LNG is a widely used and proven energy source in ships (TM = 5); it has good infrastructure available (IR = 4), is suitable for cold weather (SCW = 5), and can be regarded as a more sustainable alternative compared to crude-oil-based fuels such as the MDO. As was demonstrated previously, LNG produces less CO_2 emissions than MDO (CO_2 = 4), methanol, or MDO + H_2 and thus is a better solution from the perspective of tightening regulations, potential LNG tanks retrofit to green methanol tanks (CT = 4) [15], and public image (R = 4). It was also demonstrated that despite the high capital cost, in the long term, it can be a cost-effective solution (LCC = 5). The main obstacle lies in the required space for the fuel tanks to render LNG the only main fuel in the considered case (SU = 2). This can be tackled either through rapid redesign of the ship, as demonstrated in Section 4.3, or it can be applied only alongside DF engines and MDO as another fuel. The safety risks associated with LNG handling can be considered as not critical due to the relevant maturity of the industry. Yet, the proposed arrangement might compromise the ship's safety (RAMS = 3). Methane slip in natural gas or DF engines should be tackled so engines with very low methane slip should be preferred or the risk of methane slip regulations should be accepted (EF = 4). However, a secure supply of LNG is not guaranteed, and the war in Ukraine, resulting in reduced LNG supply, especially in Europe, restricts its application (SFS = 3). So, if a ship owner considers optimistically the evolution of LNG prices in the future and wants to secure himself against potential high carbon taxes, and improve the profile of his company, then DF engines together with LNG and MDO for pilot fuel can be a feasible choice. This option provides flexibility to adapt to the fuel markets as well as the regulatory requirements with relatively smaller changes to the vessel during its life cycle. This resulted in an average LNG score of 3.9.

Hydrogen is the most environmentally friendly fuel among the considered fuels (CO_2, EF = 5) but simultaneously it is a novel technology, especially in the Arctic (TM = 3). The supply chain CO_2 emissions of hydrogen depend on its type, but ideally, it can lead to zero emissions. Regardless of the production method, hydrogen produces zero CO_2 emissions locally, which is greatly beneficial when operating in sensitive Arctic areas (SCW = 4). Thus, this is a very future-proof fuel from the perspective of regulations (CT = 5) and public image (R = 5). However, the very low volumetric energy density of hydrogen (around 10 times less compared to MDO) poses challenges when designing a ship which requires a long operating range and endurance (SU = 1). The safety risks related to the storage and bunkering of LH_2 should not be ignored as it is very flammable in nature (RAMS = 3). Hydrogen operation is currently much more expensive than LNG, methanol or MDO for the considered case (LCC = 1). However, the price is expected to decrease with the increase in renewable energy production such as solar and wind power, which can then be exploited to produce hydrogen (SFS = 4). The infrastructure and availability of hydrogen is still in its infancy compared to more widely used MDO and LNG, which makes the operation in remote areas more difficult (IR = 2). Also, LH_2 evaporates rapidly, which is another obstacle. Achieving the required transient performance using fuel cells during manoeuvres is also challenging. So, LH_2 can be applied only together with other fuels such as MDO. In that case, a dedicated LH_2 tank connected to a fuel cell/diesel engine can cover part of the electrical load or DF engines running on MDO or hydrogen could be considered. But, despite the high capital and operational costs, the emissions reductions will be mediocre (CO_2 = 4), so it can be really challenging to employ such an option with the current state of fuel prices and technology costs. This resulted in both LH_2 and LH_2 + MDO average scores of 3.4, equal to MDO.

Methanol is emerging as a very promising fuel to be applied in the maritime industry. Its storage requirements can be considered less stringent than those for LNG and LH_2 which allows a much more flexible arrangement of the fuel tanks (SU = 4) and additionally, it has emissions slightly worse than LNG (CO_2 = 4). The capital and operational costs are also reasonable (LCC = 4), and such a concept will be positively perceived by the public (R = 4). This renders the use of methanol feasible in the investigated case. If green methanol becomes more available and cheaper in the future, as there are some promising developments [86–88], it will be possible to use it in a fully sustainable fashion (CT = 4, SFS = 4). Its application to Tangaroa seems practical as the cold temperature does not constitute a strong barrier (SCW = 5). Yet it is an unproven concept as no other Arctic-going ships running on methanol have been recorded to the best of the authors' knowledge (TM = 4, IR = 3). Safety is not a barrier to methanol implementation (RAMS = 5), and as carbon emissions are few and it is biodegradable it can be considered eco-friendly (EF = 4). So, this concept can be considered if the ship owner sees optimistically the availability of green methanol in the considered operational area in the near future, desires to avoid radical changes in the ship design, and has strong concerns about the environmental impact of his company. Alternatively, the ship can be designed methanol fuel-ready. This has resulted in an average score for methanol of 4.2.

4.6. Discussion and Limitations

The conclusions of the conducted analysis slightly deviate from those provided in DNV's report [30] and by Xu et al. [36], in which LNG was heavily promoted. We could also observe that LNG is a feasible and the most cost-efficient option for Tangaroa, but this is subject to strong modifications in the ship arrangement, which renders MDO or methanol highly attractive as well. This can be attributed to the fact that this study considered a special type of ship and space limitations and not a fleet of vessels. For the containership analysed by Xu et al. [36] the space limitations are not so stringent as containers can be removed to earn extra space. The space considerations are yet important for Arctic going vessels as has been highlighted by Kodratenko [35]. In this respect, the research findings of this study are also closer to Theocharis et al. [32], despite the fact this study followed a different approach to derive the conclusions. Furthermore, we excluded the use of batteries suggested by Kodratenko [35], as in our case the operation range requirements are completely different from the one analysed in this study [35]. Our recommendations are also different from the ones provided by Joseph et al. [31], which promoted ammonia. In contrast, this study concentrated on the currently feasible options, not the future ones such as ammonia, and ethanol which are much less available.

In this paper, the investigation concentrated mostly on four fuel types. It was found that the MDO is still the most convenient option space wise for the Tangaroa, unless radical redesign is implemented to gain more space for LNG or methanol. A similar prerequisite applies to the other promising fuels such as ethanol and NH_3. Whilst ethanol and NH_3 could be potentially stored in a similar fashion as methanol, their density poses an important limitation to the ship operations solely on those fuels, especially NH_3. Yet, with the increased availability of fuels and infrastructure and more incentives from the policymakers, they can be considered for operation alongside the other fuels.

In the analysis, we did not consider that a battery pack/solar panels could be also included alongside other fuels to improve the performance during transients and improve environmental performance. However, this is a recommendation for further research.

All the considered fuels include some safety risks, which have been briefly referred to in Section 4.1 and in more detail in Sections 4.2 and 4.5 for the selected four fuels. Despite the different levels of maturity for the technologies, we do not anticipate the safety risks to exclude the application of alternative fuels such as LH_2, CNG, ethanol, NH_3, and methanol, except nuclear. The optimism stems from the successful introduction of LNG in the maritime industry with some Arctic applications, which have an excellent safety record so far. Yet, these additional safety risks need to be considered when designing any of the proposed options considering the Arctic context and remoteness from the shore.

To support statements related to the techno-economical aspects of different fuels in the present paper, some simplifications were made. The study conducted in this paper did not proceed to any multi-objective optimisation or detailed techno-economic analysis. However, thanks to the investigation of the currently available infrastructure, fuels, and space, the options which were not currently feasible for the considered case were eliminated. Through the process, it was also found that if one wants to go towards more environmentally friendly solutions (LNG and methanol), one needs to fully redesign the investigated type of vessel and that operation solely on LH_2 is unrealistic. We also estimated that even a small fuel cell running on H_2 will not offer the same CO_2 reduction as methanol or LNG despite higher life cycle costs. We could also estimate that the use of methanol and LNG can be both more cost-efficient and contribute to CO_2 emission reduction compared to the state-of-the-art approach. These analysis results also indicate that the use of carbon capture on this ship would be extremely challenging due to space limitations, as it is a technology requiring space (1 m^3 of MDO for instance will require at least 3 m^3 storage for CO_2 in liquid form and cryogenic equipment). Follow-up research could take the considered feasible options as a basis for further investigation and verify these considerations.

In the analysis, we did not reflect on the use of DF engines combining MDO and hydrogen. However, based on the results in Sections 4.3 and 4.4 we can anticipate that regardless of whether ICE or fuel cells are used, none of the options can be considered cost-efficient due to high storage tanks cost and high volume requirements.

The analysis conducted in this paper has been significantly restricted by the currently available infrastructure and fuels in the operational area of Tangaroa. The industry is rapidly developing, and new regulations are on the horizon and novel technology is becoming more mature. Thus, it is important to keep this information updated to ensure the best possible decision-making. We also did not consider less stringent requirements for ship endurance and more frequent bunkering procedures. We reckoned that for a ship operating in such harsh conditions, it is important to have a good amount of fuel available as a reserve in case of emergencies. In our investigation, we also did not rehearse in greater depth the well-to-wake emissions, albeit we captured some of the considerations. Furthermore, during this design spiral, we decoupled the fuel selection problem from the associated machinery, as we anticipated that the impact of required space and volume for machinery would be of secondary importance. An important limitation of our analysis is the focus on CO_2 emissions, and not the GHG emitted through the process. The different preferences of the ship owners have been also omitted from the study, so the final decision is left to the ship owner/designer, whilst we provide a rationale for different options and possible paths.

We did not include any quantitative metrics in the process for comparison of various alternatives, only a few qualitative ones presented in step 1 and 5. Whilst it can be seen as a limitation, this argument-based elimination and presentation of various alternatives has its own merits. It allows the decision-makers (the owner and operators) to see deeper into the rationale behind the selected alternative which can be hidden behind the rankings provided by various experts and interact deeper with the selection process.

5. Conclusions

In this study, the feasibility of alternative fuel options for an Arctic research vessel was investigated using SWOT, simple calculations, and currently available information from research publications and other relevant literature.

The main findings of the study were as follows:

- Despite the existence of multiple alternative fuels, their availability, and regulatory and infrastructure readiness, constitute significant obstacles to their adoption for the considered research vessel at the current stage of development. This renders MDO, LNG, LH_2, and methanol the currently feasible options for an Arctic research vessel, with methanol having the best score in most of the considered attributes. However, this is rapidly changing and should be constantly reassessed.
- The harsh environmental conditions, long operational range and endurance requirements, and a varying operational profile are factors that are decreasing the feasibility

of the alternative fuels, namely LNG, methanol, and LH_2, for the considered research ship, unless radical ship arrangement changes are implemented.

- MDO is the most convenient option considering its maturity, arrangement requirements, and energy density compared to LNG, methanol, and LH_2. Yet it is the least environmentally friendly and less cost-efficient than methanol and LNG. A ship with MDO can be made retrofit-ready to be able to tackle the more stringent environmental requirements during the ship's lifetime once they arise.
- With radical ship arrangement redesign, operations using solely LNG and methanol seem feasible and more cost-efficient than diesel for the Arctic-going research ship, with 25% and 9% lifecycle cost reductions, respectively. Yet operations using only LH_2 are considered unrealistic and overwhelmingly expensive (cost increase from 50% to 175%), and the use of MDO together with LH_2 is the only realistic way of involving LH_2, but still with 22% to 42% higher lifecycle costs.
- Whilst it is anticipated that operational CO_2 emissions will be reduced compared to diesel when using LNG (24%), methanol (13%), and LH_2 (100%) they need to be produced in a green fashion if full sustainability of the supply chain (well-to-propeller) needs to be ensured.
- The space limitations require special consideration when selecting alternative fuels in Arctic vessels, and the difference in ship type should be given due consideration before planning recommendations for alternative fuels.
- By applying first principle approaches and calculations, it is possible to recursively eliminate those energy source alternatives which are not feasible and consider design factors in a more holistic fashion.

This study thoroughly analysed the currently most promising energy sources for an Arctic research vessel. Furthermore, a practical, theoretical methodology for comparing energy source options in the concept design phase was presented. This study process and results can constitute a valuable tool in the hands of marine engine practitioners. Future research could employ actual operational data from existing vessels to increase the accuracy of the assessment of the energy sources and implement a thorough techno-economic optimisation of the proposed alternatives.

Author Contributions: Conceptualization, M.P., A.L. (Ajda Lotric), A.L. (Aleksi Laakso), V.B. and M.E.; methodology, M.P., A.L. (Ajda Lotric), A.L. (Aleksi Laakso) and V.B.; formal analysis, M.P., A.L. (Ajda Lotric) and A.L. (Aleksi Laakso); writing—original draft preparation, M.P., A.L. (Ajda Lotric) and A.L. (Aleksi Laakso); writing—review and editing, V.B., M.E. and O.A.V.B.; supervision, V.B., M.E. and O.A.V.B.; project administration, O.A.V.B. and V.B.; funding acquisition, O.A.V.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was conducted as part of the GYROSCOPE project, which received funding from the Research Council of Finland under grant number 1353060.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: The authors would like to acknowledge the feedback they received from MAN-Cryo, Reunamo Juuso from Deltamarin and Elisa Mejamäki from the Finnish Meteorological Institute. The opinions expressed herein are solely those of the authors and should not be considered representative of the opinions of the acknowledged individuals, their organizations, or any of the acknowledged organizations.

Conflicts of Interest: Author Mia Elg was employed by the company Deltamarin Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Table A1. Investigated fuels' properties [11,13,61,89–94].

Energy Source	Specific Energy or (Gravimetric) Energy Density at Environmental Conditions (MJ/kg)	Density at Environmental Conditions (kg/m^3)	Volumetric Energy Density at Environmental Conditions (MJ/m^3)
Nuclear	75,000,000–85,000 000	19,000,000–20,000,000	-
Solar	-	-	200–400 (W/m^2)
Battery (electrical)	0.95	800–2000	1.6
Ethanol	26.8	793	21,252
Dimethyl ether	28.3	735 (liquid, −25 °C)	20,800
Compressed Natural Gas (CNG)	48.6	225 (at 200 bar)	10,935 (at 200 bar)
Liquified Natural Gas (LNG)	48.6	450 (liquid, −160 °C)	21,870
Liquefied Petroleum Gas (LPG)	46.4–51	530	27,030
Liquid methanol	19.9–22.9	792	18,137
Ammonia (at 10.3 bar, 25 °C)	18.5–18.8	602.8	11,333
MDO/Biodiesel	42.6	820–845	33,000–35,000
Liquid hydrogen (at 1 bar, −253 °C)	120	70.85–71.1	8532

Appendix B

Table A2. Detailed SWOT analysis.

	Strengths	Weaknesses
Technological	MDO employs tested and proven technology with a highly competitive market and developed products, which can comply with the current regulations [95,96]. Well-established fuel standards [97]. **Good and mature engines are in place for LNG [98].** *Hydrogen can be produced in different ways and utilised in different forms/transferred using various energy carriers depending on the requirements [99,100].* *Multiple engines on the market today can process high content of hydrogen [94,101].* Methanol is a versatile chemical with different available applications and an established production chain [64,102]. Methanol is compatible with most marine engines and can be used in DF engines [94,101]. Combustion characteristics of methanol are similar to diesel fuel [15]. IMO has already drafted the IGF code for methanol in addition to updated class rules [102,103]. Several vessels operating on methanol are already in operation, and bunkering is available in some ports in Sweden [19,30,64,104].	Requires extensive optimization and/or the use of additional subsystems in order to comply with the stringiest regulations [105]. **LNG engines are usually difficult to retrofit to other fuels [8,12,33].** **LNG use results in the additional need to handle Boil-off vapours created in tanks due to thermal losses of thermal insulation [106].** *The application of H_2 is still not as mature as other technologies in shipping [102,107].* *Boil-off is very rapid which might reduce the operational range when using LH_2 [108].* *Due to the high air-to-fuel ratio, very strong blowers are required [109].*
Financial considerations	MDO has lower Capex and potentially lower Opex cost than LNG or Hydrogen in some cases [110]. **LNG has low additional operating costs, including spare parts and lubrication oil [12].** **It is widely considered as a cost-effective solution [111].** Low installation costs for methanol systems [102,112]. Methanol engines are most cost-competitive for deep-sea [94,113]. Based on projected fuel prices, the payback period for methanol is lower than that for MDO [110,113].	**Increased Capex costs [8,12,33].** **Additional costs due to crew training might be required for LNG handling [114].** *The LH_2 is significantly more costly than the other fuels and green LH_2 is also very expensive [30,101].* Safety considerations can lead to a higher price for the methanol system [115].

Table A2. *Cont.*

	Strengths	Weaknesses
Environmental considerations	**Low-carbon and particulate matter emissions during the operation with LNG [11,36] render it suitable for transition to more sustainable fuels [11,12].** *H_2 is a zero-emission concept in line with IMO and EU goals [17].* *No black carbon emissions [116].* Methanol does not contain sulphur or nitrogen, which leads to a high reduction in SOx and NO_x emissions [64,94]. Almost no black carbon [116].	MDO has the highest overall (well-to-propeller) CO_2 emissions of the compared fuels [111], also higher NO_x emissions and black carbon emissions than LNG and Hydrogen [11,116]. MDO is a harmful substance to the environment, and cleaning possible oil spills in the Arctic areas is very expensive [8,117]. **Fossil LNG is not low carbon or low greenhouse gas fuel when taking into consideration the whole life cycle of the fuel and methane slips [11,36].** High methane slips can be produced during the production and combustion of LNG [8,33,36]. *Fossil fuels are usually involved in hydrogen production as alternative green production is expensive [30,101].* Methanol contains carbon which leads to CO_2 and GHG emissions [94,102]. The use of methanol increases CO and HC emissions in comparison to other fuels [112]. Fossil-based methanol has one of the highest life cycle emissions [10,15,57,104,118] with carbon emissions comparable to that of LNG [10,12,64,94,118].
Energy density	MDO is the most energy-dense fuel per volume [11] and is thus good for long-range applications. **LNG has a high energy density in comparison to other alternative green fuels [64].** In combination with fuel cells methanol-powered missions longer than 7 days offer better suitability than LH_2 for medium-sized ships [94,113,119].	**The energy density of LNG is lower than that of MDO and HFO [8], which significantly affects the ability to perform longer voyages if storage space is limited.** *H_2 energy content per litre is significantly lower than other fuels [30,101].* *Too large required tank capacity generally [101] and for remote Polar operations specifically [69].* The energy density of methanol is twice as much as that of MDO [15,64].
Reliability Availability, Maintainability, Safety	MDO is a relatively non-flammable fuel to store onboard with well-known risks [8,12]. *Hydrogen is non-toxic [120].* Methanol can be stored in liquid at ambient temperature and pressure [15]. Methanol is biodegradable if it is released into the environment [30,102,121].	Additional safety risks during the storage and bunkering of LNG related to its higher flammability [8,12]. Additional risks due to the LNG low temperature, the fire and explosion risks from potential leakages, and the feeding system components failure risks [79,122]. *Explosivity and highly flammable nature of H_2 [12].* *Very low* temperature for LH_2 storage [9]. H_2 can pass through many materials leading to metal embrittlement [15]. Methanol has a higher explosion range than LNG, HFO and ammonia [64] which requires operational safety modifications in SOLAS and class rules [15]. Methanol is toxic to humans and has corrosive properties [15,104,118]. Methanol requires extensive monitoring systems to limit the occurrence of accidental leakages [121].
Infrastructure requirements	MDO can use the same infrastructure as HFO, which has been the most popular marine fuel for decades and thus the infrastructure is the best among all options in the considered area [123]. **Mature solutions for storing and transferring LNG are in place in the operational area and in general [36].**	**Reduced LNG bunkering infrastructure, especially in the Arctic region compared to MDO [12,41,60,124].** *Lack of infrastructure and wide availability in remote regions [69] for H_2.* The bunkering capability of methanol is still not established well enough and there are limited plans to extend that network in Northern Europe [12,63,104,125].
Security of supply	The current production of MDO exceeds the needs of the marine sector and thus the availability is ensured [126]. **Increased global LNG availability [12,60].**	

Table A2. *Cont.*

	Strengths	Weaknesses
Suitability for cold weather	Good cold weather performance [8].	*Using hydrogen in the Arctic constitutes a novel concept in extreme environments [101].*
Reputational aspects	*First-mover advantage in the use of hydrogen (funding, media exposure...) also for other sectors [102].* A high percentage of ship owners are still insecure about adopting methanol as marine fuel [127] so using can be a reputational asset.	Use of MDO might result in negative public image in terms of environmental impact, due to comparatively high emissions and risk of spills in a vulnerable Arctic environment.
	Opportunities	**Threats**
Financial	Significantly lower Capex costs anticipated at least until the year 2040 [110]. The cost of crude oil is not expected to increase dramatically from 2030 to 2040 [110] and thus the costs of operating with MDO will not increase significantly during ship life cycle. **Lower emission-related fees, such as carbon tax if LNG is used [128].**	If a carbon tax is introduced for the maritime industry, the feasibility of MDO decreases most of the assessed fuel options as it has the largest GHG emissions compared to LNG and Hydrogen [128]. **High and uncertain fuel prices. The price of LNG is historically tied to crude oil prices [9,32].** **Russian natural gas is at risk of increasing sanctions. (Russia accounted for more than 40% of Europe's gas imports) [129].** **Regulations considering overall GHG emissions and methane slip of the LNG can limit the capability to keep up with the IMO regulations in the future [8].** *Prices of green hydrogen stay high due to emerging alternative technologies [101].* *Policies have to be developed in time to be able to utilize hydrogen in marine operations [69].*
Environmental	If MDO is employed, the power plant will be compatible with more sustainable and low-emission forms of diesel (e.g., biodiesel), which have low life cycle GHG emissions (well-to-propeller) if produced sustainably, and can exploit the same infrastructure as MDO [130]. **Potential use of bio and synthetic LNG [11].** **LNG can be compatible with hydrogen for reducing emissions [131–133].** *Cleaner environment with minimal/zero emissions (when using hydrogen) [30,47].* Enables "green transition" in the shipping industry per IMO requirements for GHG emissions [134] when using green methanol or carbon capture [10,64].	
Technological and infrastructure	Possibility to future-proof or retrofit with a dual-fuel (DF) engine, which can run on both MDO and LNG, MDO and methanol, or MDO and hydrogen and compensate some of the drawbacks of each fuel [10,103,104,112,130,135]. **Increased interest in LNG for new-build ships, which leads to increased maturity and development [12,36].** **Further development and increase in bunkering infrastructure and capacity for LNG [36,60].** *Increasing demand for decarbonisation of marine transportation calls for product innovation, i.e., clearly differentiated product and value proposition [94,107].* *Potentially high-efficiency combustion process in hydrogen fuel cells [108].* A high percentage of hydrogen can be found in methanol, so it can be used as a hydrogen carrier [64,103,104,118,120]. Current bunkering infrastructure requires minor modifications to handle methanol [15,19]. For internal combustion engines, alcohol fuels are the most promising alternative fuels [117].	Limited availability of diesel engine subsystems, such as efficient carbon capture systems, might result in incompliant MDO engines [8] if a carbon tax is applied.

Normal text = MDO; **bold text = LNG**; *italic = hydrogen*; underline = methanol.

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