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Environmental Life-Cycle Assessment of Eco-Friendly Alternative Ship Fuels (MGO, LNG, and Hydrogen) for 170 GT Nearshore Ferry

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Abstract: With increasing concerns about environmental pollution, the shipping industry has been considering various fuels as alternative power sources. This paper presents a study of the holistic environmental impacts of eco-friendly alternative ship fuels of marine gas oil (MGO), liquefied natural gas (LNG), and hydrogen across each of their life cycles, from their production to the operation of the ship. The environmental impacts of the fuels were estimated by life-cycle assessment (LCA) analysis in the categories of well-to-tank, tank-to-wake, and well-to-wake phases. The LCA analysis was targeted for a 170 gross tonnage (GT) nearshore ferry operating in the ROK, which was conceptually designed in the study to be equipped with the hydrogen fuel cell propulsion system. The environmental impact performance was presented with comparisons for the terms of global warming potential (GWP), acidification potential (AP), photochemical ozone creation potential (POCP), eutrophication potential (EP), and particulate matter (PM). The results showed that the hydrogen showed the highest GWP level during its life cycle due to the large amount of emissions in the hydrogen generation process through the steam methane reforming (SMR) method. The paper concludes with suggestions of an alternative fuel for the nearshore ferry and its production method based on the results of the study.

Keywords: life-cycle assessment; alternative ship fuel; marine gas oil; liquefied natural gas; hydrogen; global warming potential

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1. Introduction

As concerns about global climate change increase due to the enormous amount of environmental pollution from industrial sources, the maritime industry also faces more stringent control requirements on the emissions from seagoing commercial vessels. To reduce the amount of pollution in the shipping industry, the IMO established regulations that limit the emissions of NOx to 3.4 g/kWh for ships operating under 130 rpm in an ECA beginning in January 2016 [1]. The IMO's regulation also reduced limit on the emissions of SOx from 3.5% to 0.5% beginning in January 2020 [2]. The IMO continues to regulate the emissions from ships, especially the emissions of GHG through the 72nd to reduce the total emissions of GHG emissions by 50% compared with 2008 by 2050 [3].

Recently, the Korean government also established comprehensive plans to regulate the exhaust gases from ships by requiring the use of alternative, eco-friendly marine fuels. When the Korean government enacted a law that promoted the development of eco-friendly ships in 2018 [4], the Government presented a mid- to long-term strategy on the development and distribution of eco-friendly ships, referred to as the 'Strategy for 2030 Greenship-K', as a part of the implementation plan for making Korea carbon-neutral [5]. The key contents in the strategy are listed below.

- Technology development for future eco-friendly ships to achieve up to 70% reduction of their GHG emissions by 2030,
- Actual proof project of the eco-friendly ship propulsion technology for small-size ships operating in nearshore areas,
- Conversion of all government-owned ships into environmentally friendly ships by 2030 (2030 Eco-Friendly Vessel Conversion Plan),
- Establishment of alternative fuel supply chain and the required infrastructure.

To address the international and domestic regulations on the exhaust gases from ships, various fuels have been considered as alternative power sources. The representative alternative eco-friendly fuels are MGO, LNG, and hydrogen. To reduce the SOx from the combustion of fuel, MGO has been used extensively as one of the alternative fuels, because it is treated to reduce its sulfur content from about 5% to about 0.5%. MGO can also be used as fuel for ships without replacing their diesel engines. Even so, additional equipment is required when MGO is used, such as SCR equipment, in order to meet the IMO's NOx regulation. In recent years, LNG has been considered as one of the best alternative fuels for ships because it can achieve the requirements of the SOx and NOx regulations. The number of vessels that use LNG has been increasing gradually. Currently, more than 200 ships are using LNG [6], and more than 150 ships are ready to have the LNG propulsion system installed.

For zero-emission ships, global interests are now focused on the use of hydrogen as the ultimate alternative fuel. Furthermore, the Korean government has been trying to enter the race toward the hydrogen future, and, in 2019, the government established a 'roadmap for activation of the hydrogen economy' [7]. The aim of the roadmap is to develop key hydrogen propulsion technologies for ships that can be commercialized by 2030. Ships that use hydrogen for propulsion must be equipped with tanks to store the hydrogen fuel, and they must have fuel cells that can use hydrogen to generate the electrical power required for the propulsion system. There are many types of hydrogen fuel cells based on the electrolytes they use and their operating temperatures, two of which are (1) the PEMFC and (2) the SOFC. However, most of the fuel cells have limitations on their power capacity, volume, and weight that likely preclude their direct use as the propulsion mechanism for ships.

The alternative eco-friendly fuels for ships, i.e., MGO, LNG, and hydrogen, would be a practical way to proportionally satisfy the IMO's regulation for ship emissions, as well as a countermeasure for the Korean government's roadmap with the advancement of their application technology. However, the fuels might not be eco-friendly in the view of their life cycle, from the production of the fuel to the process of operating ships. To determine the environmental impacts, the fuels must be investigated for their holistic life cycle, including the emissions associated with their production, transportation, and other activities that make them available for use by ships as a viable fuel.

Recently, with the increasing interest in the environmental impacts over the entire life cycle of fuels, the concept of the LCA has been extensively used by various researchers. Guinée [8] presented a guideline of LCA analysis based on the ISO, and it has been used extensively with some interesting developments in various industrial studies [9–12].

Numerous studies have been performed that focused on the environmental impact of alternative fuels for ships. Bengtsson et al. [13] assessed and compared the environmental performances of various marine fuels, i.e., HFO, MGO, and LNG. The study showed that LNG could not reduce the GWP compared to the other fuels. Jeong [14] investigated the environmental impacts of alternative fuels for ships and methods of HFO with scrubber, MGO, and LNG for a bulk carrier operation and presented the results in various environmental categories of GWP, AP, EP, and POCP. Sharafian et al. [15] conducted an LCA analysis for HFO and LNG as ship fuels, and they indicated that the use of LNG would result in higher levels of GHG emissions than HFO in the case of small, high-speed ships due to its methane slip phenomenon. Hwang et al. [16] estimated the environmental impacts of an LNG-fueled ship operating in the ROK, and they expanded their work by making comparisons with MGO and hydrogen [17]. The studies also indicated that LNG might not be better than MGO from the standpoint of the emission of GHG due to the methane slip, and they suggested that renewable energy or water-splitting methods be used to generate the hydrogen fuel because a large amount of GHG can be emitted in the production of hydrogen using the SMR process. Similar results were also found by Perčić et al. [18] who studied the environmental and economic aspects in the life cycle of a ship equipped with fuel cells varying the origin of fuels as gray, blue and green. The study revealed that green hydrogen and ammonia could reduce about 84% of the emissions in CO_2 equivalent than the emissions from the diesel-powered ship. Moreover, some studies were performed for the environmental impacts of the inland shipping, which might have a significant effect on the air pollution onshore [19–22]. In recent studies, alternative ship fuels were investigated in consideration with their LCCA for a more reasonable determination of future marine fuels [23,24].

The literature sources mentioned above presented numerous environmental effects of using marine fuels, including HFO, MGO, LNG, and hydrogen, for the operation of ships. However, it was revealed that there is a lack of studies on the use of hydrogen by ships, and the details of its holistic life cycle are needed, from the production of the fuel to its usage. In particular, the previous LCA study on the use of hydrogen by ships [24] did not reflect the limitations in the application of the hydrogen fuel on ships accurately, such as the required volume for hydrogen storage and the weight of the fuel cells and associated equipment. This is due to the fact that a hydrogen-fueled ship has yet to be operated in the coastal area of ROK, while there are several ships in the world that are operating using the hydrogen produced by hydrogen fuel cells [25]. Ships that are to be fueled by hydrogen must have a unique design that takes into consideration the operating conditions, including the purpose of the operation, the area, the route, the speed, and other information; therefore, the specifications of the ship should be varied for the different operating conditions.

In this study, the environmental impact of eco-friendly, alternative fuels for ships were assessed using the LCA analysis method. The study was conducted for a nearshore ship operating in the ROK that was designed so that it could be equipped with a hydrogen propulsion system. MGO (ship operation with SCR), LNG, and hydrogen were considered as the alternative fuels for the ship, and the comparisons of the environmental effects in their life cycles are presented in the paper. The LCA model was set through GaBi software [26], which provides an extensive database of emission factors for various processes based on the ISO standards [27]. The emissions of the fuels during the life cycle were estimated, and the environmental performance was discussed in five impact categories of GWP, i.e., GHGs, AP, POCP, EP, and PM.

2. LCA Methodologies

2.1. LCA Scope and Procedure

The LCA is a method that can be used to analyze the environmental impacts of a product after considering all stages of in the life cycle of the product. The LCA can provide the analysis of the environmental impact for the holistic life cycle of a product, ranging from the production of the raw material, through manufacturing, use, and final disposal, as shown in Figure 1.

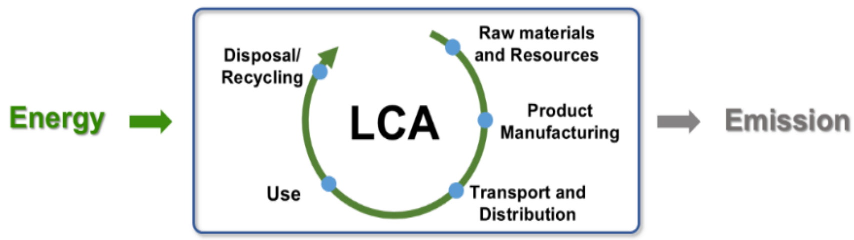

Figure 1. General concepts of the LCA procedure [27].

In this study, the LCA was performed following the workflow format suggested by the ISO 14040 standards [27]. Figure 2 shows the framework of the life-cycle assessment used in the study, and the procedure is explained below.

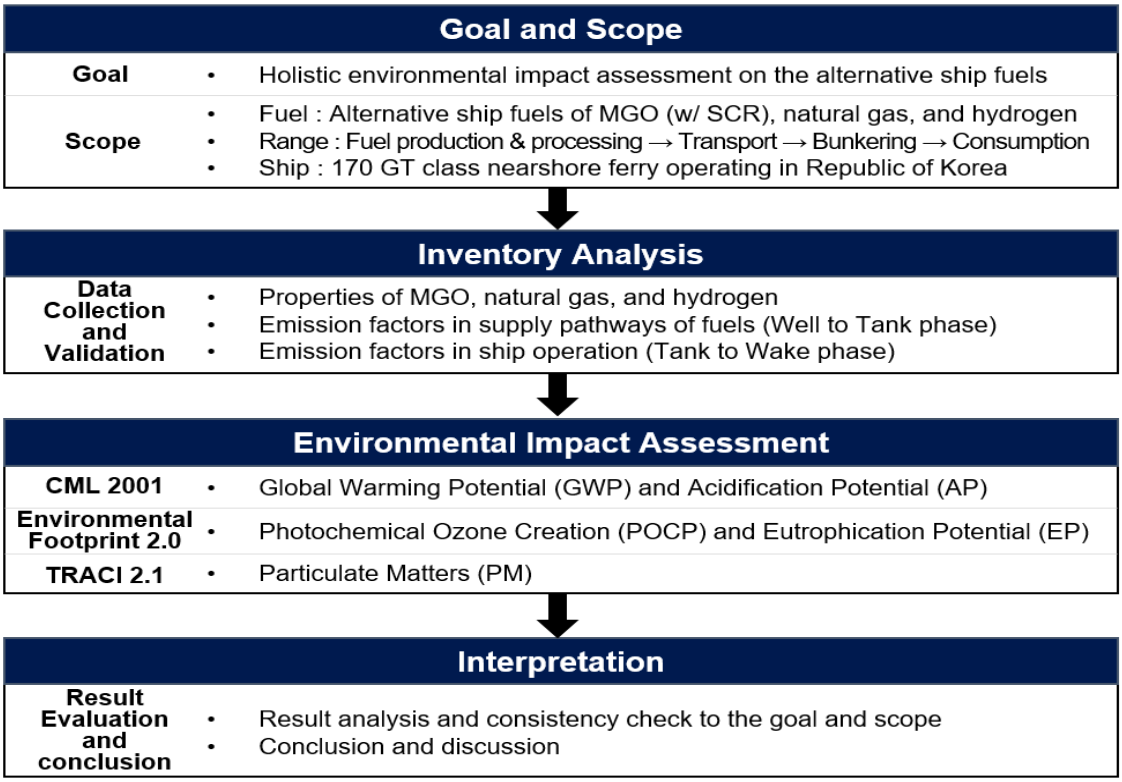

Figure 2. Framework of the life-cycle assessment for alternative fuels for ships.

- Goal and scope: This stage defines why the research was performed and the issues to be discussed with the readers.
- Inventory analysis: This stage includes the collection of data about the emission factors and properties to be used to quantify relevant inputs and outputs of a system.
- Impact assessment: In this stage, potential environmental impacts are assessed using the data collected in the previous step.
- Interpretation: In this stage, the results of the impact assessment are analyzed and summarized.

In the study, the goal of the LCA analysis was a holistic assessment of the environmental impacts of the eco-friendly alternative fuels for ships. The work scope included the LCA analysis for the alternative fuels of MGO (w/SCR), LNG, and hydrogen for a 170 GT nearshore ferry (explained in detail in Section 3.2). The LCA analyses of the ship fuels were categorized into three phases [24]:

- Well-to-tank analysis from fuel production to the fuel tank of a ship, including the transportation of the fuel;
- Tank-to-wake analysis during the operation of the ship;
- Well-to-wake analysis from the production of the fuel to the operation of the ship.

In this study, the environmental impact results were provided in five categories, i.e., GWP, AP, POCP, EP, and PM:

- Global warming potential (GWP): An indicator of the energy absorbed by the emissions of 1 kg of exhausted gas over a period of time (compared to the emissions of 1 kg of carbon dioxide (CO_2)). The GWP of the greenhouse gases can be obtained using Equation (1).

$$\text{GWP} = \left[\frac{\text{Solar energy absorption of GHGs}}{\text{1 kg of GHGs}} \div \frac{\text{Solar energy absorption of CO}_2}{\text{1 kg of CO}_2}\right]; \quad (1)$$

- Acidification potential (AP): An indicator of the acidification of the soil and rivers due air pollutants;
- Photochemical ozone creation potential (POCP): The degree to which VOCs cause ozone pollution by participating in photochemical reactions in the atmosphere;
- Eutrophication potential (EP): A measure of the phenomenon in which nutrients are oversupplied;
- Particulate matter (PM): The sum of all solid and liquid particles suspended in the atmosphere.

For the GWP and AP, the CML 2001, which is a method that uses the midpoint of outcomes during categorization and standardization [28], was used to evaluate them in terms of kg CO_2 and SO_2 equivalent. Environmental Footprint 2.0 [29] was used for the POCP and EP in terms of kg of NMVOC and kg N equivalent, respectively. TRACI 2.1 [30] was used to evaluate the PM in terms of kg $PM_{2.5}$ equivalent.

The LCA was performed using the LCA software of the GaBi platform [31], which provides an extensive data library including the emissions from the production of fuel, transportation, and the production of electricity. The GaBi software can model all of the stages of the energy flow and emissions in various sub-activities to be appropriate for the purpose and scope of the research.

2.2. Inventory Analysis: Well-to-Tank Phase

Figure 3 shows the inventory analysis range of the LCA for the alternative ship fuels of MGO, LNG, and hydrogen. In the well-to-tank phase, the environmental impact was assessed from the fuel production to a fuel tank in the ship, including processing, purification, transportation, refinery, reforming, and bunkering of each of the fuels.

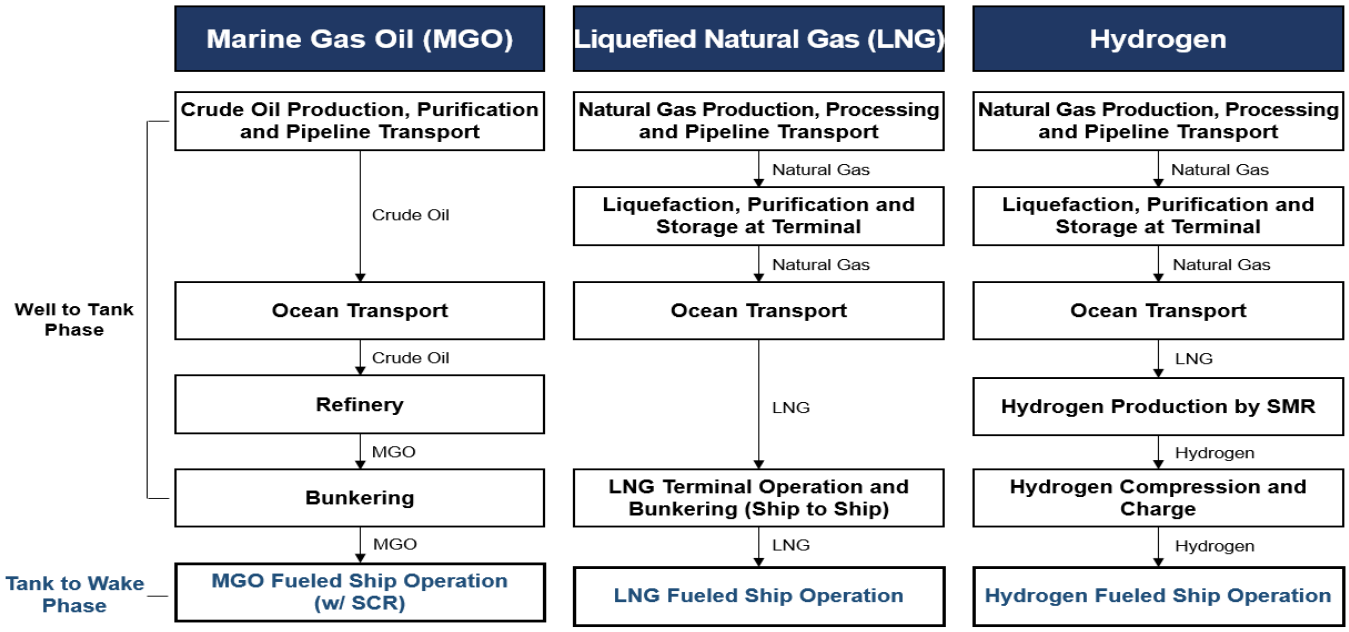

Figure 3. Inventory analysis range of LCA for each of the alternative fuels for ships.

MGO is considered as being produced and then transported via a crude oil carrier (Table 1) from oil-producing countries, i.e., Saudi Arabia, Kuwait, Iran, and others, taking into account the portion of crude oil import in ROK [31], which is shown in Figure 4a. The imported crude oil is converted to MGO in ROK through the refinery process, which was modeled as shown in Figure 5, considering the electric and steam energy input of 100.7 kJ and 649 kJ for 1 kg of MGO, respectively [32]. The amount of the input energy in the refinery process is determined as the allocated energy for the MGO on the basis of the energy fraction of all products from the process. After the refinery, the diesel fuel is transferred to a ship by an electric oil pump [20] for the ship operation in the tank-to-wake phase.

Table 1. Specifications of crude oil and LNG carrier in the well-to-tank phase [33].

	Crude Oil Carrier	LNG Carrier
Type of Engine	SS diesel engine	2-stroke Otto-cycle X-DF (with methane slip of 2.5 g CH_4/kWh)
Engine capacity (kW)	12,330	27,300
Design speed (knots)	15.2	19.5
Cargo capacity (m^3)	57,741	147,237
Type of fuel	MGO	LNG

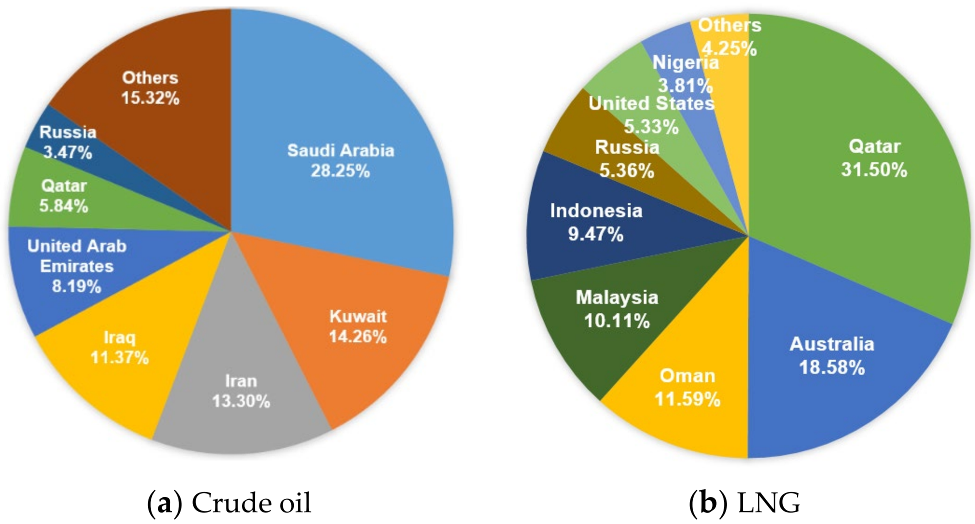

Figure 4. (**a**) Import portion of crude oil; (**b**) LNG in the Republic of Korea [31].

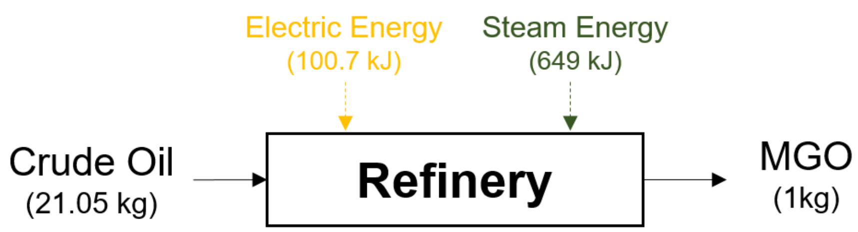

Figure 5. Modeling of the refinery process for the MGO in well-to-tank phase.

Natural gas is produced and processed in LNG-producing countries, i.e., Qatar, Australia, Oman, and others, in consideration of the proportion of the LNG import of ROK, as shown in Figure 4b. The processing step is to remove the undesired components, e.g., CO_2, water, and H_2S, at the extraction site before being transported to the LNG terminal. After being transported, the natural gas is liquefied in the terminal after the purification process, which includes the removal of acid gas, dehydration of the gas, the removal of mercury, and the recovery of the LPG in the natural gas [31]. The LNG is moved to Yeosu in ROK by an LNG carrier that is equipped with the X-DF engine, as shown in Table 1, and it is bunkered to a ship through the LNG bunkering process as modeled in Figure 6, considering the electric energy input (4.46 kJ for 1 kg of LNG) and the loss of methane during the bunkering process [31].

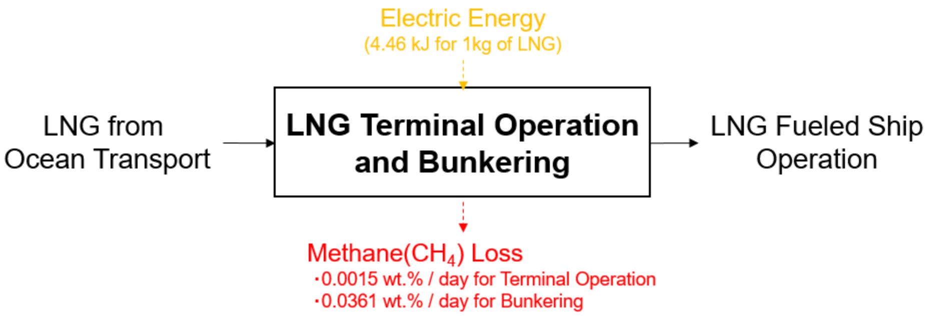

Figure 6. The LNG bunkering process for LNG in well-to-tank phase.

Hydrogen is produced from the LNG that is transported to the ROK via the SMR process, which is the most widely used process in industry for the production of hydrogen from natural gas, so-called gray hydrogen [34]. The SMR process was modeled as shown in Figure 7, with consideration of the 1.14 MJ of electric energy and 9.59 kg of DI water input for the generation of 1 kg of hydrogen [35]. The hydrogen is charged to the hydrogen tank in a ship with the compression of 700 bar, and the electricity consumption (11.52 MJ for 1 kg of hydrogen) is considered for the operation of the compression pump [36].

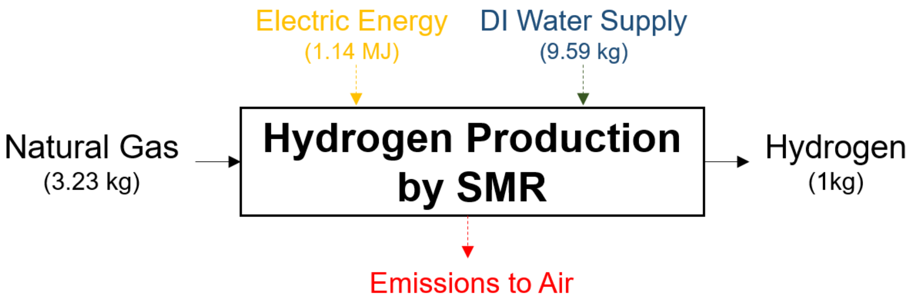

Figure 7. SMR process modeling for hydrogen in the well-to-tank phase.

In the well-to-tank phase, the subsidiary facilities, e.g., the terminals, the pipelines, the refinery plants, and the crude oil and LNG carriers, were assumed as already in use, and the emissions from their construction and decommissioning were not included in the study because the amounts of their emissions are too small to be considered in the life cycle [31].

In the ROK, electric energy is generated from various energy sources [31], as shown in Figure 8. The emissions from the production of electricity are considered for the each life cycle of the power sources, including the raw material production, import, distribution loss, infrastructure, and operation of the power plant.

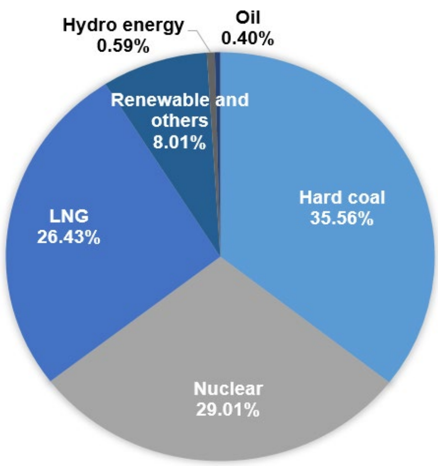

Figure 8. Energy source fractions of electricity in the Republic of Korea [31].

The emissions during the ocean transportation of each of the fuels were obtained by combining the sum of the exhausted gases from the operation of the carrier ships and the emissions from the life cycles of each of the fuels. The emissions during the LNG and crude oil carrier operation were estimated by the fuel consumption from the total energy used in the operation of the ship using Equations (2) and (3).

$$B_{fuel} = \frac{E_{tot}}{\eta \times H_L}, \tag{2}$$

$$E_{tot} = \int P_S(t)dt, \tag{3}$$

where B_{fuel} is the total amount of fuel consumption, η is the total efficiency of the propulsion system, H_L is the lower heating value of the fuel, and E_{tot} is the total energy used in the operation of the ship, which can be estimated by integrating the time history of the motor power (P_S) during the operation time.

2.3. Inventory Analysis: Tank-to-Wake Phase

In this study, the emissions during the tank-to-wake phase were defined as the exhausted gas from the operation of a nearshore ferry, which might have a dominant contribution to air pollution in coastal regions, as well as have an effect on the local policy initiatives as a kind of 'regulatory acupuncture' [37]. The nearshore ferry was conceptually designed in the study considering a hydrogen fuel cell system as a propulsion power source to be operated in the ROK. The requirements in the initial stage of the ship are listed below.

- Size of the ship: The length of the ship (L_{OA}) must be greater than 30 m to retain sufficient area for being equipped with the hydrogen tank and other equipment;
- Type and capacity of the ship: nearshore ferry, capable of transporting more than 130 people;
- Speed of the ship: 15 knots (77% of nearshore ferries in ROK, a total of 166 ships, operate at around 15 knots [38]);
- Gross tonnage: larger than 100 GT (70% of nearshore ferries in ROK are in the range of 100–500 GT [38]);
- Distance of the sea route: 100 nautical miles with two round trips per day (obtained as an average sea route distance of 100~200 GT ships in the ROK (KSA, 2019)).

The design of the concept was performed following the procedure shown in Figure 9 with iterating calculations to satisfy the initial requirements; the final principal dimensions of the ship are shown in Table 2.

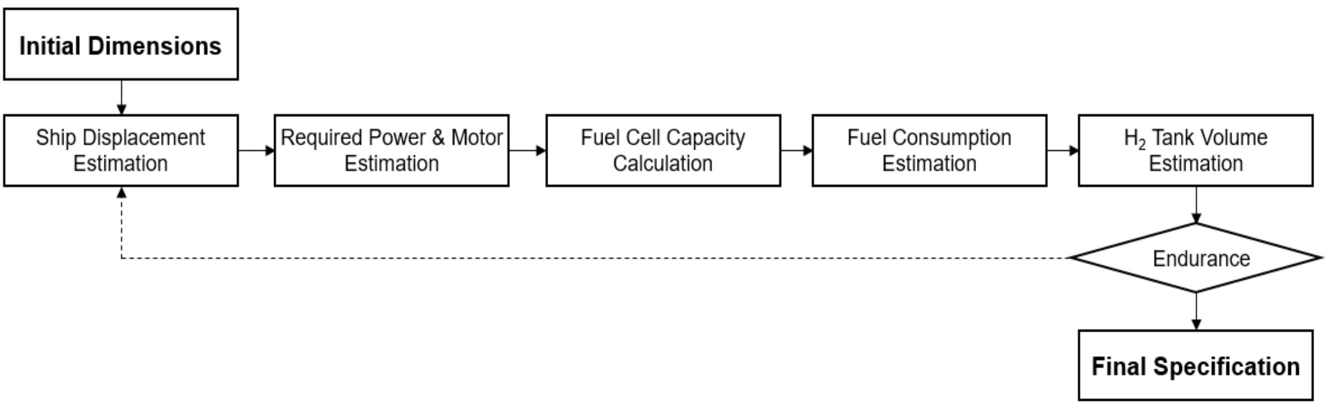

Figure 9. Concept design procedure of nearshore ferry with hydrogen fuel cell propulsion.

Table 2. Principal dimensions of the nearshore ferry with hydrogen fuel cell propulsion.

	Specific Dimensions	Remarks
$L(L_{OA}) \times B \times D$	33.0 m × 7.0 m × 3.3 m	Mono hull, aluminum
Gross tonnage	170 GT	
Passenger capacity	135	
Fuel cell	1200 kW (PEMFC)	10% margin for MCR, 25% for NCR
Propulsion motor	MCR: 1080 kW (540 kW × 2) NCR: 900 kW (450 kW × 2)	17% Margin
Speed	Maximum: 16.0 knots at MCR Operating: 15.0 knots at NCR	w/o for maximum, 10% for operation
Endurance	100 N. Miles at 15 knots	at NCR
Fuel storage	Total 525 kg	500 L H2 tank under 700 bar × 25 EA
Converter	DC-DC, DC-AC, 380 V	
Battery	120 kWh	In port

The final dimensions of the nearshore ferry had a gross tonnage of 170 GT with an overall length (L_{OA}) of 33 m, as well as the ability to transport 135 passengers. The ship could be operated at 15 knots and 16 knots at maximum with the propulsion motor with its MCR and NCR of 1080 kW and 900 kW, respectively. The capacity of the fuel cell and battery was determined as 1200 kW and 120 kWh, in consideration of the results of the electric load analysis for the propulsion and miscellaneous loads during the whole ship operation, as shown in Figure 10. The hydrogen storage was considered with the installation of 25 cylindrical hydrogen tanks that can store 500 L of hydrogen under 700 bar, resulting in the potential storage of a total of about 525 kg of hydrogen. The ship was designed to be operated with the operation profile shown in Figure 11; hence, the total energy consumption of the ship could be estimated to be 1.603×10^8 MJ with the ferry operating for a 20 year period of time. The specific trip scenarios and the estimated amount of energy consumption of the ferry are shown in Table 3.

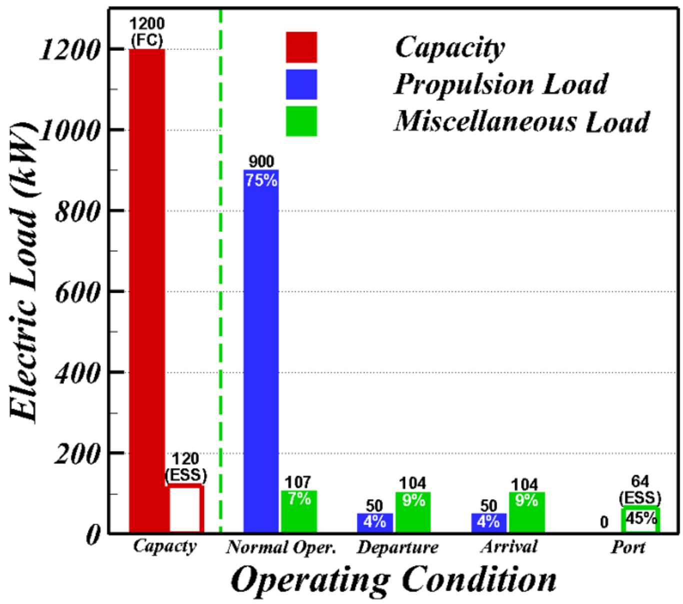

Figure 10. Results of the electric load analysis during the ship operation.

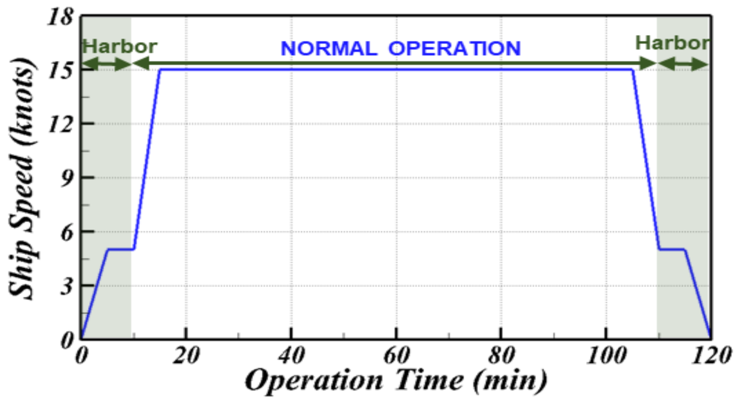

Figure 11. Operation profile of the 170 GT nearshore ferry.

Table 3. Trip scenario of the 170 GT nearshore ferry.

Trip Hour for One-Way Trip (min)	Energy Consumption for Each Round Trip (MJ)	Round Trip Frequency per Day	Lifetime (Years)	Total Energy Consumption (MJ)
120	1.098×10^4	2	20	1.603×10^8

After the determination of the final dimensions of the 170 GT nearshore ferry, the design of the hull line and the general arrangement were conducted in consideration of the installation of fuel cell propulsion system, as shown in Figure 12. The hydrogen tanks were installed on the topside of the ship so that they could be charged or changed easily at a port. The fuel cell room was located behind the main deck and was connected directly to the hydrogen tank and the propulsion motor without a gastight enclosure. In addition to the general arrangement, the basic procedures of the conceptual design of the ship were evaluated, including the design of the H_2 supply system, the design of the electric propulsion and power system, hydrostatic and intact stability analysis, and electric load analysis. The results of the conceptual design of the 170 GT nearshore ferry has received AIP from the Bureau Veritas Marine and Offshore [39].

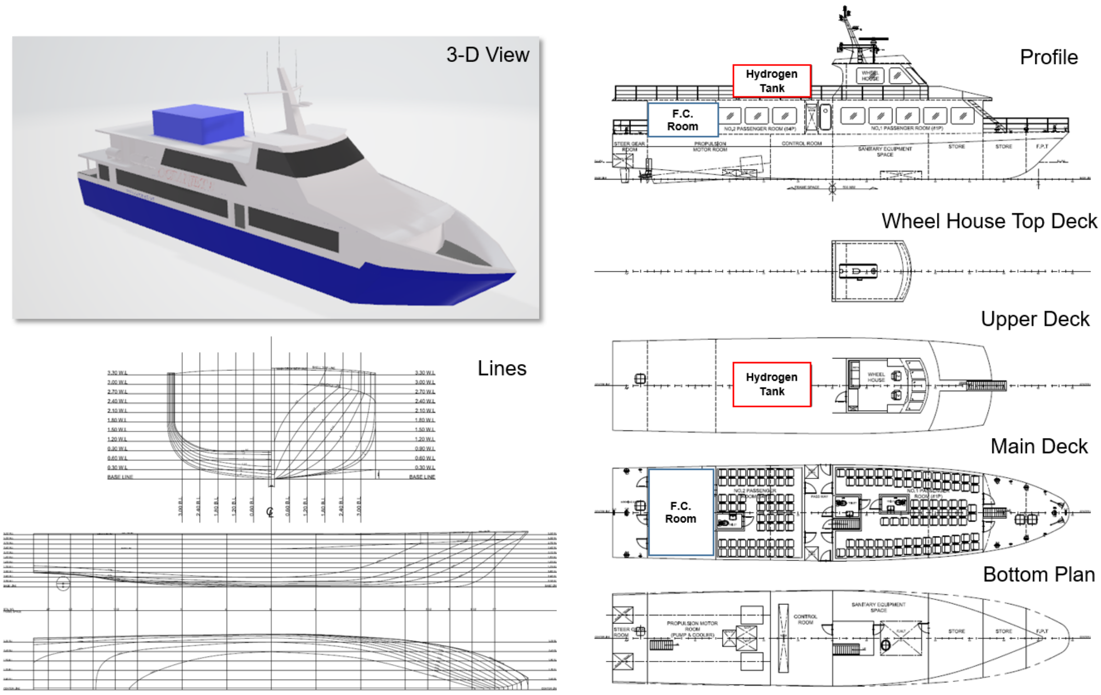

Figure 12. The 3D view, lines, and general arrangement of the 170 GT nearshore ferry.

In this study, it was assumed that the hydrogen fuel cell propulsion system in the nearshore ferry could be replaced with the MGO and LNG generator, keeping the electrical propulsion motor to compare the environmental impact of each of the eco-friendly alternative fuels. The power of each of the propulsion systems was set to be the same as the 1200 kW power capacity of the fuel cell, and the specifics are listed in Table 4. The MGO and the LNG generators were considered as a medium-speed diesel generator and a 4-stroke Otto-cycle X-DF generator, respectively. The total emissions of each propulsion system were obtained using Equations (2) and (3) with the emission factors provided by IMO [40] and NOx emissions from Bengtsson et al. [20]. Furthermore, it was assumed that SCR, which can reduce NOx emissions by as much as 85% [20], was installed with the MGO generator in consideration of the emissions in the life cycle of the generation of urea. Note that the MGO in all figures in this study refer to MGO using SCR.

Table 4. Generator and fuel cell specification in the TANK-TO-WAKE phase.

Type of Fuel	MGO	LNG	Hydrogen
Capacity (kW)		1200	
Type of generator	MS diesel generator (with SCR)	4-stroke Otto-cycle X-DF (with a methane slip of 5.5 g CH_4/kWh)	Fuel cell with electric motor
Efficiency (%)	46	47	53
Lower heating value (MJ/kg)	42.7	49.2	120
Fuel consumption for 1 round trip (g/kWh)	184.7	155.8	56.6
Total fuel consumption (tons)	8.15×10^6	6.97×10^6	2.52×10^6

3. Results and Discussion

This chapter shows the results and discussion of the environmental impact assessment by LCA in the well-to-tank, tank-to-wake, and well-to-wake phases. The results are also provided in a tabular format at Appendix A.

3.1. Environmental Impact Assessment in the Well-to-Tank Phase

Figure 13 compares the GWP emissions from the eco-friendly alternative ship fuels of MGO, LNG, and hydrogen in the well-to-tank phase. The GWP level from the LNG was the smallest among the three fuels, and most of the GWP (about 66%) was emitted during the production of natural gas. The GWP from the MGO showed a level that was about 10% greater than the emissions from the LNG due to its refinery process and the production of urea, which were not included in the well-to-tank phase of the LNG. The GWP emissions from the hydrogen were about eight times greater than those of MGO and LNG. Most of the GWP from the hydrogen (about 71%) was emitted during the process of generating hydrogen by the SMR. The electric power required to compress the hydrogen to 700 bar also contributed a large amount of GWP, i.e., an amount that was larger than the total GWP emissions of the LNG in the well-to-tank phase.

Figure 14 shows the proportion of the GWP sources of each of the alternative fuels in the well-to-tank phase. The main contributors of GHG gases to the increase in the GWP are shown in Table 5. The most dominant GHG gas was carbon dioxide (CO_2), which has the GWP level of 1 as a criterion. The methane (CH_4), nitrous dioxide (N_2O), and chlorofluorocarbons also contributed to the GWP; they had levels that were 28, 265, and 1300 to 23,900 times higher than CO_2, respectively. In the study, most of the GWP in the well-to-tank phase was from CO_2 and CH_4. For the case of MGO and LNG (Figure 14a,b), the GWP level from the CO_2 showed about double the GWP level from the CH_4. The CO_2 showed a larger portion in the GWP in the case of the hydrogen (Figure 14c), because of the SMR process, which emits most of the CO_2 in the well-to-tank phase. This indicates that the large amount of GWP during the production of hydrogen can be reduced by applying the CCUS technique, which is the process of capturing the CO_2 emissions to be recycled for further usage. It is known that the CCUS technique can produce only 6.14% of GWP compared to the SMR [41].

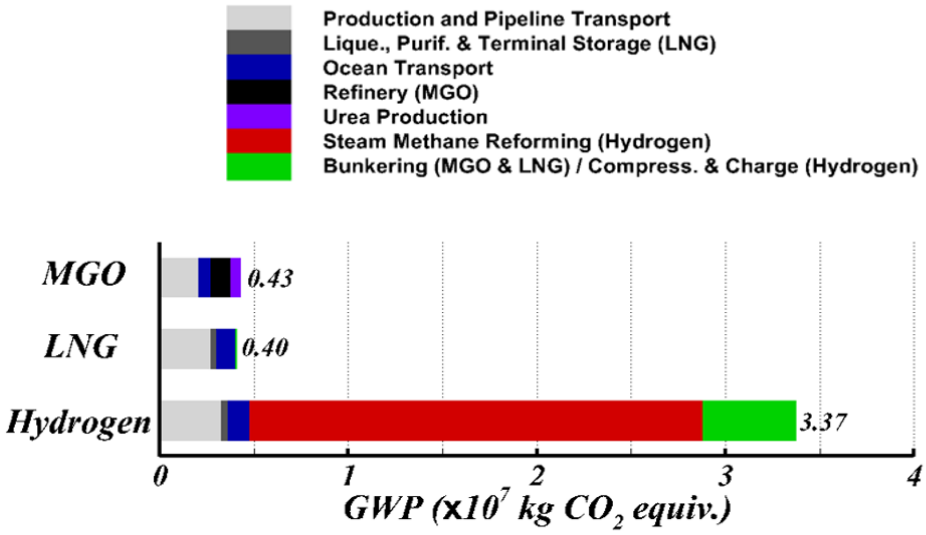

Figure 13. GWP results in the well-to-tank phase.

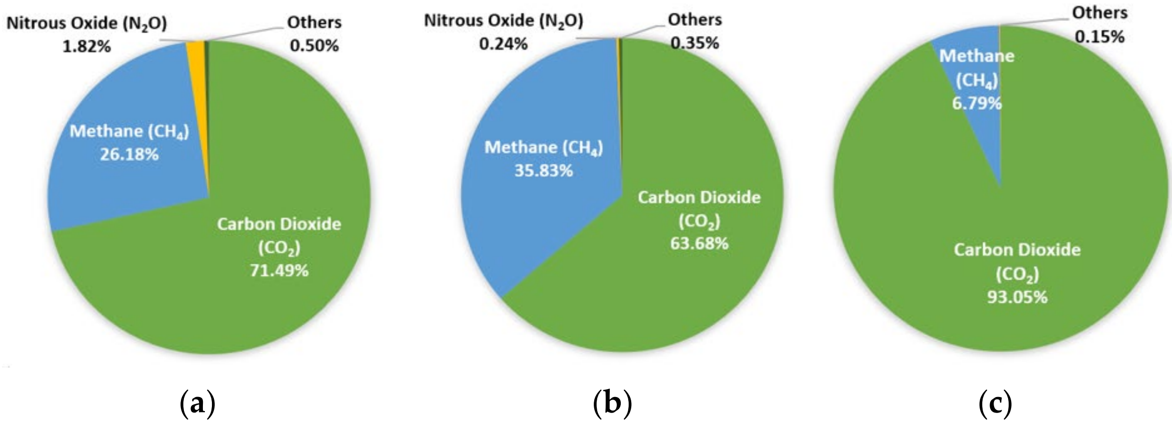

Figure 14. Portion of GWP sources for each of the alternative fuels in the well-to-tank phase ((**a**) MGO, (**b**) LNG, (**c**) Hydrogen).

Table 5. GWP comparison of the main greenhouse gases [28].

	Carbon Dioxide (CO_2)	Methane (CH_4)	Nitrous Oxide (N_2O)	Chlorofluorocarbons (CFCs)
Global warming potential	1	28	265	1300~23,900

The emission levels of AP, EP, POCP, and PM in the well-to-tank phase are shown in Figure 15. The emissions from the hydrogen showed the greatest amount for all categories, except PM which was largest from MGO with double the amount of emissions from the hydrogen. The PM was emitted mainly during the ocean transport of the crude oil. Generally, LNG showed the lowest level for all environmental impact categories except EP, which is the potential to cause over-fertilization of water and soil, resulting in the growth of biomass. The hydrogen produced more than three times as much AP, EP, and POCP compared to MGO and LNG, mostly from the SMR process and hydrogen compression.

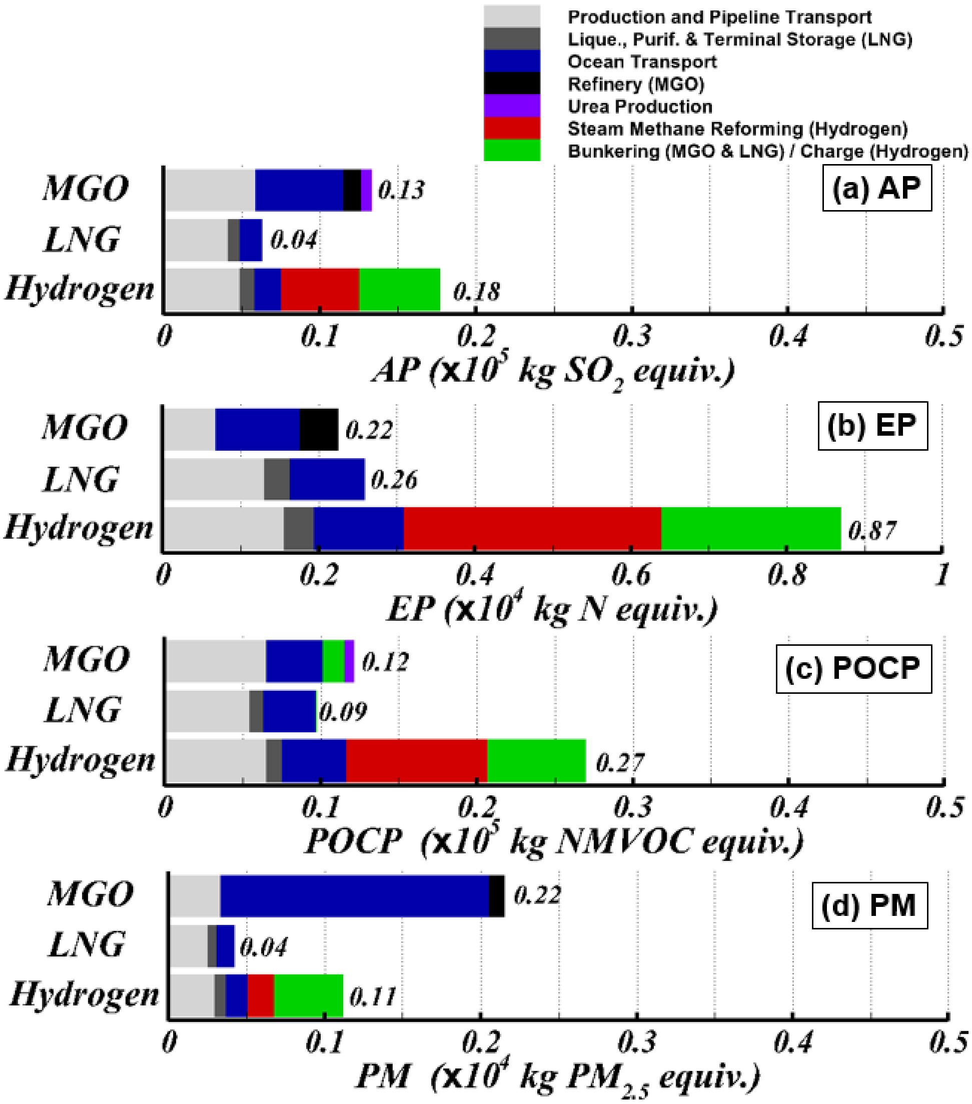

Figure 15. AP, EP, POCP, and PM results in the well-to-tank phase.

3.2. Environmental Impact Assessment in the Tank-to-Wake Phase

Figure 15 shows the amounts of NOx, SOx, and CO_2 emissions in the tank-to-wake phase, denoting the total emissions during the operation of the ship, for each eco-friendly alternative ship fuel (MGO, LNG, and hydrogen) during the ship's 20 year lifetime. The results of the operation of the ship with the fuel of HFO and the MGO without SCR were included in Figure 16 to compare the environmental effect of each of the alternative fuels and methods. For the case of NOx (Figure 16a), it is shown that the SCR remarkably reduced the emissions of NOx, about 85% reduction compared to the emissions from HFO and MGO without installation of the SCR. The MGO also showed a significant reduction in SOx emissions (Figure 16b), because MGO has a lower sulfur content than HFO. The emissions of NOx and SOx were lower from LNG than from MGO, and the SOx emissions were almost zero. In the case of CO_2 (Figure 16c), it was shown that MGO and SCR had no significant effect on the CO_2 emissions during the operation of the ship (CO_2 emissions were increased slightly when SCR was installed due to the use of urea), while LNG showed an emission reduction that was about 25% greater than that of HFO. Hydrogen, which is well known as a zero-emission fuel, did not produce any NOx, SOx, or CO_2 in the tank-to-wake phase because the fuel cell only produced water during the operation of the ship.

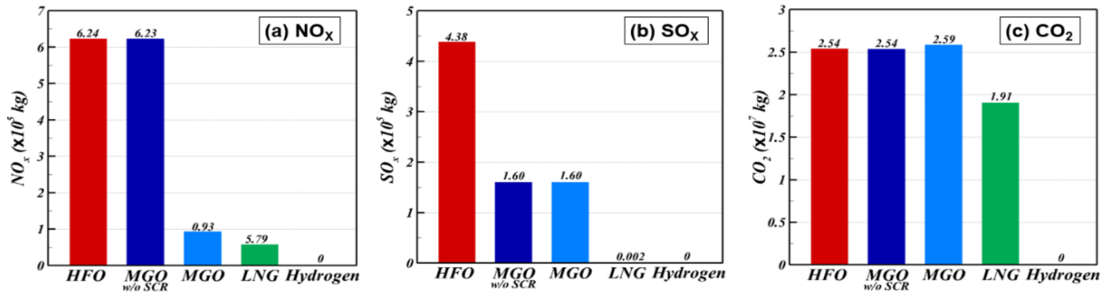

Figure 16. Comparison of NOx, SOx, and CO_2 emissions in the tank-to-wake phase.

The GWP emissions in the tank-to-wake phase are shown in Figure 17. MGO and LNG produced significant amounts of GWP in this phase with an almost similar amount of GWP despite the fact that LNG reduced CO_2 emissions by about 25% more than MGO did (Figure 16c). This is because methane, which was emitted in smaller amounts but has a higher GWP level than CO_2, was exhausted from the LNG-fueled ship during its operation due to the methane slip phenomenon. The GWP was estimated as zero from the hydrogen propulsion because it did not produce any emissions during the operation of the ship.

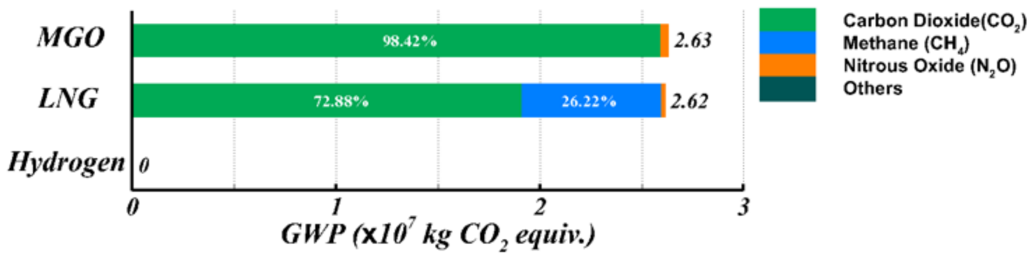

Figure 17. GWP results in the tank-to-wake phase.

Figure 18 shows the environmental impacts of the AP, EP, POCP, and PM in the tank-to-wake phase. The emissions from the MGO showed large levels for all categories, with magnitudes that were 2–8 times higher than the emissions from the LNG. In particular, AP, which is a measure of the decrease in the pH value of soil and rivers, showed an amount that was about eight times larger compared to MGO than the result of LNG. This means that an MGO-fueled ship might have a relatively higher effect on the acidification of soil and water on land than ships using other fuels, because of the ship's operation in the nearshore area. The hydrogen-fueled ship also did not produce any emissions for AP, EP, POCP, and PM in the phase.

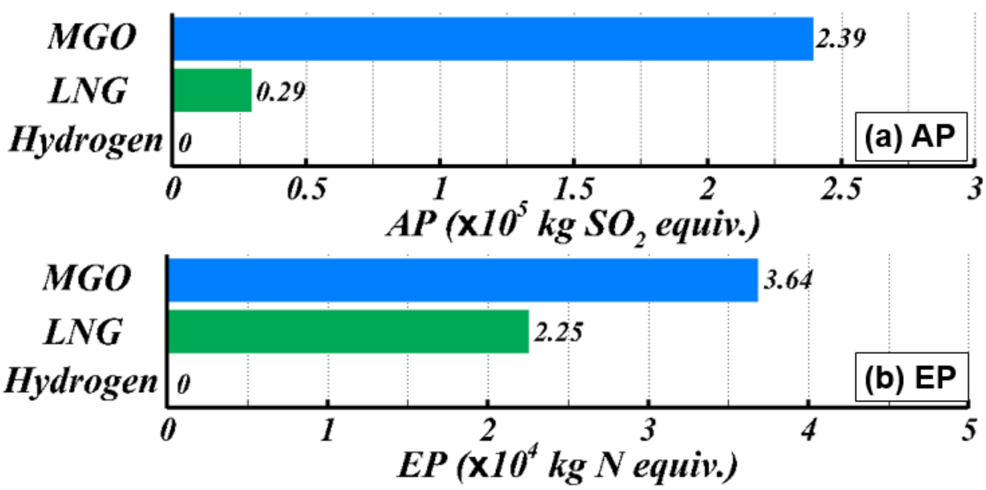

Figure 18. *Cont.*

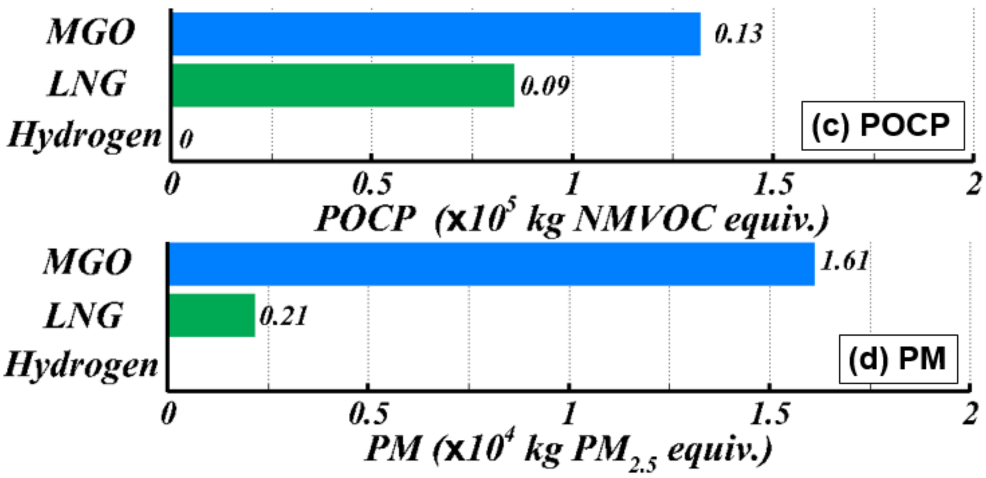

Figure 18. AP, EP, POCP, and PM results in the tank-to-wake phase.

3.3. Environmental Impact Assessment in the Well-to-Wake Phase

Figure 19 compares the GWP emissions of the alternative fuels for ships in the well-to-wake phase, i.e., the total GWP emissions during the life cycle of each of the fuels. The GWP level in the well-to-wake phase could be obtained as sum of the GWP emissions in the well-to-tank phase (Figure 13) and the tank-to-wake (Figure 17) phase. The GWP emissions in the phase showed the lowest level for LNG, but the difference with MGO was less than 1%. The GWP emissions from hydrogen were all from the well-to-tank phase, but showed about a 10% higher amount than the total GWP of the MGO and LNG due to the significantly large amount of emissions during the hydrogen production process by the SMR method.

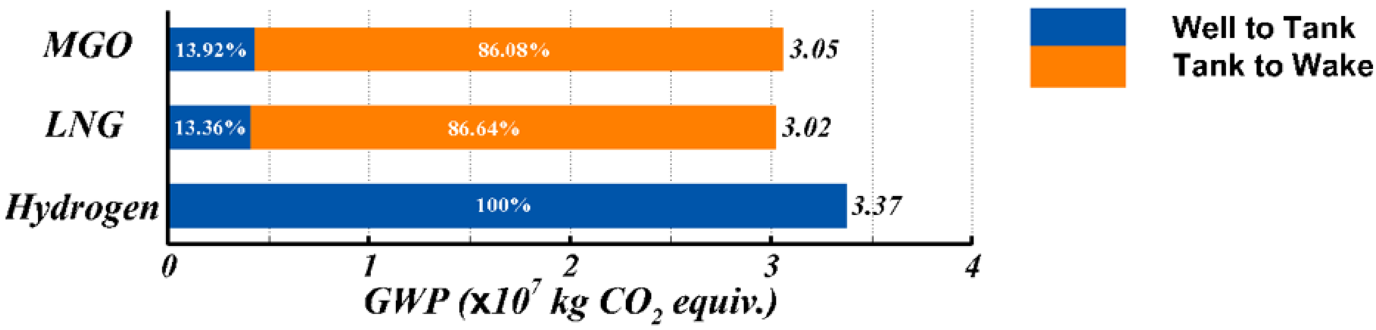

Figure 19. GWP results in the well-to-wake phase.

Figure 20 shows the AP, EP, POCP, and PM emissions in the well-to-wake phase. For all environmental impacts, MGO showed more significant emission levels than LNG and hydrogen, and most emissions from MGO were from the tank-to-wake phase. The LNG and hydrogen fuels could remarkably reduce the emission level compared to MGO. In addition, the emissions of AP, EP, POCP, and PM from LNG even showed higher levels than those from hydrogen over their total life cycle, in contrast with the emissions estimated in the well-to-tank phase. This means that MGO and LNG might not be better alternative fuels than hydrogen in view of the AP, EP, POCP, and PM considering the pollution produced over the total life cycle of each fuel.

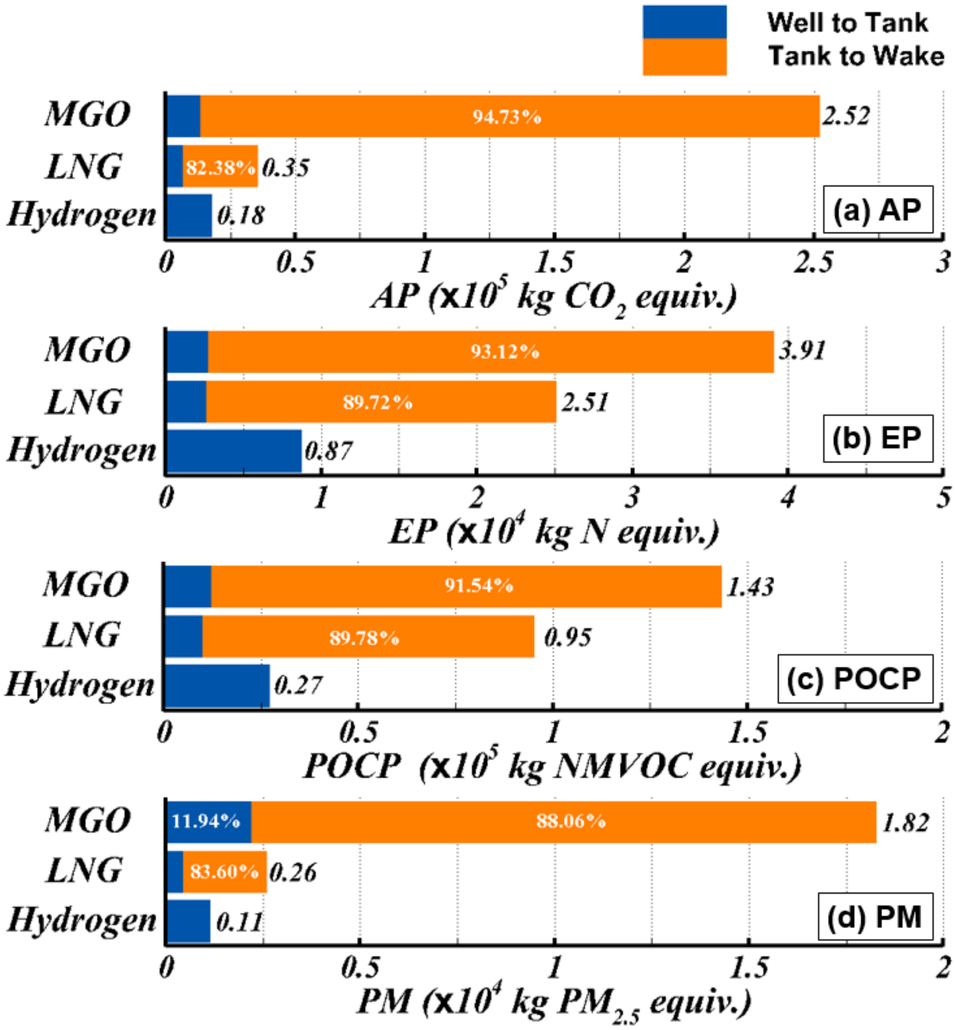

Figure 20. AP, EP, POCP, and PM results in the well-to-wake phase.

4. Conclusions

In this study, the environmental impacts of eco-friendly alternative ship fuels, i.e., MGO, LNG, and hydrogen, were assessed over the life cycle of each of the fuels for a nearshore ferry operating in the ROK. The life cycle was divided into the well-to-tank and the tank-to-wake phases, and the environmental effects were assessed in the categories of GWP, AP, EP, POCP, and PM. The 170 GT nearshore ferry operating in the ROK was considered in the study with its conceptual design to be available to install a hydrogen propulsion system.

The key results of the study are listed below.

- In the well-to-tank phase, hydrogen showed the highest level of GWP among the alternative ship fuels. This is because of the large amount of CO_2 emissions during the hydrogen generation process of the SMR and the electricity consumed in the hydrogen compression process. The hydrogen also showed the largest level of AP, EP, POCP, and PM emissions.
- In the tank-to-wake phase, it was found that MGO and LNG could remarkably reduce the SOx and NOx emissions to levels lower than the emissions of HFO. Furthermore, LNG could reduce the CO_2 emissions, but the GWP level in the phase was similar to the results of MGO due to its methane slip phenomenon during the operation of the ship. The hydrogen fuel did not emit any gases in the phase because the fuel cell only produced water.

- In the well-to-wake phase, as the sum of the well-to-tank phase and tank-to-wake phase, MGO and LNG showed similar GWP emissions, while hydrogen emitted about a 10% higher GWP level than the others. However, hydrogen showed a significantly lower level of emissions for all other environmental categories of AP, EP, POCP, and PM than MGO and LNG, while the maximum level was recorded from MGO in the phase.
- The GWP emissions were shown to be the maximum from hydrogen among the alternative fuels over their life cycles; however, in the other environmental categorizes of AP, EP, POCP, and PM, hydrogen could reduce the amount of emissions to a significantly greater extent than the others. Normally, GWP is taken into account to assess the environmental impacts of the alternative ship fuels considering the greenhouse effect, based on IMO's 2050 GHG regulation. However, other environmental categories, i.e., AP, EP, POCP, and PM, should also be considered in order to acquire an accurate assessment of the environmental impact of the alternative fuels for ships.

Hydrogen is known as a zero-emission fuel for the operation of ships, but it showed a significant amount of GWP emissions in the well-to-tank phase. However, hydrogen seems to be the most suitable alternative fuel for ships in the future when considering the environmental impacts of AP, EP, POCP, and PM. On the basis of the results, it is suggested that the CCS or CCUS methods be used because they can reduce the CO_2 emissions during the production of hydrogen by SMR. Ultimately, for zero-emission hydrogen, it is recommended that green hydrogen be used, which is produced via the water splitting method with a remarkably reduced production of GWP compared to SMR. Moreover, the cost effect of each fuel, i.e., CAPEX and OPEX, also needs to be investigated for the determination of future alternative ship fuels not considered in the study.

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Abbreviations

NOx	Nitrogen oxides
ECA	Emission control area
IMO	International maritime organization
SOx	Sulphur oxides
GHG	Greenhouse gases
MEPC	Marine environment protection committee
MGO	Marine gas oil
LNG	Liquefied natural gas
SCR	Selective catalytic reduction
PEMFC	Proton-exchange membrane fuel cell
SOFC	Solid oxide fuel cell

LCA	Life-cycle assessment
ISO	International Organization for Standardization
HFO	Heavy fuel oil
GWP	Global warming potential
AP	Acidification potential
EP	Eutrophication potential
POCP	Photochemical ozone creation potential
SMR	Steam methane reforming
LCCA	Life-cycle cost assessment
PM	Particulate matter
GT	Gross tonnage
VOCs	Volatile organic compounds
NMVOC	Non-methane volatile organic compounds
TRACI	Tool for the reduction and assessment of chemical and other environmental impacts
DI	Deionized
AIP	Approval in principle
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization, and storage
CAPEX	Capital expenditures
OPEX	Operating expenditure

Appendix A

The results of the environmental impact assessment in the well-to-tank, tank-to-wake, and well-to-wake phases are shown in Tables A1–A3, respectively.

Table A1. Results of the environmental impact assessment in the well-to-tank phase.

	MGO	LNG	Hydrogen
GWP (kg CO_2 equiv.)	4,250,620.10	4,033,280.24	33,706,772.69
AP (kg SO_2 equiv.)	13,283.88	6245.23	17,693.00
EP (kg N equiv.)	2687.37	2579.93	8691.01
POCP (kg NMVOC equiv.)	12,122.20	9712.52	26,980.69
PM (kg $PM_{2.5}$ equiv.)	2178.95	421.60	1116.39

Table A2. Results of the environmental impact assessment in the tank-to-wake phase.

	MGO	LNG	Hydrogen
GWP (kg CO_2 equiv.)	26,280,812.67	26,156,802.07	0
AP (kg SO_2 equiv.)	239,341.28	29,206.76	0
EP (kg N equiv.)	36,816.46	22,517.70	0
POCP (kg NMVOC equiv.)	131,671.37	85,280.95	0
PM (kg $PM_{2.5}$ equiv.)	16,100.50	2148.41	0

Table A3. Results of the environmental impact assessment in the well-to-wake phase.

	MGO	LNG	Hydrogen
GWP (kg CO_2 equiv.)	30,531,432.37	30,190,082.31	33,706,772.69
AP (kg SO_2 equiv.)	251,955.04	35,451.98	17,693.00
EP (kg N equiv.)	39,057.29	25,097.62	8691.01
POCP (kg NMVOC equiv.)	143,152.76	94,993.46	26,980.69
PM (kg $PM_{2.5}$ equiv.)	18,249.31	2570.01	1116.39

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