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Life Cycle Assessment of Alternative Ship Fuels for Coastal Ferry Operating in Republic of Korea

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Abstract: In this study, the environmental impacts of various alternative ship fuels for a coastal ferry were assessed by the life cycle assessment (LCA) analysis. The comparative study was performed with marine gas oil (MGO), natural gas, and hydrogen with various energy sources for a 12,000 gross tonne (GT) coastal ferry operating in the Republic of Korea (ROK). Considering the energy imports of ROK, i.e., MGO from Saudi Arabia and natural gas from Qatar, these countries were chosen to provide the MGO and the natural gas for the LCA. The hydrogen is considered to be produced by steam methane reforming (SMR) from natural gas with hard coal, nuclear energy, renewable energy, and electricity in the ROK model. The lifecycles of the fuels were analyzed in classifications of Well-to-Tank, Tank-to-Wake, and Well-to-Wake phases. The environmental impacts were provided in terms of global warming potential (GWP), acidification potential (AP), photochemical potential (POCP), eutrophication potential (EP), and particulate matter (PM). The results showed that MGO and natural gas cannot be used for ships to meet the International Maritime Organization's (IMO) 2050 GHG regulation. Moreover, it was pointed out that the energy sources in SMR are important contributing factors to emission levels. The paper concludes with suggestions for a hydrogen application plan for ships from small, nearshore ships in order to truly achieve a ship with zero emissions based on the results of this study.

Keywords: life cycle assessment; coastal ferry; marine gas oil; natural gas; hydrogen

1. Introduction

As concerns increase about the potential results of global climate change, the maritime industry has become even more aware of its environmental responsibilities. From a study conducted by the International Maritime Organization (IMO) [1], exhaust gases from ships accounted for the following percentages of the total worldwide transportation-related emissions of the listed pollutants, i.e., 60% of SOx, 40% of NOx, and 15% of CO_2. These percentages reflect the remarkable growth in sea-borne trade, which has increased about three times in the last 30 years.

To mitigate the air pollution from maritime shipping, IMO has developed regulations for the exhaust gases from ships. Beginning in January 2016, IMOs Tier III [2] regulations took effect, limiting the emissions of nitrogen oxides (NOx) to 3.4 g/kWh for ships operating in an emission control area (ECA). For regulations of sulphur oxides (SOx), MARPOL Annex VI Reg. 14 [3], in January 2020, imposed limitations for the sulphur content in the fuels used by ships, i.e., the content had to be reduced to 0.5% in a non-emission control area (NECA) and to 0.1% in an ECA. In addition, the 72nd

maritime environmental protection committee (MEPC) enacted a regulation requiring the reduction of greenhouse gas (GHG) emissions by at least 50% by 2050 compared to 2008 and a 70% reduction of total carbon emissions [4]. Due to these regulations, the shipping industry is facing a serious challenge as it attempts to replace the conventional heavy fuel oil (HFO) with cleaner fuels to meet the IMO regulations.

To meet the SOx emission regulations, marine gas oil (MGO) has been used extensively as an alternative fuel for ships. MGO is one of the marine fuels that is made only from the distillate of conventional diesel oil with a sulphur content of 0.5% or less. MGO can be used with conventional ship engines due to its low viscosity, but the high cost and emissions of NOx and GHG are considered as its major disadvantages of the eco-friendly fuels.

Currently, natural gas is one of the most spotlighted alternative ship fuel which can meet the SOx and NOx regulations from IMO. The number of liquefied natural gas (LNG) fueled ships have been rapidly increased and reached to over 150 ships [5], with an increase of LNG carrier ships. However, LNG-fueled ships are not sufficient to satisfy the GHG regulations by 2050 [6], and it has led interests in hydrogen fuel which produces only water in operation with zero emissions.

To use hydrogen as a fuel for ships, the propulsion systems in ships must be replaced as an electric propulsion system with fuel cell systems which is a power generation device converting chemical energy into electrical energy using hydrogen. Based on their operating temperature and electrolyte, fuel cells are classified into proton-exchange membrane fuel cells (PEMFCs), solid oxide fuel cells (SOFCs), molten carbonate fuel cells (MCFCs), and phosphoric acid fuel cells (PAFCs) [7]. About 30 ships with hydrogen fuel cells are now in operation, and 25 of those ships are equipped with PEMFCs, which have dramatically smaller volumes and weights than the other fuel cells due to their relatively low operating temperature, i.e., 80–100 °C.

Since hydrogen is not a primary fuel such as natural gas and oil, the process of producing hydrogen is one of the major issues for the operators of ships that are powered by hydrogen fuel cells. Based on the production method used to produce hydrogen, it is classified as either gray or green hydrogen. Gray hydrogen is generated using fossil fuels, such as brown coal with burning, natural gas with steam methane reforming (SMR) with CO_2 emissions during the generation procedure. Green hydrogen is generated using nuclear or renewable energy resources, including solar and wind with much less CO_2 emissions. Currently, most of the hydrogen (97%) is generated by SMR from natural gas and other fossil fuels [8]. However, to generate green hydrogen, it is suggested that thermochemical cycles be used to directly split water into hydrogen and oxygen without any emissions [9]. Several cycles have been identified as potential approaches for commercial use, e.g., sulphur-iodine (S-I), copper-chlorine (Cu-Cl), cerium-chlorine (Ce-Cl), iron-chlorine (Fe-Cl), etc. Among them, the focus has been on the Cu-Cl cycle because of its relatively lower temperature requirement, i.e., around 530 °C [9,10]. However, energy also is required to maintain the desired temperature during the water splitting procedure, and the problem of wasted heat remains to be solved. Therefore, for application of the alternative fuels in shipping, assessment of environmental impacts should be conducted that include all of the procedures involved during the life cycle, i.e., from the production of the fuel to the operation of the ship.

The aim of this paper was to analyze the environmental impacts of the ships based on their alternative power sources, i.e., MGO, natural gas, and hydrogen. The analysis was conducted using the life cycle assessment (LCA) of a coastal ferry to provide the assessment of the environmental prospects and potential environmental impacts. The LCA model was established using the Gabi software [11], which provides a database for the assessment of the environmental impact based on the standards of the International Organization for Standardization (ISO) [12]. A 12,000 gross tonne (GT) coastal ferry was used for the LCA analysis with different alternative fuels, i.e., MGO, natural gas, and hydrogen with different hydrogen production methods. In Chapter 2, the purpose and method of performing the LCA analysis are explained, and the environmental impacts associated with the various approaches are presented in Chapter 3, and Chapter 4 presents the conclusions.

2. Materials and Methodologies

2.1. Procedure of Life Cycle Assessment (LCA)

Figure 1 shows the LCA framework performed in this study. The main procedures consist of four steps, 'goal and scope', 'inventory analysis', 'impact assessment', and 'interpretation' based on the workflow format in the ISO standards [12], as shown below:

- Goal and scope: This stage defines why the study was conducted and the arguments to be communicated with target audiences. The scope should be sufficiently defined at this stage to ensure that the details of the study are compatible and sufficient to address the stated goal.
- Inventory analysis: This stage involves the collection of data and the calculation procedures used to quantify relevant inputs and outputs of a product system.
- Impact assessment: The aim of this stage was to assess potential environmental impacts based on the data collected in the inventory analysis stage.
- Interpretation: This stage presents conclusions and recommendations based on the results of the impact assessment.

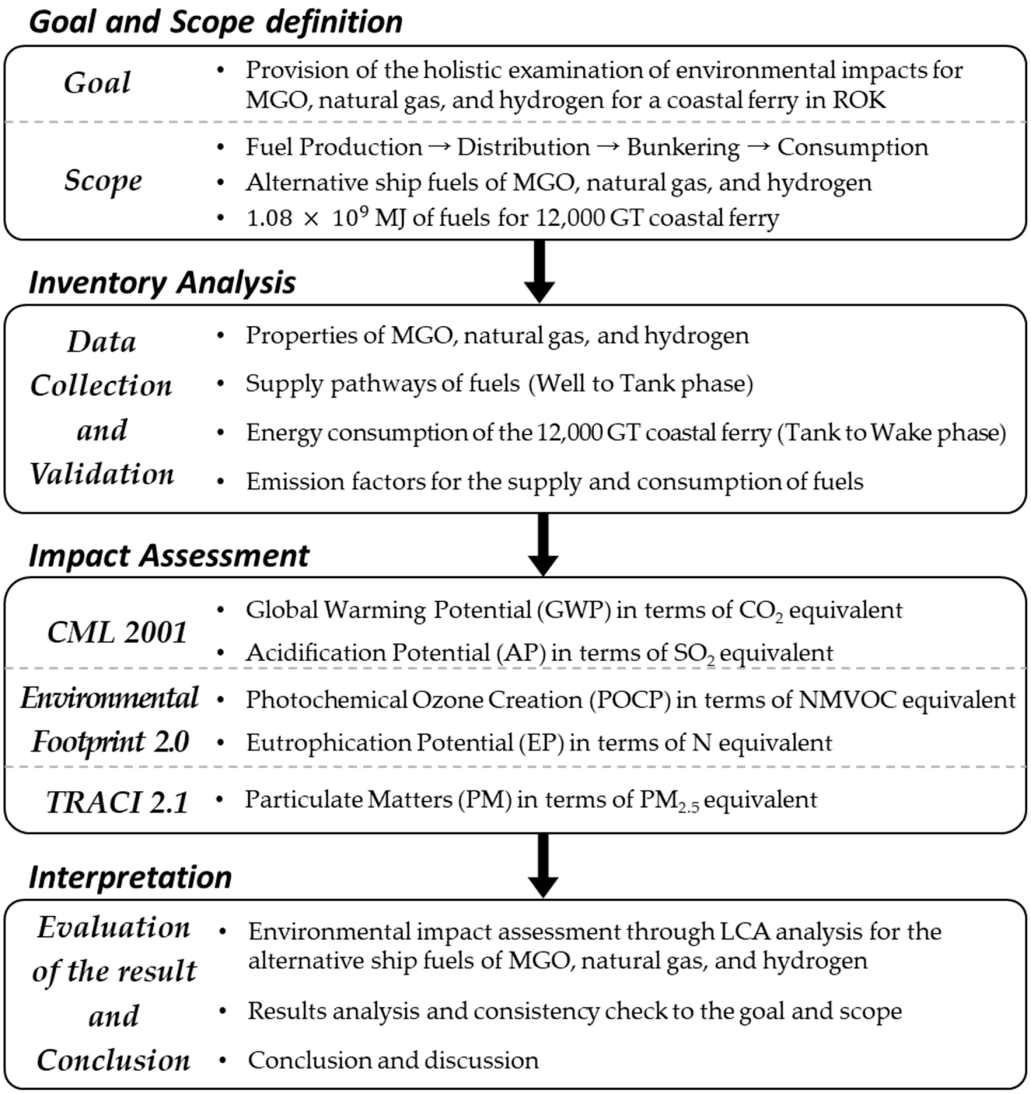

Figure 1. Life cycle assessment framework for various alternative fuels for ships.

In this study, LCA analysis was performed with various fuels for ships, i.e., MGO with a sulphur content of 0.5% (Case 1), natural gas (Case 2), and hydrogen (Case 3). Specific contents and procedures are explained in the next paragraph.

The life cycles of fuels are categorized into three phases (Figure 2), as shown below:

- Well-to-Wake: From a fuel production to fuel consumption to operate ship.
- Well-to-Tank: From a fuel production to a fuel tank of ship.
- Tank-to-Wake: From a fuel tank of ship to fuel consumption to operate ship.

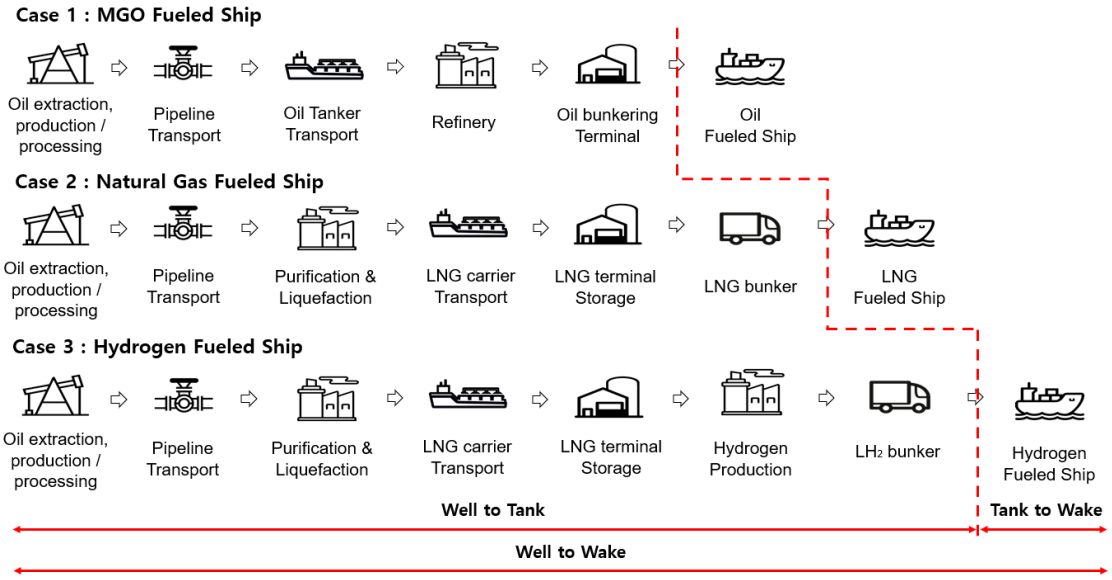

Figure 2. Life cycle of marine gas oil (MGO), natural gas, and hydrogen.

At the Well-to-Tank phase, detailed pathways of the fuels have been established, including the production, distribution, bunkering, and consumption of the fuel [13]. After the production process, MGO is transported by oil tankers on the land to the ship. Natural gas is transported by an LNG carrier after purification and liquefaction, and it is supplied for the ship by the truck-to-ship method [14]. Hydrogen is produced from LNG by SMR, and it is transported by truck as liquefied hydrogen (LH_2). In this study, various energy sources for the production of hydrogen production are considered, including hard coal, nuclear energy, renewable energy, and electricity in the Republic of Korea (ROK). The total fuel cases are listed in Table 1.

Table 1. Cases of alternative fuels for ship in the study.

Case	Case 1	Case 2	Case 3-1	Case 3-2	Case 3-3	Case 3-4
Fuel	MGO	Natural gas	Hydrogen			
Production methods	Import	Import	SMR from LNG			
Electricity source	-	-	Hard coal	Nuclear energy	Renewable energy	Electricity in ROK

The emissions from the production of electricity sourced by hard coal, nuclear, and renewable energy are considered for each life cycle of the sources, including production of the raw material, and the construction, operation, and decomposition of the plant. The electricity in ROK is provided by several energy sources with a ratio [15], as shown in Figure 3.

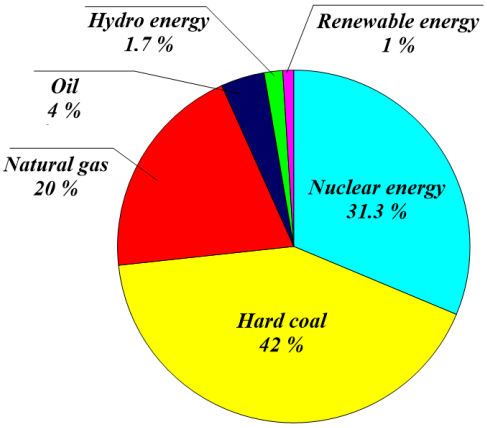

Figure 3. Energy source fractions of electricity in Republic of Korea (ROK).

2.2. Life Cycle Inventory Analysis: Well-to-Tank Phase

Table 2 shows the fuel transport pathways of each of the fuels considered in the Well-to-Tank phase. For the pathway of MGO, the transportation from Saudi Arabia to ROK is considered because the crude oil produced in Saudi Arabia accounts for 29% of the imports of ROK, which is the largest portion of the country's oil imports [16]. The crude oil that is transported to ROK is processed to MGO in the refinery procedure at the Yeosu Oil Terminal, and it is transported to the oil bunkering terminal in Yeosu. The importation route of natural gas also has been determined as the main pathway in the ROK. The natural gas produced in Qatar is liquefied at the Ras Laffan LNG terminal, and is transported to ROK by an LNG carrier, which is considered to use a steam turbine with the boil-off gas with an efficiency of 30%, and the boil-off gas produces 0.15% of the tank capacity per day [17]. The LNG is collected in Tongyeong, where the largest LNG terminal in the ROK is located, and it is transported by trucks to the bunkering port in Yeosu. During the bunkering procedure, the amount of methane loss is considered as 0.0361 weight % [18]. The specifications of the crude oil carrier and the LNG carrier are shown in Table 3. Hydrogen is produced in Ulsan, where the largest petrochemical plant in the ROK is located. The hydrogen is liquefied and returned to Yeosu to be supplied by ships. The ocean transportation routes of MGO and natural gas are described in Figure 4, and the related emissions at the Well-to-Tank phase of each of the fuels are provided in terms of their emission factors in Appendix A. Please note that the buildings and facilities used in the Well-to-Tank stage, such as the terminals, the refinery plants, and the LNG carriers, are assumed as those already in use, and the emissions from construction and decommission of them are not considered in the study.

Table 2. Fuel transport pathways for each of fuels in the Well-to-Tank phase.

Type of Fuel	MGO	Natural Gas	Hydrogen
Origin (country)	Ghawar field (Saudi Arabia)	North Dome gas field (Qatar)	
Terminal 1 (country)	Ras Tanura oil terminal (Saudi Arabia)	Ras Laffan LNG terminal (Qatar)	
Terminal 2 (country)	-	Tongyeong LNG terminal (ROK)	
Terminal 3 (country)	-	-	Ulsan Petrochemical Plant (ROK)
Destination (country)	Yeosu Oil Terminal (ROK)		
Ocean transport distance [19] (km)	11,400	11,350	11,350

Table 3. Specifications of crude oil carrier and liquefied natural gas (LNG) carrier in the Well-to-Tank stage [20].

Ship Type	Engine Type	Engine Capacity (kW)	Design Speed (Knots)	Dead Weight (Tonne)	Fuel Type
Crude oil carrier	Diesel Engine	18,796	16.0	165,000	HFO (2.5% Sulphur)
LNG carrier	Steam turbine—4 stroke Otto cycle	22,600	18.5	60,000	LNG

Figure 4. Ocean transportation routes of MGO and natural gas.

2.3. Life Cycle Inventory Analysis: Tank-to-Wake Phase

In this study, the Tank-to-Wake phase was set for a 12,000 GT coastal ferry operating in the ROK, which is one of the largest coastal ships in ROK, because the coastal ships might have the potential to contribute significantly to air pollution on the land, especially in coastal areas [21]. It is assumed that the ferry travels between Yeosu and Jeju, and the total energy consumption is estimated to be 1.08×10^9 MJ when the ferry provides a daily roundtrip for a 20-year period of time. Table 4 provides the specific trip scenarios of the ferry.

Table 4. Trip scenario of 12,000 gross tonne (GT) coast ferry.

Trip Scenario	
Tonnage (GT)	12,000
Capacity (Persons)	1500 passengers and 140 cars
Trip Hour (min)	5 h and 50
Energy Consumption per Each Round Trip (MJ)	148,050
Trip Frequency (Times/Day)	1
Lifetime (Years)	20
Total Energy Consumption (MJ)	1.08×10^9

Table 5 shows the specifications of the engine and the fuel cell with motor for the ferry at the Tank-to-Wake phase. The power of each propulsion system is set as 4 MW, and the emissions during the consumption of MGO and natural gas as fuel provided the emission factor provided in Appendix B. Note that a methane slip of 5% is considered during the operation of the engine with natural gas.

Table 5. Engine and fuel cell with motor specifications in the Tank-to-Wake stage.

Fuel	MGO	Natural Gas	Hydrogen
Efficiency (%)	46 [20]	47 [20]	53 [22]
Fuel Consumption (g/kWh)	184.7	155.8	56.6
Consumed Fuel (ton)	41,267	35,053	12,745
Total Energy (MJ)		1.08×10^9	
Power Output (MW)		4	
Type	4-stroke medium speed Otto-SI	4-stroke medium speed CI	PEMFC (34×120 kW)

2.4. Life Cycle Impact Assessment

The environmental impacts assessed by LCA can be classified into the five categories shown below:

- Global Warming Potential (GWP): An index measuring a radiative forcing following the emission of a unit mass of a given substance, accumulated over a chosen time horizon, relative to that of the reference substance, carbon dioxide (CO_2) [23].
- Acidification Potential (AP): An index that describes the acidifying effect of substances; their acid formation potential is calculated and compared with a reference substance, i.e., sulphur dioxide (SO_2) [24].
- Photochemical Ozone Creation Potential (POCP): An index that indicates the potential capacity of an organic compound to create ozone in the troposphere. The value for ethene was set as the reference [25].
- Eutrophication Potential (EP): An index for the assessment of the excessive biological activity of organisms due to over-nutrification relative to that of the reference substances of N, P, and C.
- Particulate Matter (PM): PM refers to the secondary fine dust emitted into the atmosphere or produced by photochemical reactions, expressed as a single indicator based on $PM_{2.5}$.

The environmental impact categories were evaluated in the study using three methodologies. CML 2001, which is a method that uses the midpoint of outcomes during categorization and standardization [26], is used to assess the categories for the GWP and AP in terms of kg CO_2 and SO_2 equivalent. For the POCP and EP, Environmental Footprint 2.0 based on the International reference Life Cycle Data System (ILCD) [27] is used for better visualization of results. The method focuses on the green products by taking into account various environmental issues, such as climate change, land use, ecotoxicity, and others, and it provides the results of the analysis of POCP in terms of kg of non-methane volatile organic compounds (NMVOC) equivalent, EP in kg N equivalent. In the case of PM, the tool for the reduction and assessment of chemical and other environmental impacts (TRACI) 2.1 method [28] is used to assess the environmental impact of particulate matter in the atmosphere, and it presents the result of PM in terms of kg $PM_{2.5}$ equivalent.

3. Results and Discussion

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

Figure 5 shows the GWP level at Well-to-Tank phase from various fuels for ships and their production methods. Generally, GWP from natural gas shows the smallest level, and that from MGO is estimated to be about 1.7 times larger than that of natural gas due to the contributions of oil production and the refinery process. The interesting thing is that the GWP emissions from hydrogen are at a higher level than those from MGO and natural gas for all of the electricity sources. The amount of GWPs from hydrogen is about 10 times greater than that of natural gas. The GWP emissions from the SMR process and the liquefaction of hydrogen especially are dominant in the Well-to-Tank phase of the hydrogen. Moreover, it was shown that GWP from the hydrogen liquefaction process could be

reduced by obtaining electricity from nuclear and/or renewable energies, but the effect is not critical due to the GWP from the SMR process.

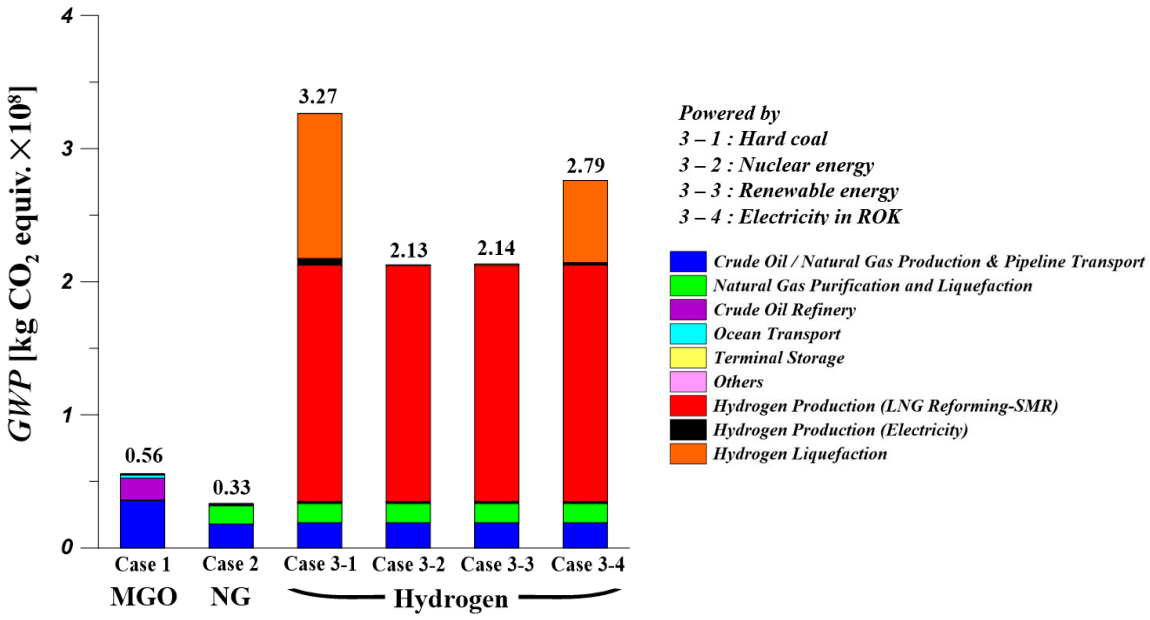

Figure 5. Global warming potential (GWP) at the Well-to-Tank phase from MGO, natural gas, and hydrogen.

Figure 6 shows the detailed GWP fractions from the case of using hydrogen to produce electricity in the ROK (Case 3-4). The SMR process accounts for about 65% of the total GWP emissions in the Well-to-Tank phase, followed by the liquefaction process of 23%. As an alternative fuel for eco-friendly ships, emissions from SMR and the process of liquefying hydrogen must be reduced to meet the IMOs 2050 GHG regulation [4].

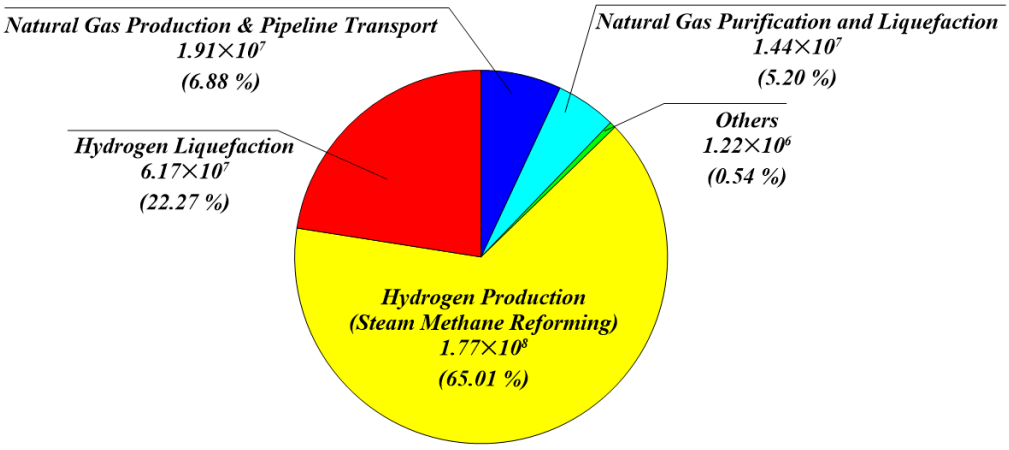

Figure 6. GWP fractions from hydrogen using electricity in the ROK (Case 3-4) in the Well-to-Tank phase.

Figure 7 presents the results of the impact assessments of AP, POCP, EP, and PM in the Well-to-Tank phase. For the emissions of AP (Figure 7a), hydrogen with an energy source from hard coal was charted as the largest level in which the liquefaction process emits most of the AP emissions. The SMR process also produced a remarkable amount of AP emissions. The emissions from MGO showed the next level, with large amounts of emissions from the refining and ocean transport processes. EP and PM emissions (Figure 7b,d, respectively) had trends similar to that of AP, i.e., the smallest amounts of emissions were produced by natural gas and MGO and hydrogen, while the energy obtained from hard coal is associated

with a higher level of emissions than the other fuels. In terms of POCP (Figure 7c), MGO had the highest level of emissions and most of them are from the ocean transport process. In general, the emissions from natural gas had the smallest values in the all of the fields in the Well-to-Tank phase. For the emissions from hydrogen, the SMR and liquefaction processes account for a significant portion of the total amount, but the electricity sources made remarkable contributions to the reduction of those emissions.

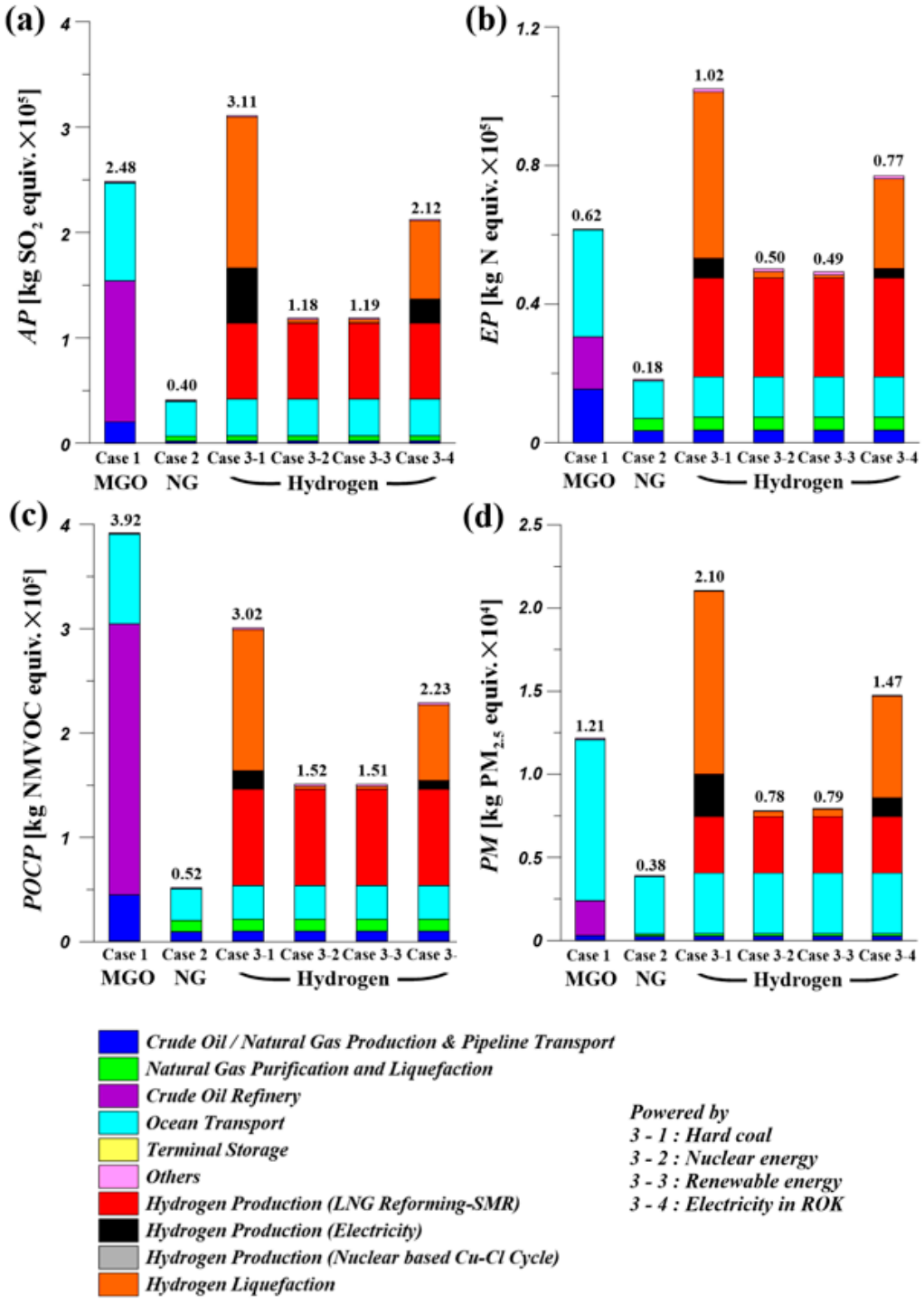

Figure 7. Acidification potential (AP), photochemical potential (POCP), eutrophication potential (EP), and particulate matter (PM) emissions at the Well-to-Tank phase: (**a**) AP; (**b**) EP; (**c**) POCP; and (**d**) PM.

3.2. Environmental Impact Assessment Results at the Tank-to-Wake Phase

Figure 8 shows the GWP level for the Tank-to-Wake phase from MGO, natural gas, and hydrogen. The hydrogen does not produce any GWP in the Tank-to-Wake phase because PEMFC produces only water and does not emit any gases. However, MGO and the natural gas engine produced remarkable amounts of GWP in the Tank-to-Wake phase. It was shown that the level of the GWP emissions from natural gas was larger than that from MGO, because the methane, which has a 21 times higher effect on GWP than CO_2, is emitted mostly from the natural gas engine rather than MGO [29].

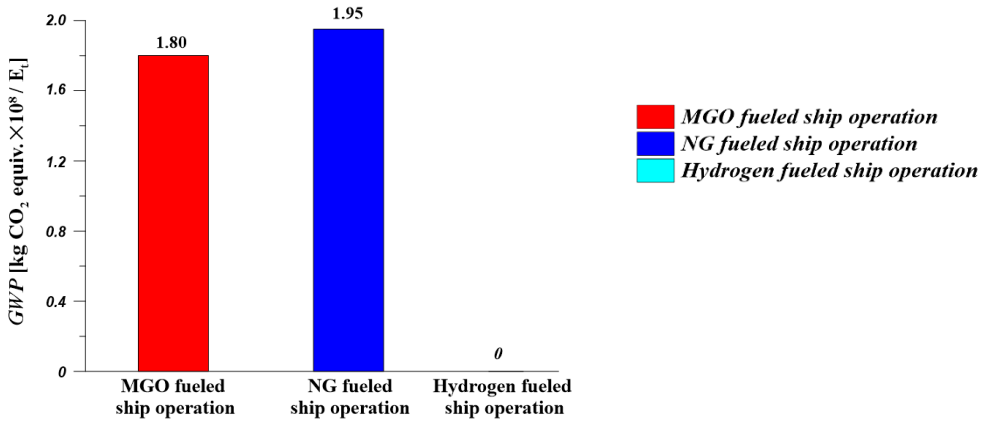

Figure 8. GWP at the Tank-to-Wake phase from MGO, natural gas, and hydrogen.

Figure 9 shows the environmental impacts of AP, POCP, EP, and PM in the Tank-to-Wake phase. The hydrogen-powered ship using PEMFC does not produce any field of emissions in the Tank-to-Wake phase. For the field of AP, POCP, EP, and PM in the Tank-to-Wake phase, MGO had emissions that were approximately 6 to 7.5 times higher than natural gas. This was different from GWP emissions in that the natural gas had the higher level of emissions.

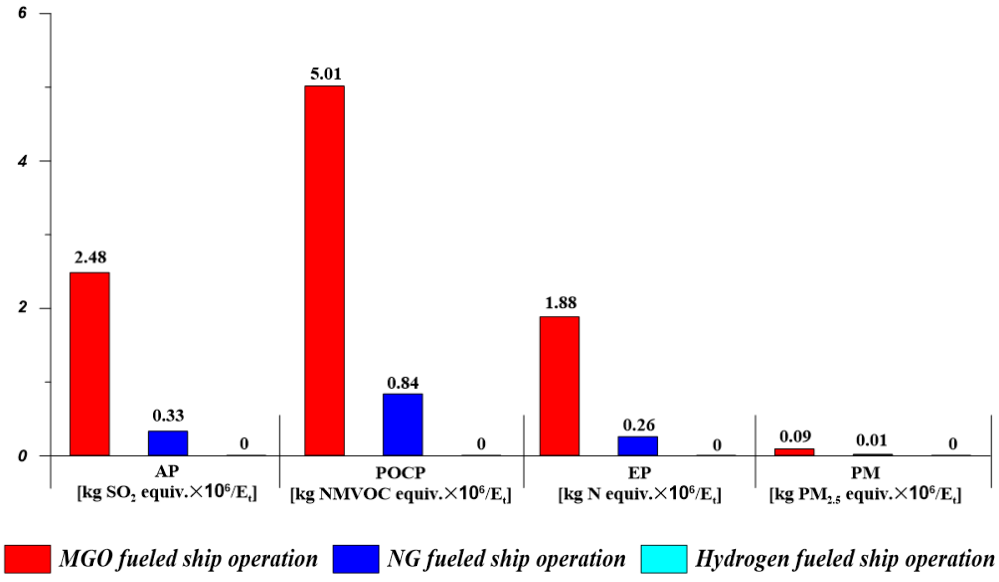

Figure 9. AP, POCP, EP, and PM emissions in the Tank-to-Wake phase.

Table 6 compares the compliances of the alternative fuels (MGO, natural gas, and hydrogen) for the 12,000 GT coastal ferry with IMOs regulations on emissions from ships. The comparison was based on the results of the Tank-to-Wake analysis, because the regulations are only for the ship operations.

The alternative fuels in this study could satisfy the global regulations of NOx and SOx emissions [2,3], but the MGO shows larger amount of NOx emissions than the criteria in ECA. In terms of GHG, MGO and natural gas could not meet IMOs 2050 GHG regulation [4]. Hydrogen fuel is the only fuel that could meet all of the regulations of NOx, SOx, and GHG.

Table 6. Comparison of compliance to the International Maritime Organization (IMO) regulations for ship emissions.

	MGO	NATURAL GAS	Hydrogen
2016 IMO NOx Regulation (Global 14.4, ECA 3.4 g/kWh) *	○(Global) ×(ECA)	○	○
2020 IMO Sulphur Regulation (Global 0.5% S)	○	○	○
2050 IMO new road map for GHG (at least 50% compared to 2008)	×	×	○

* For rated engine speed less than 130 rpm.

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

Figure 10 shows the GWP level in the Well-to-Wake phase of MGO, natural gas, and hydrogen fuel. The emissions in the Well-to-Wake phase can be obtained from the combination of the Well-to-Tank and Tank-to-Wake phases. In the case of hydrogen with electricity sourced from nuclear and renewable energy, the GWP levels in the Well-to-Wake phase were slightly lower than those from natural gas and MGO. However, the GWP from hydrogen with hard coal and electricity in the ROK had the largest level. The emissions of hydrogen were zero in the Tank-to-Wake phase, but those in the Well-to-Wake phase were similar to or higher than those of MGO and natural gas due to the large emissions in the SMR and liquefaction process in the Well-to-Tank phase.

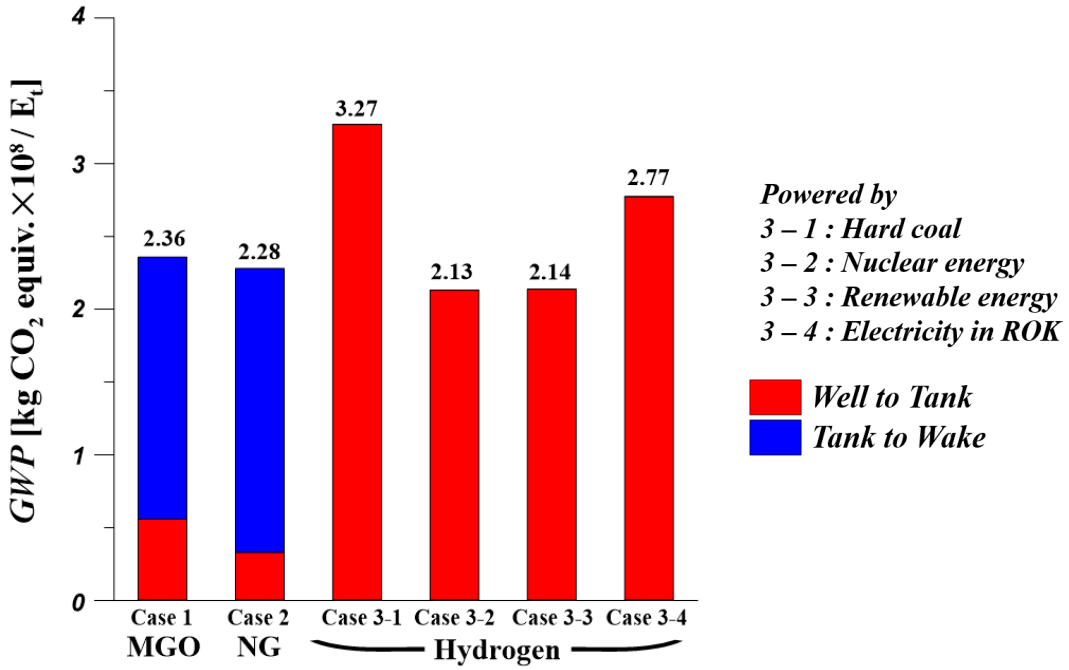

Figure 10. GWP in the Well-to-Wake phase from MGO, natural gas, and hydrogen.

Figure 11 shows the emissions of AP, POCP, EP, and PM in the Well-to-Wake phase. It is remarkably shown that the emissions from MGO were significantly higher than the emissions from the other fuels for all of the fields, and the dominant emissions occurred in the Tank-to-Wake phase. The emissions

from natural gas were much less than those from MGO. In terms of AP, POCP, and EP (Figure 11a–c), hydrogen shows the lowest emission level for all of various energy sources except PM (Figure 11d), for which natural gas has lower emissions than hydrogen. As also shown in the GWP level (Figure 10), depending on the energy sources, hydrogen produces greater or lesser emissions than those from natural gas.

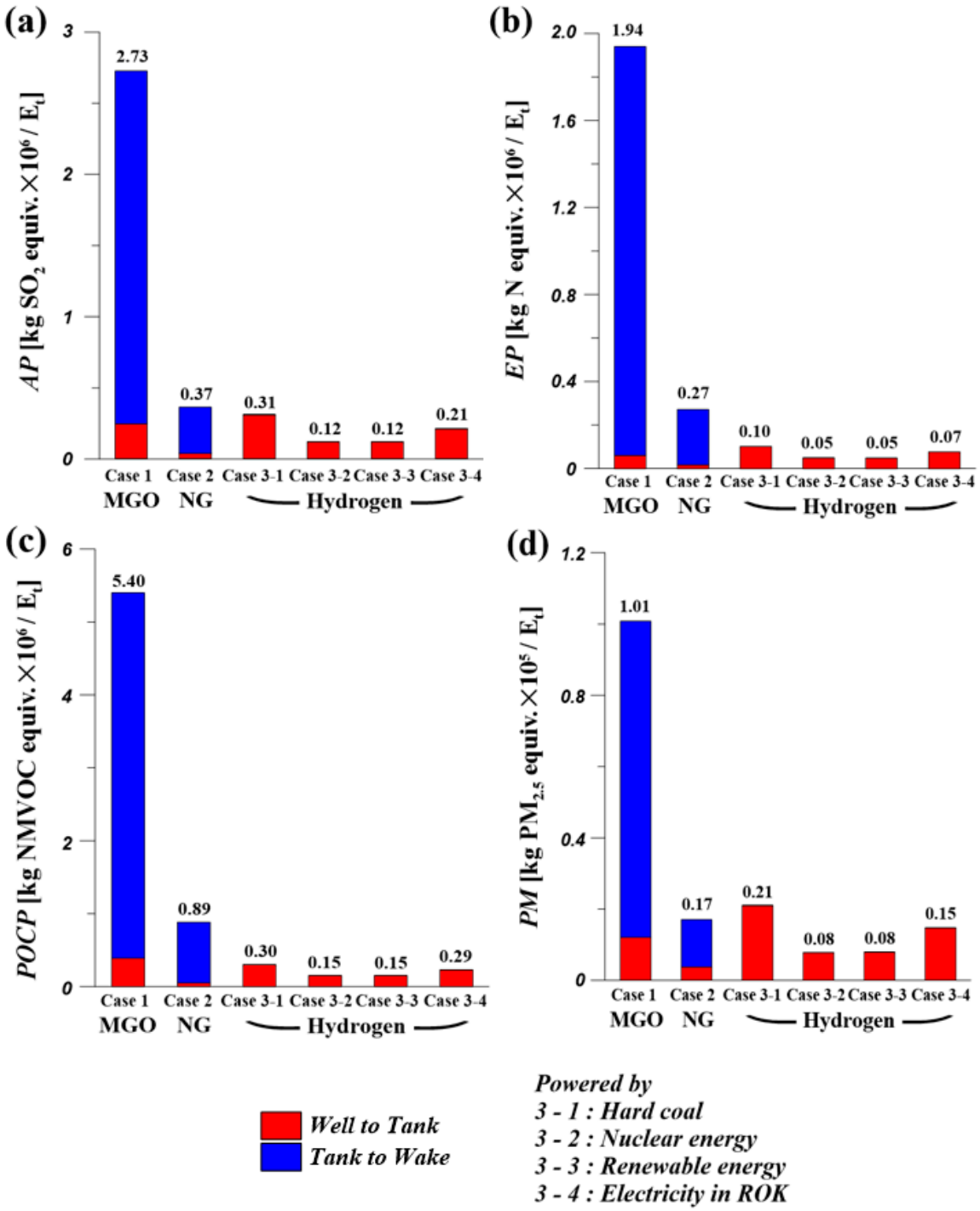

Figure 11. AP, POCP, EP, and PM emissions in the Well-to-Wake phase: (**a**) AP; (**b**) EP; (**c**) POCP; and (**d**) PM.

4. Conclusions

In this study, the environmental impacts from various alternative ship fuels, i.e., MGO, natural gas, and hydrogen, were analyzed for a coastal ferry operating in the ROK. The life cycle assessment (LCA) was used to assess the environmental prospects and potential environmental effects during their life cycles. In the Well-to-Tank phase, MGO and natural gas were considered as being transported from Saudi Arabia and Qatar, and the hydrogen was assumed to be produced by the SMR process with various electrical power sources. In the Tank-to-Wake phase, the 12,000 GT coastal ferry that operates between Yeosu and Jeju was considered when it was using different fuels. The environmental impact results associated with the alternative fuels used by the ship are provided in the terms of GWP, AP, POCP, EP, and PM for each phase of the Well-to-Tank, Tank-to-Wake, and Well-to-Tank in the study.

The key findings are summarized below:

1. The GWP emitted from the MGO at its Well-to-Wake phase was almost the same as with natural gas, and it was at even a smaller level than the hydrogen with hard coal and electricity in the ROK. However, the emissions of AP, POCP, EP, and PM from MGO were much higher in the Tank-to-Wake phase than natural gas and hydrogen.
2. The emissions of natural gas in the Well-to-Tank phase were relatively lower than those of MGO and hydrogen. However, the GWP of natural gas in the Tank-to-Wake phase had a slightly higher level than that of MGO, which was due to the large emissions of methane, which create a more severe greenhouse effect, i.e., 21 times greater GWP than CO_2. It was verified that the coastal ferry with natural gas is proper for IMOs regulation of NOx and SOx, but it still is not able to meet IMOs GHG regulation by 2050.
3. The emissions from hydrogen depend highly on its energy sources. It was shown that the GWP emissions were remarkably larger than those from MGO and natural gas at the Well-to-Tank phase, and most of the emissions were from the SMR and liquefaction process. The emissions from the liquefaction process can be reduced by using nuclear or renewable energy sources.
4. The SMR process is the way that is most commonly used to produce hydrogen, but the hydrogen from SMR, which is called gray hydrogen, is not more eco-friendly than natural gas due to the high level of GWP emissions in the Well-to-Tank phase. This means that hydrogen is the most suitable fuel for ships to meet IMOs 2050 GHG regulation with zero emissions in the Tank-to-Wake phase, but it is not a good solution because of the GWP emissions at the Well-to-Tank phase. As an alternative ship fuels with truly zero emission, green hydrogen is recommended using the water splitting method, which produces 6.14% more GWP than those from the SMR process [30].

The results of this study might be useful data for the applications of the alternative fuels, especially to meet the IMOs regulations on ship emissions, although the changes of the internal design and layout of the ship is not considered. The following suggestions are provided for the hydrogen application for a ship based on the LCA result of various alternative fuels for ships to meet IMOs 2050 GHG regulation.

- By-product hydrogen, which is produced during processes in the petrochemical industry, can be used as fuel for ships. The amount of by-product hydrogen in the ROK is approximately 192 M tons, and 73% of that amount is reused in the chemical process [31]. The residual by-product hydrogen can be used to power ships, and the amount is sufficient to power all of the coastal ships in the ROK.
- For the larger ships that operate in the ocean, large amounts of hydrogen must be produced, and it is inevitable that some brown coal or fossil fuels also will have to be used. The suitable way to produce hydrogen with the resources is the SMR process in combination with the carbon capture and storage (CCS) technique [32], which can reduce the environmental impact of GWP in the Well-to-Tank phase.
- For truly zero emission ships during their life cycle, it would be a solution to use the green hydrogen produced from the water splitting method. Moreover, the water splitting method can

use either nuclear or renewable energy to produce the hydrogen without any emission during its life cycle.

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Appendix A

The lifetime of main greenhouse gases in this study are listed in Table A1 for CO_2, CH_4, and N_2O, and the related emission factors at the Well-to-Tank phase of MGO, natural gas, SMR process to produce hydrogen and energy sources from hard coal, nuclear energy, renewable energy, and electricity in ROK are obtained from the literatures [19], and listed in Tables A2–A8, respectively.

Table A1. Lifetime of greenhouse gases in the study [29].

Greenhouse Gas	Life Time (Years)
Carbon Dioxide (CO_2)	50~200
Methane (CH_4)	12.4
Nitrous Oxide (N_2O)	121

Table A2. Emission factors of MGO in the Well-to-Tank phase.

Production and Pipeline transport [kg per 1 kg of Crude Oil]	CO_2 2.00×10^{-1}	CO 3.33×10^{-5}	NOx 2.94×10^{-4}	N_2O 2.33×10^{-4}
	SOx 2.51×10^{-6}	NMVOC 3.72×10^{-5}	PM 7.17×10^{-7}	- -
Ocean Tanker Transport (Saudi → ROK) [kg per 1 kg of Crude Oil]	CO_2 3.36×10^{-1}	CO 9.83×10^{-4}	NOx 9.16×10^{-3}	SOx 2.65×10^{-4}
	NMVOC 2.73×10^{-4}	PM 2.19×10^{-4}	- -	- -
Refinery [kg per 1 kg of MGO]	CO_2 3.00×10^{-1}	CO 3.70×10^{-4}	NO_2 5.65×10^{-6}	NOx 6.99×10^{-4}
	SOx 1.72×10^{-3}	NMVOC 3.84×10^{-3}	PM 3.26×10^{-5}	- -
MGO Terminal Storage [kg per 1 kg of MGO]	CO_2 1.80×10^{-4}	CO 1.30×10^{-6}	H_2S 1.00×10^{-9}	NOx 2.60×10^{-9}
	NMVOC 1.10×10^{-5}	SOx 4.10×10^{-7}	- -	- -
Bunkering Operation [kg per bunkering 1 MJ of MGO]	CO_2 1.80×10^{-4}	CO 1.30×10^{-6}	H_2S 1.00×10^{-9}	NOx 2.60×10^{-9}
	SO_2 4.10×10^{-7}	NMVOC 1.10×10^{-5}	- -	- -

Table A3. Emission factors of natural gas in the Well-to-Tank phase.

Production and Pipeline Transport [kg per 1 kg of Natural gas]	CO_2 6.76×10^{-2}	CO 9.17×10^{-5}	N_2O 1.50×10^{-4}	CH_4 9.50×10^{-5}
	NOx 4.28×10^{-4}	S_2O 9.89×10^{-4}	NMVOC 9.02×10^{-4}	- -
Purification and Liquefaction [kg per 1 kg of LNG]	CO_2 2.28×10^{-1}	CO 1.24×10^{-4}	N_2O 7.47×10^{-6}	CH_4 1.94×10^{-3}
	NOx 1.87×10^{-4}	SO_2 1.27×10^{-6}	NMVOC 1.24×10^{-5}	PM 1.24×10^{-6}
LNG Carrier Transport (Qatar → ROK) [kg per 1 kg of LNG]	CO_2 3.08×10^{-1}	CO 2.10×10^{-4}	N_2O 5.64×10^{-6}	CH_4 5.64×10^{-6}
	NOx 2.00×10^{-4}	NMVOC 1.39×10^{-5}	PM 1.90×10^{-5}	- -
LNG Terminal Storage [kg per 1 kg of LNG]	CO_2 1.80×10^{-4}	CO 1.30×10^{-6}	H_2S 1.00×10^{-9}	NOx 2.60×10^{-9}
	NMVOC 1.10×10^{-5}	SOx 4.10×10^{-7}	- -	- -
Bunker Truck [kg per 108 km transport of 1 kg of LNG]	NH_3 1.97×10^{-8}	Benzene 3.20×10^{-9}	CO_2 5.72×10^{-3}	CO 3.83×10^{-6}
	PM 1.17×10^{-7}	CH_4 4.59×10^{-9}	NO_2 8.44×10^{-7}	NO 6.64×10^{-6}
	N_2O 3.43×10^{-7}	NMVOC 1.87×10^{-7}	SO_2 3.60×10^{-8}	
Bunkering Operation [kg per bunkering 1 MJ of LNG]	CO_2 1.80×10^{-4}	CO 1.30×10^{-6}	CH_4 8.86×10^{-6}	H_2S 1.00×10^{-9}
	N_2O 2.60×10^{-9}	SO_2 4.10×10^{-7}	NMVOC 1.10×10^{-5}	- -

Table A4. Emission factors of steam methane reforming (SMR) process to produce hydrogen in the Well-to-Tank phase.

Natural Gas Steam Methane Reforming [kg per 1 kg of production of hydrogen]	CO_2 9.87	CO 3.96×10^{-3}	CH_4 2.63×10^{-2}	NO_2 3.45×10^{-7}
	NO 3.07×10^{-6}	NOx 4.41×10^{-3}	N_2O 3.52×10^{-6}	SO_2 1.73×10^{-3}
	PM 5.22×10^{-5}	NMVOC 3.09×10^{-5}	Butane 5.63×10^{-5}	- -

Table A5. Emission factors of energy source from hard coal at the Well-to-Tank phase.

Emission factor from hard coal [kg per 3.6 MJ electricity production]	CO_2 9.14×10^{-1}	CO 1.91×10^{-4}	CH_4 2.26×10^{-3}	NO_2 4.28×10^{-8}
	NO 4.28×10^{-7}	NOx 1.11×10^{-3}	N_2O 2.71×10^{-5}	SO_2 5.98×10^{-4}
	PM 2.62×10^{-5}	NMVOC 3.27×10^{-5}	Ethane 3.17×10^{-6}	- -

Table A6. Emission factors of nuclear energy at the Well-to-Tank phase.

Emission factor from nuclear energy [kg per 3.6 MJ electricity production]	CO_2 4.42×10^{-3}	CO 6.29×10^{-6}	CH_4 7.37×10^{-6}	NO_2 6.35×10^{-7}
	NO 1.12×10^{-8}	NOx 1.87×10^{-5}	N_2O 1.28×10^{-7}	SO_2 1.57×10^{-5}
	PM 4.89×10^{-7}	NMVOC 2.90×10^{-6}	Ethane 2.88×10^{-7}	- -

Table A7. Emission factors of renewable energy at the Well-to-Tank phase.

Emission factor from renewable energy [kg per 3.6 MJ electricity production]	CO_2 1.04×10^{-2}	CO 3.64×10^{-5}	CH_4 1.47×10^{-5}	NO_2 8.69×10^{-7}
	NO 1.45×10^{-5}	NOx 1.45×10^{-5}	N_2O 2.53×10^{-7}	SO_2 1.55×10^{-5}
	PM 9.88×10^{-7}	NMVOC 1.61×10^{-6}	Ethane 3.44×10^{-7}	- -

Table A8. Emission factors of electricity in ROK at the Well-to-Tank phase.

Emission factor from electricity in ROK [kg per 3.6 MJ electricity production]	CO_2 5.35×10^{-1}	CO 1.69×10^{-4}	CH_4 9.54×10^{-4}	NO_2 3.64×10^{-7}
	NO 3.28×10^{-7}	NOx 6.08×10^{-4}	N_2O 1.36×10^{-5}	SO_2 2.57×10^{-4}
	PM 2.08×10^{-5}	NMVOC 1.46×10^{-5}	Butane 1.33×10^{-6}	Ethane 9.27×10^{-8}

Appendix B

The related emission factors at the Tank-to-Wake phase of MGO and natural gas are listed in Table A9 [1].

Table A9. Emission factors of MGO and natural gas at the Tank-to-Wake phase.

MGO consumption [kg per 1 kg consumption of MGO]	CO_2 3.21	CO 2.77×10^{-3}	N_2O 1.60×10^{-4}	CH_4 6.00×10^{-5}
	NOx 8.70×10^{-2}	NMVOC 3.08×10^{-3}	PM 9.70×10^{-4}	SO_2 1.00×10^{-3}
Natural gas consumption [kg per 1 kg consumption of natural gas]	CO_2 2.75	CO 7.83×10^{-3}	N_2O 1.08×10^{-4}	PM 1.80×10^{-4}
	CH_4 5.00×10^{-2}	NOx 1.40×10^{-2}	NMVOC 3.00×10^{-3}	- -

References

1. Smith, T.W.P.; Jalkanen, J.P.; Anderson, B.A.; Corbett, J.J.; Faber, J.; Hanayama, S.; O'Keeffe, E.; Parker, S.; Johansson, L.; Aldous, L.; et al. *Greenhouse Gas. Study*, 3rd ed.; International Maritime Organization (I.M.O.): London, UK, 2015.
2. *Resolution MEPC. 176 (58)*; International Maritime Organization (I.M.O.): London, UK, 2008.
3. *Resolution MEPC. 259 (68)*; International Maritime Organization (I.M.O.): London, UK, 2015.
4. *Resolution MEPC. 304 (72)*; International Maritime Organization (I.M.O.): London, UK, 2018.
5. *Business Status of Nearshore Ferry in 2020*; Korea Shipping Association (K.S.A.): Seoul, Korea, 2020. (In Korean)
6. Verbeek, R.; Verbeek, K. *LNG for Trucks and Ships: Fact Analysis Review of Pollutant and GHG Emissions Final*; TNO Report; TNO Innovation for Life: The Hague, The Netherlands, 2015.

7. Luckose, L.; Hess, H.L.; Johnson, B.K. Fuel cell propulsion system for marine applications. In Proceedings of the Electric Ship Technologies Symposium, Baltimore, MD, USA, 20–22 April 2009; pp. 574–580.
8. Bailey, C.; Bain, A.; Birk, J.; Hainsselin, M.; Kamal, M.; Linden, H.; Lloyd, A.; Lynch, F.; MacKenzie, G.; Nahmias, D.; et al. *The Green Hydrogen Report*; National Renewable Energy Laboratory (N.R.E.L): Washington, DC, USA, 1995.
9. Serban, M.; Lewis, M.A.; Basco, J.K. Kinematic study of the hydrogen and oxygen production reactions in the copper-chloride thermochemical cycle. In Proceedings of the 2004 AIChE Spring National Meeting, New Orleans, LA, USA, 15–19 April 2009; pp. 1–10.
10. Naterer, G.F.; Suppiah, S.; Lewis, M.; Gabriel, K.; Dincer, I.; Rosen, M.A.; Fowler, M.; Rizvi, G.; Easton, E.B.; Ikeda, B.M.; et al. Recent Canadian advances in nuclear-based hydrogen production and the thermochemical Cu-Cl cycle. *Int. J. Hydrog. Energy* **2009**, *34*, 2901–2917. [CrossRef]
11. Kupfer, T.; Baitz, M.; Colodel, C.M.; Kokborg, M.; Schöll, S.; Rudolf, M.; Thellier, L.; Gonzalez, M.; Schuller, O.; Hengstler, J.; et al. *GaBi Database & Modelling Principles*; Thinkstep: Stuttgart, Germany, 2017.
12. International Standard Organization (ISO). *ISO 14040: Environmental Management-Life Cycle Assessment-Principles and Framework*; International Standard Organization (ISO): London, UK, 2006.
13. International Standard Organization (ISO). *ISO 14041: Environmental Management-Life Cycle Assessment-Goal and Scope Definition and Inventory Analysis*; International Standard Organization (ISO): London, UK, 1998.
14. Lee, C. Status and prospects of LNG bunkering by KOGAS. In Proceedings of the Int. LNG Fueled Ship & Bunkering Conference, Busan, Korea, 15 November 2018.
15. KEPCO. Available online: https://blog.kepco.co.kr/918 (accessed on 18 March 2020).
16. *Yearbook of Energy Statistics in 2018*; Korea Energy Economics Institute (K.E.E.I.): Ulsan, Korea, 2018.
17. Bengtsson, S.; Andersson, K.; Fridell, E. *Life Cycle Assessment of Marine Fuels: A Comparative Study of Four Fossil Fuels for Marine Propulsion*; Chalmers University of Technology: Gothenburg, Sweden, 2011.
18. *Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel*; Thinkstep: Stuttgart, Germany, 2019.
19. SEAROUTES. Available online: http://www.searoutes.com (accessed on 4 May 2020).
20. Thinkstep. GaBi Database. Available online: http://www.gabi-software.com/international/databases (accessed on 15 June 2020).
21. Endresen, Ø.; Sørgård, E.; Sundet, J.K.; Dalsøren, S.B.; Isaksen, I.S.; Berglen, T.F.; Gravir, G. Emission from international sea transportation and environmental impact. *J. Geophys. Res. Atmos.* **2003**, *108*. [CrossRef]
22. Pratt, J.W. *Feasibility of the SF-BREEZE: A Zero-Emission Hydrogen Fuel Cell High-Speed Passenger Ferry*; Sandia National Lab (SNL-CA): Livermore, CA, USA, 2017.
23. Stocker, T.F.; Qin, D.; Plattner, G.-K.; Tignor, M.M.B.; Allen, S.K.; Boschung, J.; Nauels, A.; Xia, Y.; Bex, V.; Midgley, P.M. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013; p. 1535.
24. GHK, B.A. *Study to Examine the Benefits of the End of Life Vehicles Directive and the Costs and Benefits of a Revision of the 2015 Targets for Recycling, Re-Use and Recovery Under the ELV Directive*; DG Environment: Birmingham, AL, USA, 2006; pp. 3–4.
25. Preiss, P. Photochemical ozone formation. In *Life Cycle Impact Assessment*; Springer: Dordrecht, The Netherlands, 2015; pp. 115–138.
26. Dreyer, L.C.; Niemann, A.L.; Hauschild, M.Z. Comparison of three different LCIA methods: EDIP97, CML2001 and Eco-indicator 99. *Int. J. Life Cycle Assess.* **2003**, *8*, 191–200. [CrossRef]
27. Chomkhamsri, K.; Wolf, M.A.; Pant, R. International reference life cycle data system (ILCD) handbook: Review schemes for life cycle assessment. In *Towards Life Cycle Sustainability Management*; Springer: Dordrecht, The Netherlands, 2011; pp. 107–117.
28. Bare, J.C. TRACI: The tool for the reduction and assessment of chemical and other environmental impacts. *J. Ind. Ecol.* **2002**, *6*, 49–78. [CrossRef]
29. Myhre, G.; Shindell, D.; Breon, F.-M.; Collins, W.; Fuglestvedt, J.; Huang, J.; Koch, D.; Lamarque, J.-F.; Lee, D.; Mendoza, B.; et al. Chapter 8-Anthropogenic and Natural Radiative Forcing. In *5th Assessment Report (AR5)*; Intergovernmental Panel on Climate Change (IPCC): Geneva, Switzerland, 2014; p. 151.
30. Ozbilen, A.; Dincer, I.; Rosen, M.A. A comparative life cycle analysis of hydrogen production via thermochemical water splitting using a Cu–Cl cycle. *Int. J. Hydrog. Energy* **2011**, *36*, 11321–11327. [CrossRef]

31. MOTIE. Road Map for Hydrogen Economy Activation. Available online: http://www.motie.go.kr/motie/py/td/tradefta/bbs/bbsView.do?bbs_cd_n=72&cate_n=3&bbs_seq_n=210222 (accessed on 25 June 2020).
32. Haszeldine, R.S. Carbon capture and storage: How green can black be? *Science* **2009**, *325*, 1647–1652. [CrossRef] [PubMed]