Greenhouse Gas Emissions of a Cargo Ship from a Life Cycle Perspective

Pham Ky Quang, Duc Tuan Dong, Tuyen Vu Van, and Pham Thi Thanh Hai

***Abstract*—Shipping transportation plays an important role in global trade as it is cheaper and greener than the other transportation modes. The greenhouse gas emissions emitted from ships are especially concerned due to the development of shipping transportation. Greenhouse gas emissions cause many negative effects on the environment including global warming potential (*GWP*). This study uses the life cycle assessment (*LCA*) method to estimate the *GWP* of a cargo ship in its entire life cycle. The ship's life cycle contains five main phases: material production, shipbuilding, maintenance, ship operation, and ship's end of life. *GaBi* software application is used to model the ship's life cycle and to obtain the results. The *GWP* indicator in *CML*2001 methodology is used to assess the impact of the ship on the environment. The results show the dominance of the ship operation phase to the life cycle. Carbon dioxide emissions are the main factor which have significant impact on *GWP* due to its huge amount in comparison with other greenhouse gas emissions. The research shows the advantages of *LCA* method and indicates that this method should be used in maritime industry as it could give a holistic view of a product in terms of the environment.**

***Index Terms*—Greenhouse gases, life cycle assessment, ship, environmental impact, emissions.**

I. Introduction

In recent years, the impacts of greenhouse gas emissions due to human activities on the environment are more serious. The increase in greenhouse gas emissions is the cause of global warming potential (*GWP*). *GWP* leads to the increase in sea level, natural disasters and threatens human's life and creature on the world. The *Intergovernmental Panel on Climate Change* (*IPCC*) warns that, by 2050, one billion people will live in areas which are low-lying due to sea level increment [1]. Therefore, it is necessary to have attention of governments, organizations and scientists all over the world to cut down pollution.

Seaborne transport is considered as a greener transport mode than the others as it emits only 2.1% global greenhouse gas emissions. It is reported by *IMO* that the CO_2 emissions from shipping will increase rapidly in the future (up to 250% by 2050 when comparing to 2007) [2]. To reduce the emissions and pollution from ships, *IMO* requires to cut down the sulfur content (%S) in marine fuel and limits it when the ships operate in some emissions control areas. By 2020, the sulfur content will be cut down to 0.5% for global shipping transportation [2].

LCA is a method standardized in *ISO*14040 which could evaluate the impacts of a product or a service from its entire life cycle. It is considered an applicable approach to obtain a "*real environmental results*" of a product. Its structure contains four phases as shown in Fig. 1.

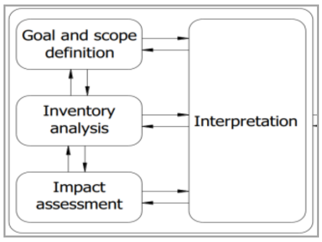

Fig. 1. *LCA* method structure in *ISO*14040 [3].

The first stage of *LCA* presents the purpose of the study and its limitation. Some important definitions such as functional unit, system boundary, etc. are also given in this stage. The life cycle inventory (second stage) is the most time-consuming stage as the inputs and outputs of product are gathered. The inputs and outputs of product include material and energy consumption, emissions, waste in the whole life cycle of a product. The sufficiency of data in this second stage will increase the accuracy level of the results. In the third stage - life cycle impact assessment (*LCIA*), the inputs and outputs of the product's life cycle will be converted into the environmental indicators such as Global warming potential (*GWP*), acidification potential (*AP*), eutrophication potential (*EP*), etc. The final stage is interpretation which will present some assessment, and recommendation for improving the quality of the product.

It is reasonable when concerning the emissions from ships because emissions will cause pollution and have negative impacts on the environment. However, only considering emissions and the environmental impacts from only the ship operation phase are not enough. It is because the emissions and the environmental impacts do not come only from this phase. A ship has it life cycle and the emissions come from all of phases the life cycle. In order to assess the environmental performance of a product or a ship, a holistic tool called Life Cycle Assessment (*LCA*) can be used.

In shipbuilding and shipping industry, some initial *LCA* reports were carried out in 1990s by *Fet* [4-6]. Recently, some important researches about the *LCA* of ships were carried out with the assistance of software applications. For instance, a framework for estimating the life cycle emissions of oil tanker was established and this framework was suggested to be used to calculate the emissions of a ship at any time of the life cycle [7], [8]. In [9], [10], the environmental and economic assessment of a ferry using

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solar energy were conducted by using *LCA* method. In order to save time in inventory phase, a data framework of marine structure was developed an Italian researchers in [11]-[13]. From 2016, a project named SHIPLYS has been carrying out by some European researchers. This project aims to assess the life cycle cost, environmental assessments and risk assessments of offshore structures [14].

Regarding the marine engines, *Ling-Chin et al.* developed a *LCA* framework which contains database for the marine engines' life cycle [15]-[17]. These researches are very useful for *LCA*-practitioners as the authors collected the database of marine engines adequately. In ship scrapping industry, the *LCA* method was also applied in [18], [19].

In order to introduce the *LCA* to the researchers, the main purpose of this study is to apply the *LCA* method to evaluate the *GWP* and some greenhouse gas emissions of a cargo ships from its entire life cycle. The authors also suggest this method should be used in the future researches to evaluate the marine structures and technology in terms of the environment. The paper has four main sections. After a brief introduction in the first section, the goal and scope of *LCA* and the life cycle inventory will be presented in Section II. Section III shows and discusses the results obtained from *GaBi* software. The last section will give some conclusions.

II. Method

The method presented in this study is followed the instruction of *ISO*14040.

A. Goal and Scope

The main goal of this study is to estimate the greenhouse gas emissions of a cargo ship from its entire life cycle. The amounts of CO_2, CH_4, N_2O, and CF_6 will be evaluated. This study also introduces the application of *LCA* method in the shipbuilding and shipping industry to naval architects and *LCA*-practitioners.

The chosen ship in this study is a bulk carrier built in Korea. This ship and its life cycle will be investigated in details. Bulk carrier is considered as a typical cargo ship type which carries bulk cargo in its hold directly. The technical specifications of this ship are shown in Table I. The functional unit of this *LCA* research is the construction, operation and end of life of the reference ship in its life cycle. Therefore, the results of this study are obtained based on this functional unit.

TABLE I: Reference Ship's Particulars

Items	Quantity
Year built	1997
Build place	Korea
Length overall – LOA	224.97 m
Length between perpendiculars - LPP	218.69 m
Breadth – B	32.25 m
Depth – D	19.03 m
Draft – T	13.765 m
Deadweight – DWT	73000 ton
Speed – v	13.3 knot

The system boundary of this research is illustrated in Fig. 2. In this system boundary, five phases of the ship are considered: (*i*) raw material extraction and steel fabrication (material consumption), (*ii*) shipbuilding phase, (*iii*) ship operation, (*iv*) ship maintenance, and (*v*) ship scrapping (ship's end of life). The results of this study are also presented following the ship's life cycle phases. As the entire life cycle is considered, this *LCA* is called "*cradle to grave LCA*". The detailed processes in each stage will be presented in the life cycle inventory. In each phase and process, the inputs and outputs of the product's life cycle (energy, material consumption, and emissions) are collected from journal papers and technical reports. For simplicity, the weight of steel is equal to the displacement tonnage, and human factors and malfunction of main engine are emitted in this study.

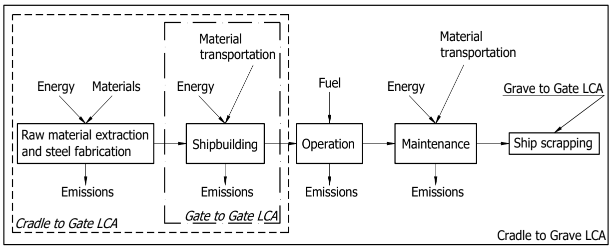

Fig. 2. System boundary of the study.

The life cycle impact assessment used in this study is *CML*2001 which is developed by Leiden University in Netherlands. Because only greenhouse gas emissions are considered in this study, the *GWP* indicator of this *LCIA* methodology will be calculated. *GWP* indicator is calculated as presented in (1) as follows:

$$GWP = 1.m_{CO_2} + 28.m_{CH_4} + 265.m_{N_2O} + 23500.m_{SF_6} + ... = \sum CF_i.m_i \quad (1)$$

where, CF_i is the characterization factor of the emission i, m_i is the mass of emission i (kg).

B. Life Cycle Inventory

As the ship's life cycle includes five phase, the life cycle emission could be calculated as follows:

$$E_{life\_cycle} = E_{material} + E_{shipbuilding} + E_{operation} + E_{maintenance} + E_{scrapping} + E_{transportation} \quad (2)$$

where, E_{life_cycle}, $E_{material}$, $E_{shipbuilding}$, $E_{operation}$, $E_{maintenance}$, $E_{scrapping}$, and $E_{transportation}$ are the greenhouse gas emissions emitted from the entire life cycle, material consumption, shipbuilding phase, ship operation, ship maintenance, ship scrapping, and material transportation activities, respectively. The amount of emission type i from a specific process can be evaluated based on this equation:

$$m_{emission.i} = EF_i.A \quad (3)$$

where, EF_i is the emission factor of emission type i from a process, A is the amount of material, fuel, or energy used in a process. *EF* can be taken by collecting from technical reports or be implemented in *GaBi* software. This study only investigates the *GWP* indicator of the ship, therefore, the processes which emit greenhouse gas emissions are considered.

1)Greenhouse gas emissions from material production

Emissions of this phase come from raw material extraction and steel production processes. Fortunately, the emission factors of these two processes are available in the software. The steel consumption used for construction is assumed to be equal to the light displacement tonnage (11,400 ton) with regard to about 10% steel loss in cutting process [5]. The steel consumption for maintenance is assumed to be equal to 10% of steel consumption in ship construction.

2)Greenhouse gas emissions from shipbuilding and maintenance phases

In these two phases, greenhouse gas emissions could emit from the electricity and fuel consumption. Electricity is used for various activities in shipyard such as cutting, welding, sandblasting, painting, etc. processes and the fuel is used for the ship trial activities. Electricity consumption could be assumed based on the steel weight in the ship construction and maintenance [5]. The emission factors of electricity production processes are provided in *GaBi* software, while the emission factors of fuel consumption are taken from IMO report [2]. Some processes emit the emissions that are not greenhouse emissions such as particulate matter (from abrasive sandblasting), volatile organic compounds (from painting) are not considered.

3)Greenhouse gas emissions from ship operation

Greenhouse gas emissions emit from this phase due to a huge amount of marine fuel consumption for the operation of ship at sea. The fuel consumption for this reference ship is taken from [20], and the emission factors of fuel combustion in main engine is the same as the ship trial activities. The fuel extraction and production processes are also considered with the emission factors in *GaBi* software.

4)Greenhouse gas emissions from ship scrapping

At the end of its life cycle, the ship is shredded and then, the scrap steel will be recycled in the steel mill. Emissions in this phases come from the usage of cutting gas (propane). It is assumed that 60 kg of propane is consumed to cut one ton of steel, and three kg of CO_2 is emitted when one kg of propane gas is used [20]. The propane production is also considered in this study.

5)Greenhouse gas emissions from material transportation

The transportation modes used to transport materials are bulk carrier and trucks. The emission amounts depend on the distance of transportation and mass of materials. The emission factors of transportation activities are provided in GaBi software adequately.

After the life cycle phases are defined and the data of processes are collected, the ship's life cycle is modelled in *GaBi* software application to get the results (Fig. 3). This application is developed by *thinkstep* company in Germany. It contains the database of many industrial processes and the database of life cycle impact assessment. This helps the *LCA*-practitioners to obtain results conveniently.

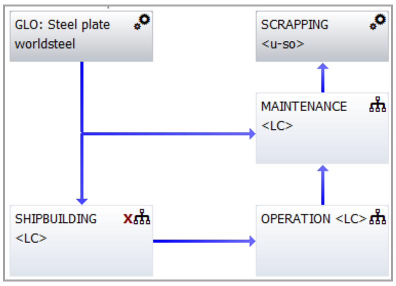

Fig. 3. Life cycle model of the reference ship in *GaBi* software.

III. Results and Discussion

As presented in the system boundary, the results of this study are divided into six categories following five life cycle phases of a ship and material transportation activities. The results of four greenhouse gas emissions CO_2, methane (CH_4), laughing gas (N_2O), and sulfur hexafluoride (SF_6) are selected to discuss.

A. Emission Inventory Results

The emissions of the entire life cycle and five phases are presented in Table II. It can be seen that the amount of CO_2 emissions is much higher than that of N_2O, SF_6, and CH_4. For example, the material production phase emits to the environment 3.15E+07 kg of CO_2 emissions, higher than the other emissions three to 11 orders of magnitude. The ship operation phase dominates the amount of CO_2, N_2O and CH_4 emission in comparison with other phases. It should be noted that the SF_6 emissions emit mostly in material production and are not reduced in steel recovery processes. However, the amount of SF_6 are very small, about 9.49E-04 kg in the ship's life cycle.

Fig. 4 illustrates the share of the ship's life cycle phases of four greenhouse gas emissions. Material consumption in the ship's life cycle accounts for a considerable amount of CH_4 emission, with more than 10%. For CO_2 and N_2O, the percentages emissions from material are lower, lower than 5%. Transportation activities and maintenance phases emit a small amount of emissions in the ship's life cycle. The huge amount of fuel consumption leads to the dominance of ship operation in comparison with other phases.

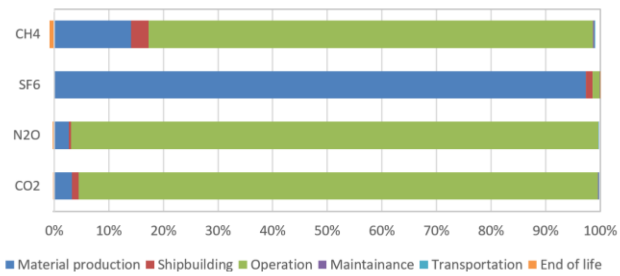

Fig. 4. Share of life cycle phases of greenhouse gas emissions.

TABLE II: Emissions Results in the Ship's Life Cycle and Phases (kg)

Emissions	Material production	Shipbuilding	Operation	Maintenance	Transportation	End of life	Total
CO_2	3.15E+07	1.28E+07	9.33E+08	1.06E+06	1.15E+06	-1.57E+06	9.78E+08
N_2O	1.22E+03	2.01E+02	4.45E+04	1.41E+01	2.72E+01	-1.28E+02	4.58E+04
SF_6	9.24E-04	1.13E-05	1.25E-05	7.82E-07	2.22E-09	1.51E-08	9.49E-04
CH_4	9.04E+04	2.07E+04	5.23E+05	1.55E+03	9.96E+02	-5.70E+03	6.31E+05

TABLE III: *GWP* OF THE SHIP IN LIFE CYCLES (KG CO_2 EQUIVALENT)

Emissions	Material production	Shipbuilding	Operation	Maintenance	Transportation	End of life	Total life cycle
CO_2	3.15E+07	1.28E+07	9.33E+08	1.06E+06	1.15E+06	-1.57E+06	9.78E+08
Other emissions	2.93E+06	7.17E+05	2.69E+07	5.06E+04	3.90E+04	-1.72E+05	3.05E+07
GWP (total)	3.44E+07	1.35E+07	9.60E+08	1.11E+06	1.19E+06	-1.74E+06	1.01E+09

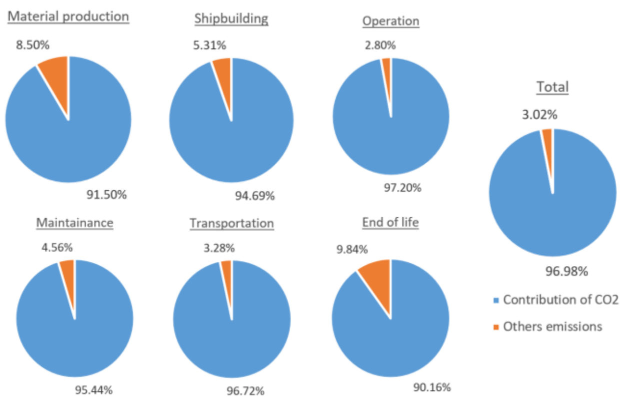

Fig. 5. Share of CO_2 and other emissions on the ship's *GWP*.

B. Greenhouse Gas Emissions Results

Table III presents the value of CO_2 emissions and the other emissions *GWP* value of life cycle phases by multiplying the emissions amounts with their characterization factors. As the normalization factor of CO_2 emissions is equal to 1, the value of this emissions are the same as shown in Table II. In 30 years of the ship's life cycle, it emits to the environment more than one trillion kg of greenhouse gas emissions (1.01E+09 kg CO_2 equivalent).

Fig. 5 shows the comparison between the contribution of CO_2 emissions and the other greenhouse gas emissions to the *GWP* indicator. Despite of the lowest characterization factor of CO_2 on the *GWP* indicator, the contribution of CO_2 emissions is much higher than the other. In general, CO_2 emissions account for more than 90% in each individual phase and account for 96.98% in the ship's life cycle. Therefore, it may be appropriate when only considering CO_2 emissions as the main emissions of a product. However, the results will be more persuasive if the other emissions could be estimated by using *LCA* method.

Although this study only applies the LCA method to the life cycle of a ship, the advantages of this method should be recognized. The *LCA* method does not merely evaluate the environmental impact of a ship in life cycle, it brings to the researchers a clear view on the ship's environmental performance. By using *LCA* method, the life cycle phases of a ship are considered together, and the change in one phase could affect the others. In other words, by using the *LCA* method, the "*real environmental impacts*" of a product or a service will be assessed.

In the maritime sector, the energy efficiency design index (*EEDI*) and energy efficiency operation index (*EEOI*) are used as the measurement of ship's impact on the environment. However, these two indexes are not enough to ensure that a ship is environmentally friendly or not as it only consider CO_2 emission and only consider the operation phase. Some researchers combined the *LCA* method with *EEDI* and *EEOI* to improve the efficiency of these two indexes by considering the effects of the entire life cycle of ships. This could access the environmental performance of a ship more efficiently and entirely.

In *LCA* method, the emissions are converted into environmental impacts to assess the environmental performance of a product. However, it should be reminded that there are many types of impacts on the environment that a product could have. For example, the *CML*2001 methodology gives 12 environmental indicators to assess a product in terms of the environment comprehensively. Moreover, the other methodologies try to combine the human factor in the LCA method. This requires a lot of attempts to improve the method and collect data in the product's life cycle.

IV. CONCLUSIONS

This research evaluates the greenhouse gas emissions of a cargo ship from a life cycle perspective by using the *LCA* method. Four typical greenhouse gas emissions including CO_2, CH_4, N_2O, and SF_6 are selected. The life cycle impact methodology used in this study is *CML*2001 and only *GWP* indicator of this methodology is evaluated. The life cycle emissions and *GWP* results are obtained by using *GaBi* software.

The results show the dominance of ship operation phase to the life cycle emissions of the ship and *GWP* indicator. Thanks to the material recovery in the ship scrapping, a small amount of emissions and *GWP* could be reduced. Generally, a ship has a great impact on the environment due to a very high fuel consumption in its entire life cycle.

This research clearly has some limitations. Firstly, some uncertainty factors in the ship's life cycle such as the effects of operation condition on ship's resistance, the maintenance time, fuel consumption, etc. are not considered. Secondly, some estimations taken from other researches and the inadequacy of inputs and outputs may affect the final results. However, these limitations could be acceptable as the ship structure is very complex and it is very difficult to investigate the uncertainty factors in its long life cycle. Future researches will apply the LCA method to the other types of ship and the other environmental indicators will be also evaluated if the database for the ship's life cycle are available.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Conceptualization and methodology, P. K. Quang, D. T. Dong and T. V. Van; software, validation, formal analysis, investigation and resources, P. K. Quang, D. T. Dong, T. V. Van and P. T. T. Hai; data curation, writing—original draft preparation, review and editing, P. K. Quang and D. T. Dong; visualization, P. T. T. Hai and T. V. Van.; supervision, P. K. Quang and D. T. Dong.

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