A LIFE CYCLE ASSESSMENT ON CARBON CAPTURE AND SOLIDIFICATION METHOD ON SHIPS

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Abstract
Greenhouse gas reduction has become a severe topic in the shipping industry and researchers are striving to investigate different GHG reduction technologies to determine their feasibility especially on the environment impact. However, there is no specific evaluation process currently available so this paper presents a Life Cycle Assessment for a carbon emission reduction method to introduce Life Cycle Assessment as a systematic evaluation approach which can guide policy makers to evaluate the performances and help ship owners to select suitable reduction technologies. The carbon reduction method proposed by authors was proved to be cost effective in previous works and this paper applies life cycle analysis focusing on all stages of ship life to investigate, determine and compare the feasibility of this method. The environmental impacts are considered to be the most significant standard for the assessment. From the results of the assessment, the proposed reduction method meets the carbon reduction target and can lead to a lower global warming potential while leveling up the carbon reduction target. This paper also indicates, to achieve carbon reduction target set up by regulations, a marginal target will be necessary due to the energy requirement and efficiency of the method/system as well as the consideration of activities in different life stages. It is also recommended that the evaluation of carbon reduction method could apply Life Cycle Assessment so that policy makers and ship owners are provided with comparable results for reasonable decision makings.
Keyword *Life cycle assessment, global warming, carbon emission reduction, carbon solidification*

1. Introduction

The global warming has been attractive to researchers from all over the world for decades. It is because the global warning effect is actually influencing human beings' living environment. For instance, sea level arising is one of the most significant impact due to the accumulation of global warming gases (greenhouse gases), especially carbon dioxide which is known to be the largest contributor of global warming. ICCT has been considering the reduction of Greenhouse Gas Emissions from ships since 2011 [1]. The consideration is not only focused on the emission abatement but also the costs due to the abasement. Nowadays researchers are striving to develop and investigate novel and efficient carbon reduction methods and techniques in order to mitigate the severe impacts of global warming.

There are large numbers of new developed carbon reduction methods with evaluations:

Perera and Mo have presented their measuring method based on EEDI, EEOI, SEEMP and ECAs to analysis the energy efficiency of a ship. Their results indicate using suitable navigation strategies will help reduce emissions from ships [2]. Wang and Chen also investigate the strategy of refuelling, sailing and containership deployment and how they could affect the emissions, especially carbon emissions, from ship. The research work shows there are many different factors affecting the emissions released and it also considered the cost associated with these factors such as the impacts of fuel price, container transportation quantity, carbon credits, etc [3]. Chen's team evaluate the impact of shipping route on the emissions from ships with data between Asia and Europe. As a fact of emission restriction in ECA area, ships are intended to changing route to go around the area which means the optimal route for fuel saving will not be optimal any more [4]. Demirel et al. [5] developed a CFD model to estimate the variation of plate roughness in different coating types in order to reduce the hull roughness and increase the energy efficiency. An experimental study was also carried out by Demirel et al. [6] to determine the relationship between bio-fouling and ship resistance for an oil tanker and an LNG carrier. Their CFD results were validated with experiments by Owen et al. [7].

However, these methods are proposed and evaluated by different researchers and the standard or criteria applied are varied based on these researchers' proposal. It is essential to develop and validate a comprehensive approach with standard processes and criteria to help both policy makers and ship owners to evaluate and select the suitable carbon reduction methods.

Life cycle assessment is a popular method which has been widely used in many different disciplines. Styles' team used LCA to quantify the growing of willow on river buffer zones and results showed the benefit of willow cultivation on these area [8]. In fishing industry, Vázquez-Rowe's research group investigated the edible protein energy return on investment (ep-EROI) in Spain and LCA was to assess the energy consumption and environmental impact. These results were expected to provide recommendations for EU's Common Fisheries Policy [9]. LCA is also applied to evaluate the power systems, both state-of-art and under developed, by Fredga and Maler, especially on biofuel. A full scope of LCA model considering both emission released and resource required is established in order to provide comprehensive analysis and retrieve precise results [10]. There are also many valuable LCA works and researches in the field of shipping industry: Blanco-Davis's works have applied LCA to aid the shipyards to evaluate retrofitting performances of innovative ballast water treatment system and fouling release coating [11][12]. The performance of fuel cell and diesel engines for marine applications has been investigated and compared by Alkaner and Zhou with the help of LCA [13]. Strazza's research team applied LCA to evaluate the environmental impact of paper stream on a cruise ship with implementation of different green practices [14]. In addition, Nicolai's team investigated the environmental impact related to commercial ships by optimization of raw material and energy consumption, and recycle processes using LCA [15]. two case ship studies have been carried out by Ling-Chin and Roskilly to compare the hybrid power system with the conventional marine engine systems in a comprehensive ship life cycle phases - namely, construction, operation, maintenance, and scrapping [16][17]. With inspiration from these researches, the authors have also carried out two case studies which help shipyards and ship-owners to determine the optimal propulsion system for a short-routed hybrid ferry and for an off-shore tug vessel from the perspective of economic and environment[18][19].

Since the evaluation processes are different from different research works, the main aim of this paper is to develop a life cycle assessment model which provide a standard and comprehensive evaluation model by considering four stages of ship: construction, operation, maintenance and scrapping and a large scope of activities in these stages.

2. Methodology

2.1. Life cycle assessment

Life cycle assessment is an evaluation approach, considering all the activities from cradle to grave of a system or product [20]. The definition of 'from cradle to grave' is that starting from the raw material exploiting, all the processes related to the system or product are covered, such as manufacturing, transportation, utilization, maintenance and disposal and recycle at the end of life. Through including and assessing the impact of all these processes and activities in the life cycle of the system or product, LCA provides a comprehensive view of product/system as well as relevant activities from the perspective of environmental impact. With these views and insights, all the participants in the life cycle of the product/system will have a clear and precise understanding about the overall environmental performance which will enable them make reasonable decisions at the design and operation stages.

Basically, to carry out a LCA analysis, there are four main parts interactive with each other (Figure 1): goal and scope definition, life cycle inventory analysis, life cycle impact analysis and the interpretation of different parts. It is obvious that the first part is to set up goal and define the scope which also means the target and the boundaries. Then the next step is to evaluate the life cycle inventory which are basically considering and identifying the quantities of substances related to environmental potentials (i.e. emission groups) in all the life phases of the system/product, such as energy consumption, material investment, emission released and waste generation. In order to evaluate the environmental impacts, a normalization database will be selected and used such as CML 2001, ReCiPe, ILCD and TRACI [21][22][23][24]. Only after the normalization, the environmental potentials due to different energy consumption, raw materials, emissions and wastes could be converted into a same key unit (key function). For global warming potential (GWP), the equivalent carbon dioxide is the key unit but for other potential, the key unit will be different. For example, for acidification potential (AP), the key unit is equivalent sulphur dioxide [21].

Sensitivity analysis is also an essential part of LCA which will indicate the consequence of input data changing. As there are many data involved in one LCA analysis, the analysis usually focuses on the most fluctuated data and also the ones clients cared most. After changing the value of one input data, a series of results will be obtained which will illustrate how the life cycle assessment results changing with the varying of data.

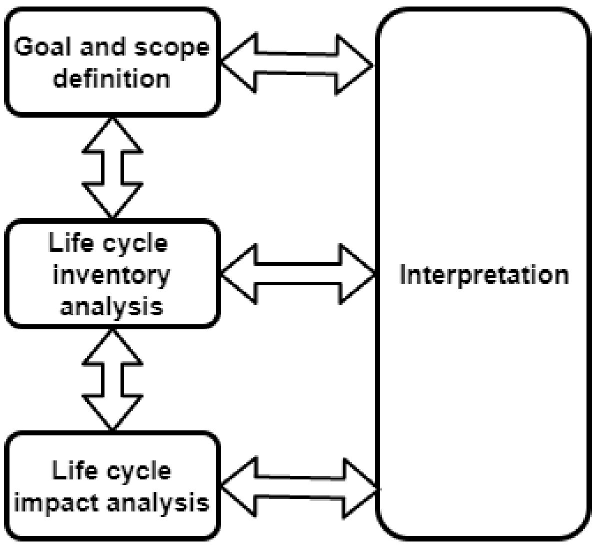

Figure 1 Life cycle assessment framework

Apart from the framework of LCA, the processes consideration in an analysis is also significant. Usually, the life cycle is comprised of four consecutively phases: raw material acquisition, manufacturing, use/reuse/maintenance and recycle. In this paper, the target is about ships in the shipping industry, the phases considered will be constrained and modified into a more relevant life cycle to ships (Figure 2): construction, operation/maintenance and scrapping.

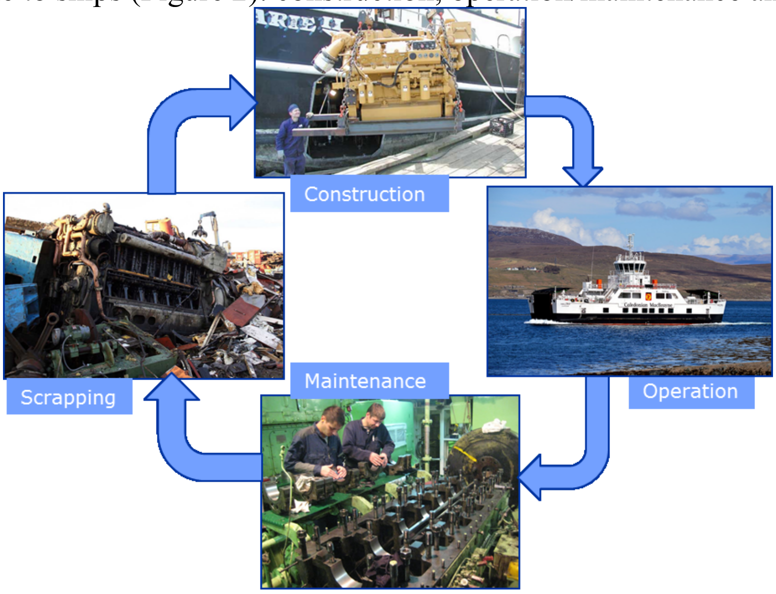

Figure 2 A general flowchart of ship life cycle

2.2. Carbon solidification

For carbon reduction method, there are many different technologies as mentioned previously focusing on different parts of ships, for examples, coating applications, route optimizations, speed optimizations and after treatment. This paper tests authors' previous work, carbon solidification on ship, and applies LCA model to evaluate the results in order to compare with the results from previous work.

The carbon solidification method applies chemical substances to absorb and solidify carbon content from the exhaust gases. The chemical reactions are listed as following (Zhou & Wang, 2014):

$$CO_2\ (g) + 2NaOH\ (l) = Na_2CO_3\ (l) + H_2O\ (l) - \Delta H_1 \quad (1)$$

$$Na_2CO_3\ (l) + Ca(OH)_2\ (s) = CaCO_3\downarrow(s) + 2NaOH\ (l) - \Delta H_2 \quad (2)$$

A schematic diagram is presented in Figure 3 to indicate how these reactions are involved and applied for carbon solidification. Also the pre-treatment and after treatment are also shown in this figure. According to the flow diagram, the exhaust gas will be partially extracted from funnel connected with the main engines. The removals of SOx and NOx are to increase the carbon reduction efficiency because the alkaline solution (NaOH solution) will be degraded due to the presences of these acid gases. After the purification, the gas will be transported in to a physical separation process which applies membrane system to increase the purity of CO2. In this process, water, oxygen and nitrogen will be separated from CO2 to obtain high concentration gas which is certainly preferred for absorption reaction. The absorption reaction with alkaline solution will take place when the gas feeding starts and after the absorption, the Na2CO3 solution who contains carbon content captured will be transported for precipitation. Based on the second reaction, the sediment CaCO3 will be generated which is well known in many industries as raw material, such as building industry and medicine industry. After filtration and drying, the CaCO3 powders will be stored on ship and will be traded when arrival at the destination.

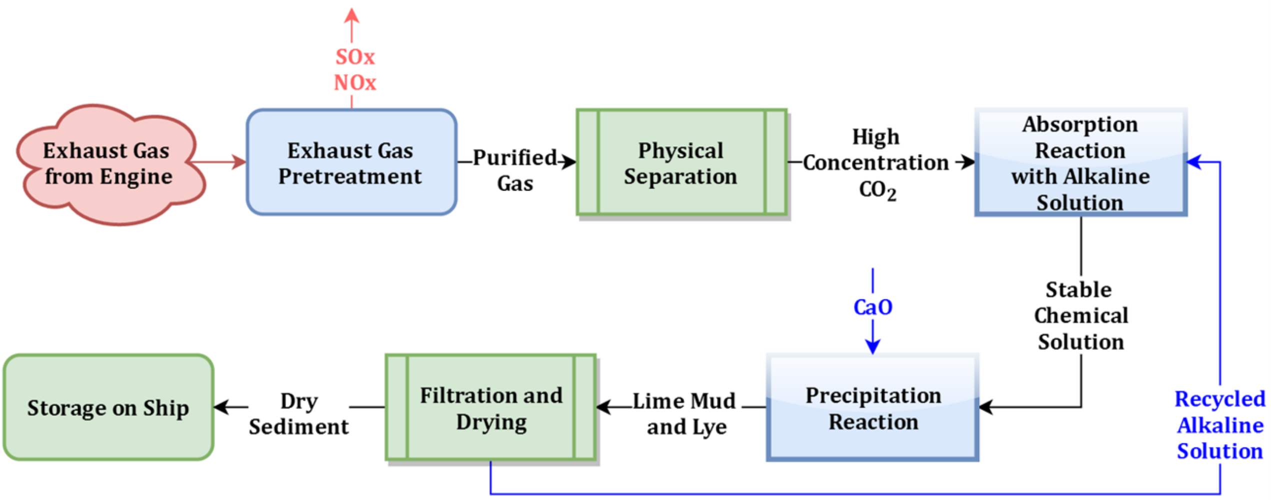

Figure 3 Schematic of chemical processes for carbon solidification on ships

To test the feasibility and evaluate the efficiency of the solidification processes, an experiment test rig was constructed (Figure 4) [25] and a series of experiments were carried out with promising results (Table 1). These results were applied in the case ship study in previous works and also will be used in the LCA modelling.

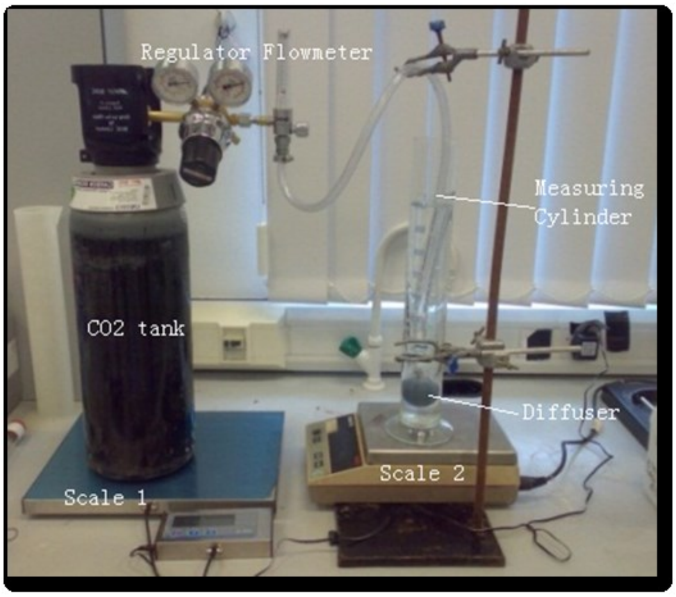

Figure 4 Experiment rig for carbon solidification process

Table 1Experiment results

Measurements	Results
CO2 Absorption Rate	67.85%
NaOH Regeneration Rate	85.37%
CaCO3 Filtration Efficiency	82.17%

3. LCA modelling

Based on the methodology in previous section, this section will present the LCA model built with GaBi 5, a LCA software, covering the main phases of ships and a large scope of activities. In Figure 5, the processes of ship life are presented in the schematic diagram. From this figure, three main phases are considered. Maintenance phase is one important phase but the data for maintenance are difficult to derive and the data vary for different ships.

The first phase considered in the ship life span is the construction, where we considered engines and the CCS system. The engines are considered due to the power requirement will be increased after installing the CCS system. The fuel consumption in the operation phase will be related to engine specification from the construction phase. Therefore, the purchase, transportation and installation of engines are included. In the operation phase, there are two different cycles: one for engine operation and one for CCS system operation. During the operation of engines, there will be fuel consumptions due to power requirement and accumulated over operation hours. In this LCA model both fuel oil and lubricating oil are considered. While the operation of CCS system, there are chemical substances consumptions related to the carbon reduction target and quantity of engine exhaust gas generation. The connection between engine and CCS cycle is that the engine power requirement will be increased due to application of CCS system, such as separation, transportation, stirring, filtration and heating. While the carbon reduction target is changed, the power required will be varied so that the engine output will be charged respectively. The last phase involved is the scrapping of the engine and CCS system. Three factors are considered here: dismantling energy consumption, transportation and recycle energy consumption.

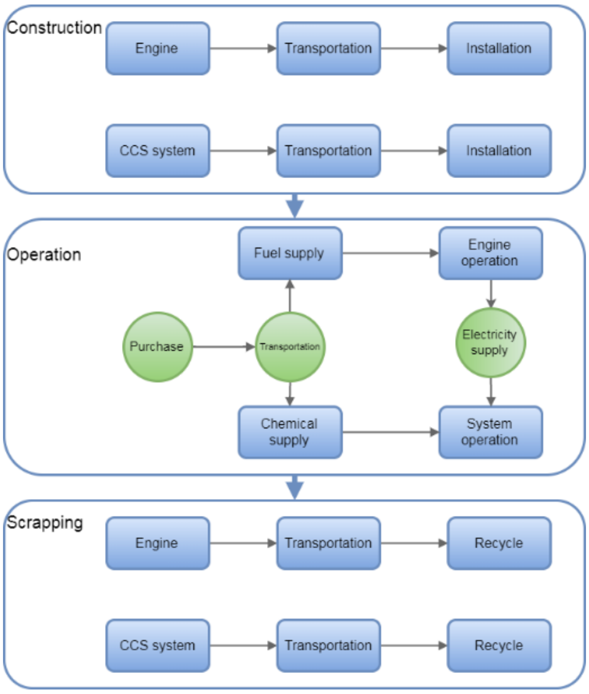

Figure 5 Schematic diagram of LCA scope and processes

3.1. Goal and scope definition

The goal of the life cycle assessment is to evaluate the environmental impacts of application of CCS system on ship. The main impact considered is the global warming potential which is used to assess all the energy, emission and material flows on their contributions to the global warming impact. As the application of CCS system will have an effect on engine output, the scope of the study is limited to engines and CCS system. The rest parts of the ship and its activities will not be impacted greatly. To initialize the life cycle assessment, several assumptions are made due to lack of data and also reduce the model complexity:

a) Carbon factor of HFO is 3.114 kg CO_2/ kg fuel consumed [26];

b) GWP factor of significant emissions are listed in the following table [21];

Table 2 Global warming potentials of emissions

Type of Pollutant	**Symbol**	**GWP (kg CO_2 equiv.)**
Carbon dioxide	CO_2	1
Carbon monoxide	CO	0.027
Dinitrogen oxide	N_2O_3	265
Methane	CH_4	25

c) Case ship specification is presented in the following two tables:

Table 3 Case ship specification

Type	**Bulk Carrier**	
LOA	292	m
LBP	283.5	m
Breadth	45	m
Depth	24.8	m
Draught	16.5	m
Gross	94,360	ton
DWT	157,500	ton
Water ballast	78,000	m^3
Fuel type	HFO	

Table 4 Engine specification

Main Engine	**MAN B&W: 6S70MC-C7**	
No. of main engine	1	
MCR	18,660	kW
SFOC	174	g/kWh

d) To consider the scrapping of engines, engine materials are listed in the following table [27]:

Table 5 Engine contents

Engine Material	**Weight ratio (%)**
Steel	40
Cast iron	46
Aluminium [Al]	8
Copper [Cu] and Zinc [Zn]	0.2
Lead [Pb]	0.1
Other	5.7
Total	100

e) Energy requirements for different material scrapping are presented below [16]:

Table 6 Energy requirements of engine materials in scrapping phase

Item			**Steel and cast iron**	**Al**	**Cu**	**Zn**	**Pb**
Energy	MJ	Electricity	1.71	0.1	-	0.7	-
		Natural gas	0.62	10.22	-	0.3	-
Emission	kg	CO2	1.05E-01	5.45E-01	2.00E-01	-	2.00E-01
		CO	2.40E-03	8.83E-04	1.50E-05	-	1.50E-04

f) The transportation distances for engine and CCS after purchasing and before scrapping are assumed. The distance between engine retailer and ship yard is assumed to be 1000km and the distance between CCS system retailer and shipyard is assumed to be 200km. The distance to scrapping shipyard is assumed to be 500km;

g) Emissions from transportation and fuel/lubricating oil productions are based on GaBi database. Emissions from transportation are related to the distance and weight of cargos. To derive the emission from fuel productions, the quantity of fuel/lubricating oil required is required and will be provided by calculation of consumptions by engines in operation phase [28];

h) The specific consumptions of NaOH and CaO are calculated based on engine specifications, carbon factor, absorption target and chemical reaction equilibrium. Based on the engine specification, the specific fuel oil consumption (SFOC) is 174g/kWh and specific lubricating oil consumption (SLOC) is 0.65g/kWh [29]. The carbon factor (CF) of HFO is 3.114kg CO_2/ kg fuel consumed. The emission reduction target is 20%. The molar masses of chemicals are listed below:

Table 7 Molar masses of chemicals

Chemical names	**Formula**	**Molar mass (g/mol)**
Carbon dioxide	CO2	44
Sodium hydroxide	NaOH	40
Calcium oxide	CaO	56

With all these information, the specific consumptions of NaOH and CaO (SNC and SCC) can be derived based on power generation:

$$SNC = SFOC * CF * 20\% * 80/44 = 197 g/kWh \quad (3)$$

$$SCC = SFOC * CF * 20\% * 56/44 = 138 g/kWh \quad (4)$$

i) The additional energy consumption is assumed to be proportional to the absorption target;

j) The life span of the ship is assumed to be 30 years which means the operation phase will last 30 years. The construction phase is done in year 1 and the scrapping phase will be carried out in year 31.

3.2. Life cycle inventory assessment

With the LCA schematic diagram and all these assumptions in Section 4.1, a full LCA model was established with the software, GaBi 5. The flows in the model are presented in Figure 6 considering material flows and energy flows. The blue arrows indicate all the material flows, such as, engine, CCS system, fuel oil, lubricating oil, NaOH and CaO. The black arrows present the diesel oil used in transportation. The red arrows show the electricity flow in construction and scrapping phases. The green arrow indicates the flow of nature gas which is only used in scrapping phase.

To evaluate the Global warming potential, CML 2001 is applied to normalize all the emissions involved. CML 2001 converts different emissions in to the unit of kg CO2 equivalent applying different normalization factors.

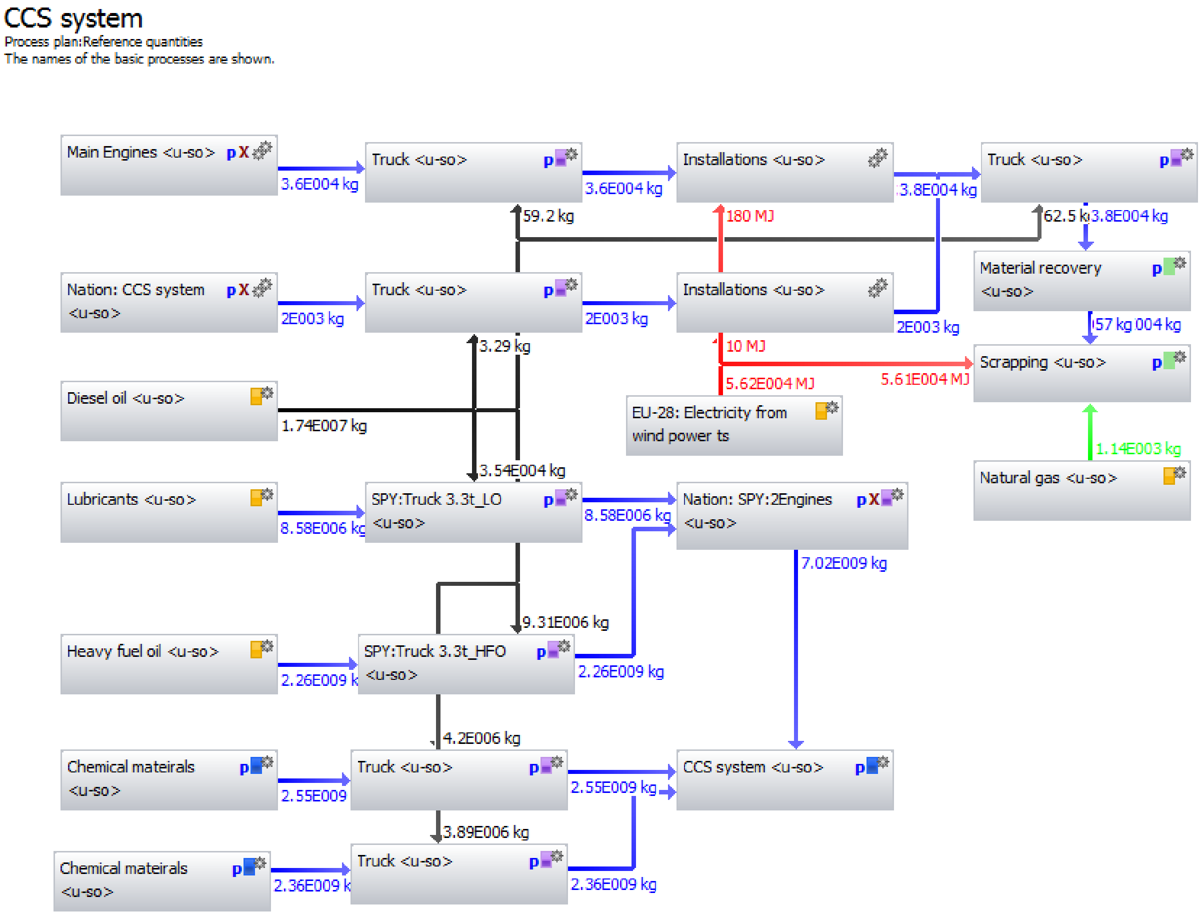

Figure 6 Full LCA model of ship

Based on this model, the emissions from three phases are determined and presented in Table 8. From this table, it is apparent that most of the global warming effect is generated from operation phase. It is because the ship is continuously consuming fuel and release emissions during its operation. After accumulation of 30 years, the amount becomes significant. The potential results from construction and scrapping phases are extremely small because the details in these phases are not considered. It is because for the same ship, majority of the processes in these two phases are identical. In this model, only the different parts of construction and scrapping are covered.

Table 8 Emission inventory

Phase	**Quantity**	**Unit**
Construction	240	kg CO2 equivalent
Operation	6.75E+09	
Scrapping	988	
Total	6.75E+09	

3.3. Life cycle impact assessment

Results from LCA model for CCS are derived and presented in Figure 7. There are 9 different scenarios considered with different carbon reduction targets from 0% to 50%. From the figure, it is obvious that with higher reduction target, the lower total life cycle GWP value is. The reason is that the extra emissions generated from the application of CCS system is far less than the absorbed emissions by the system.

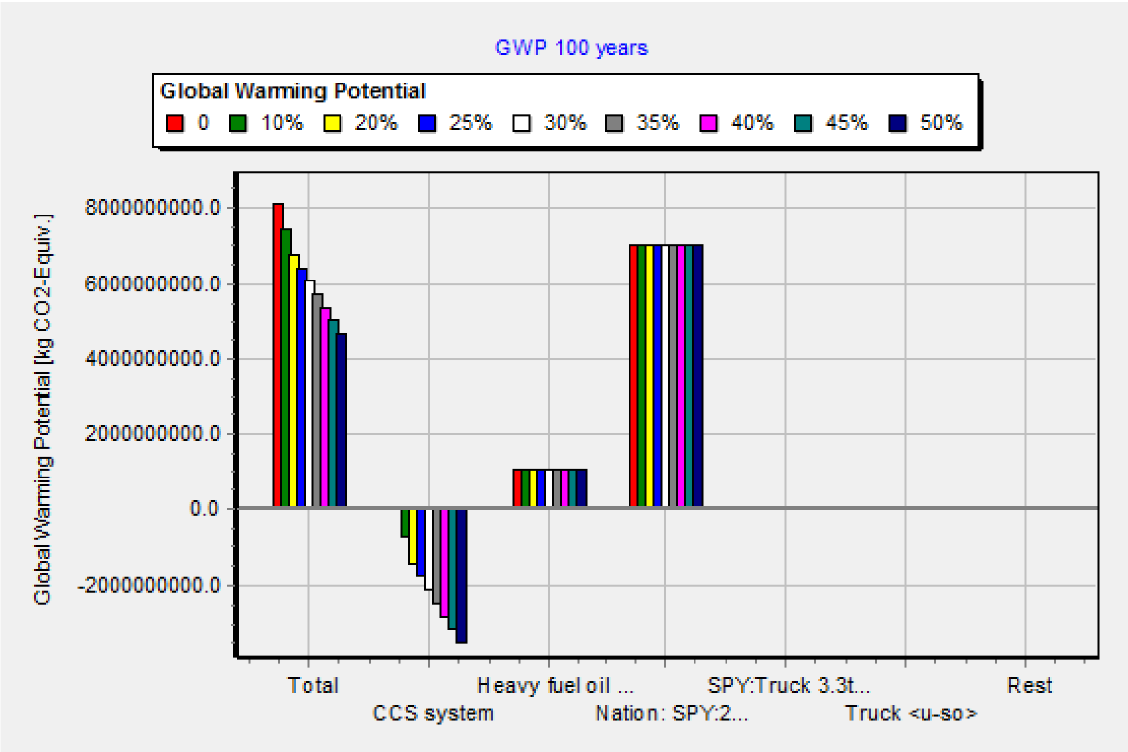

Figure 7 GWP over ship life span (30 year) vs carbon reduction targets

3.4. Sensitivity analysis on reduction targets

To examine the impact of the emissions from CCS system application to the real emission reduction rate. One table is generated to present the quantities of released and absorbed GWP under different emission reduction targets which are listed in Table 9. After evaluation, the actual reduction rates are derived and listed in the last row of the table. It illustrates that to reach a certain amount of reduction targets, there will be more emission generated due to the application of the CCS system. For example, if the reduction target is 20%, after 20% of emission is absorbed there will be extra emission generated due to the absorption.

Table 9 Carbon reduction rate under different reduction targets

Reduction targets	**0%**	**10%**	**20%**	**25%**	**30%**	**35%**	**40%**	**45%**	**50%**
Released GWP (10^9 kg CO2 equiv.)	8.13	7.44	6.75	6.41	6.07	5.72	5.38	5.03	4.69
Absorbed GWP (10^9 kg CO2 equiv.)	0	0.702	1.4	1.76	2.11	2.46	2.81	3.16	3.51
Total GWP (10^9 kg CO2 equiv.)	8.13	8.142	8.15	8.17	8.18	8.18	8.19	8.19	8.2
Real reduction rate	0%	9%	17%	22%	26%	30%	34%	39%	43%

Rate difference	0%	1%	3%	3%	4%	5%	6%	6%	7%

4. Discussions

As the objective of this paper is to provide a comprehensive method to evaluate current and under developed carbon reduction method, LCA technique and software are applied to established a model considering a large scope in a ship's life span. From this paper, different regulation levels, ranging from 0% to 50% reduction targets, are considered and the environmental impacts are presented in this paper. With these assessments, the performances of the selected methods could be determined and compared from the perspective of environment. The LCA evaluation processes are recommended to policy maker and ship owners so some advantages of the LCA evaluation processes are listed as following:

a) Large scope can be considered in the life span:
   A large scope makes difference results when the new installations or retrofits in one phase have an indirect relationship with different stages. In this case study, the CCS system is considered from construction to scrapping phase and in previous study, only operation phase was involved.
b) Quantities of individual flow can be tracked:
   For transportation as an example, the energy flows for different transportation activities are traceable in the LCA model. Similarly, the energy flows of electricity and natural gas can be tracked.
c) Environmental impact assessment:
   Environmental impacts are determined and compared. Future work will be done to consider the economic impact.
d) Reduce repeated works:
   The system includes many sub-models which could be modified and reused for other system.
e) Comparable results:
   Since the evaluations go through the same processes, the results are comparable and it could help make reasonable decisions.

5. Conclusions

This paper presents a comprehensive LCA assessment on carbon solidification system with evaluations on its environment impact. The results are compared with previous work and the results have a good agreement. With this validated LCA model, the impact of different emission reduction targets is evaluated. The results indicate although the targeted quantity of emission could be absorbed, there are extra emissions generated due to the application of the system. Therefore, in order to achieve certain emission reduction target, a higher target should be set up. The results present a high target will have a higher profit due to saving from carbon credits and trading of final products.

As an initial GHG reduction strategy will be adopted in 2018, this paper also recommends shipping industry to apply the LCA method to evaluate the candidates of carbon reduction technologies and strategies. It will provide an overall view of the system covering the installation, operation, maintenance and decommission phases from the aspects of environmental protection. Apart from policy maker, this LCA evaluation processes will be in favours of ship designers and ship owner because it will provide a detail review on the financial feasibility of the candidate method.

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