

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 warming 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 abatement. 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

51 and it also considered the cost associated with these factors such as the impacts of fuel
52 price, container transportation quantity, carbon credits, etc [3]. Chen's team evaluate
53 the impact of shipping route on the emissions from ships with data between Asia and
54 Europe. As a fact of emission restriction in ECA area, ships are intended to changing
55 route to go around the area which means the optimal route for fuel saving will not be
56 optimal any more [4]. Demirel et al. [5] developed a CFD model to estimate the
57 variation of plate roughness in different coating types in order to reduce the hull
58 roughness and increase the energy efficiency. An experimental study was also carried
59 out by Demirel et al. [6] to determine the relationship between bio-fouling and ship
60 resistance for an oil tanker and an LNG carrier. Their CFD results were validated with
61 experiments by Owen et al. [7].

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

66 Life cycle assessment is a popular method which has been widely used in many different
67 disciplines. Styles' team used LCA to quantify the growing of willow on river buffer zones and
68 results showed the benefit of willow cultivation on these area [8]. In fishing industry, Vázquez-
69 Rowe's research group investigated the edible protein energy return on investment (ep-EROI)
70 in Spain and LCA was to assess the energy consumption and environmental impact. These
71 results were expected to provide recommendations for EU's Common Fisheries Policy [9].
72 LCA is also applied to evaluate the power systems, both state-of-art and under developed, by
73 Fredga and Maler, especially on biofuel. A full scope of LCA model considering both emission
74 released and resource required is established in order to provide comprehensive analysis and
75 retrieve precise results [10]. There are also many valuable LCA works and researches in the
76 field of shipping industry: Blanco-Davis's works have applied LCA to aid the shipyards to
77 evaluate retrofitting performances of innovative ballast water treatment system and fouling
78 release coating [11][12]. The performance of fuel cell and diesel engines for marine
79 applications has been investigated and compared by Alkaner and Zhou with the help of LCA
80 [13]. Strazza's research team applied LCA to evaluate the environmental impact of paper
81 stream on a cruise ship with implementation of different green practices [14]. In addition,
82 Nicolai's team investigated the environmental impact related to commercial ships by
83 optimization of raw material and energy consumption, and recycle processes using LCA [15].
84 two case ship studies have been carried out by Ling-Chin and Roskilly to compare the hybrid
85 power system with the conventional marine engine systems in a comprehensive ship life cycle
86 phases - namely, construction, operation, maintenance, and scrapping [16][17]. With
87 inspiration from these researches, the authors have also carried out two case studies which help
88 shipyards and ship-owners to determine the optimal propulsion system for a short-routed
89 hybrid ferry and for an off-shore tug vessel from the perspective of economic and
90 environment[18][19].

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

97 **2. Methodology**

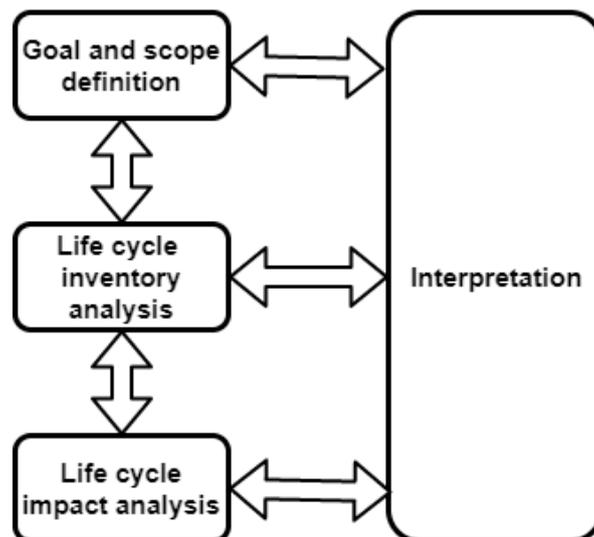
98 **2.1. Life cycle assessment**

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

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

124 Sensitivity analysis is also an essential part of LCA which will indicate the consequence of
125 input data changing. As there are many data involved in one LCA analysis, the analysis usually
126 focuses on the most fluctuated data and also the ones clients cared most. After changing the
127 value of one input data, a series of results will be obtained which will illustrate how the life
128 cycle assessment results changing with the varying of data.
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130
131 *Figure 1 Life cycle assessment framework*
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133 Apart from the framework of LCA, the processes consideration in an analysis is also significant.
134 Usually, the life cycle is comprised of four consecutively phases: raw material acquisition,
135 manufacturing, use/reuse/maintenance and recycle. In this paper, the target is about ships in

136 the shipping industry, the phases considered will be constrained and modified into a more
 137 relevant life cycle to ships (Figure 2): construction, operation/maintenance and scrapping.

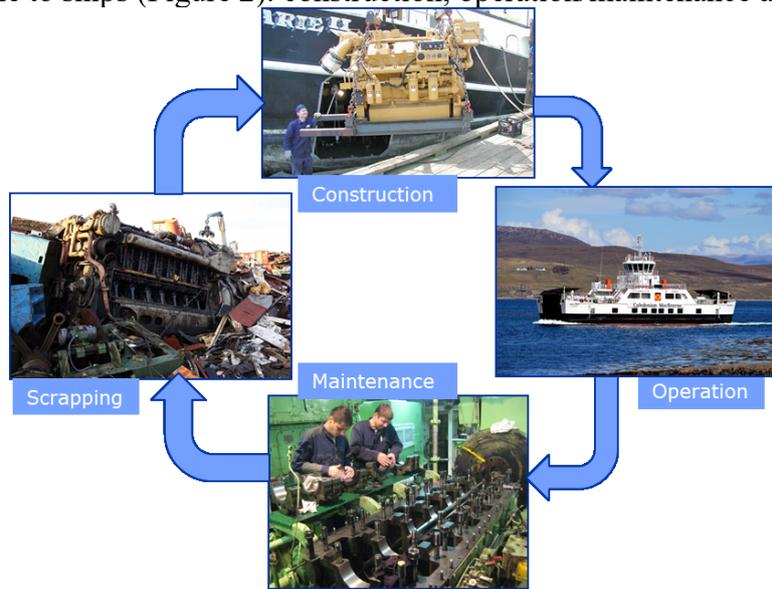


Figure 2 A general flowchart of ship life cycle

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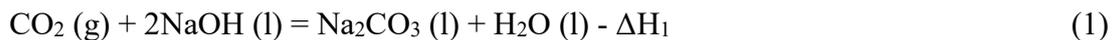
2.2. Carbon solidification

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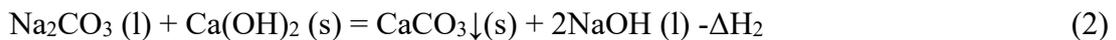
143 For carbon reduction method, there are many different technologies as mentioned previously
 144 focusing on different parts of ships, for examples, coating applications, route optimizations,
 145 speed optimizations and after treatment. This paper tests authors' previous work, carbon
 146 solidification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

148 The carbon solidification method applies chemical substances to absorb and solidify carbon
 149 content from the exhaust gases. The chemical reactions are listed as following (Zhou & Wang,
 150 2014):

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

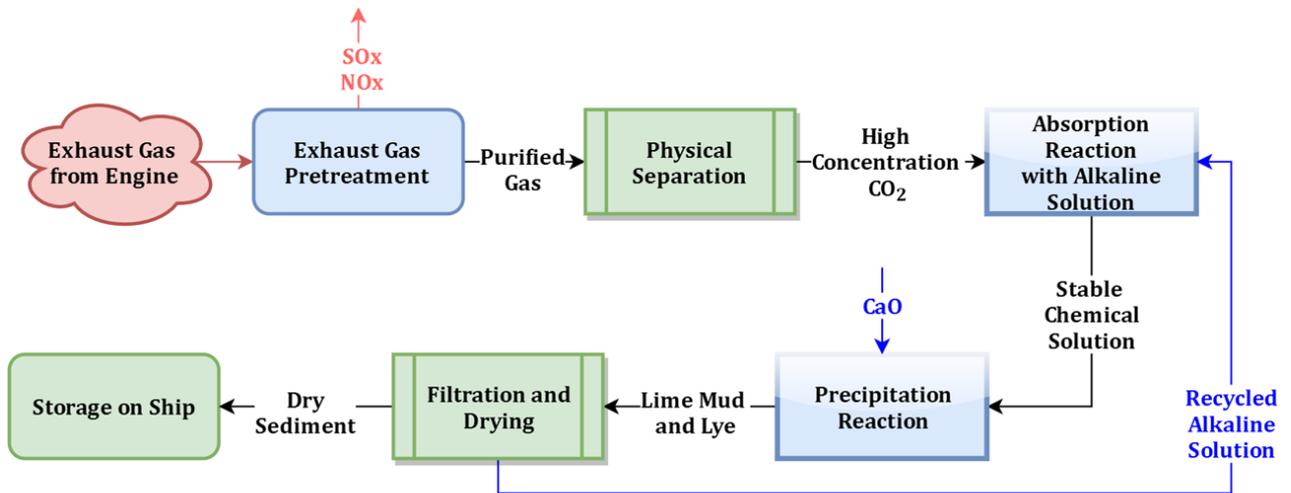


Figure 3 Schematic of chemical processes for carbon solidification on ships

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.

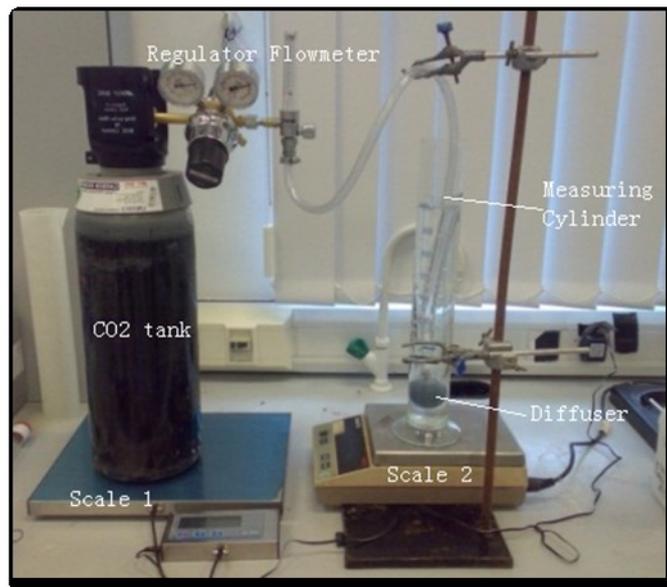


Figure 4 Experiment rig for carbon solidification process

Table 1 Experiment results

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

188 **3. LCA modelling**

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

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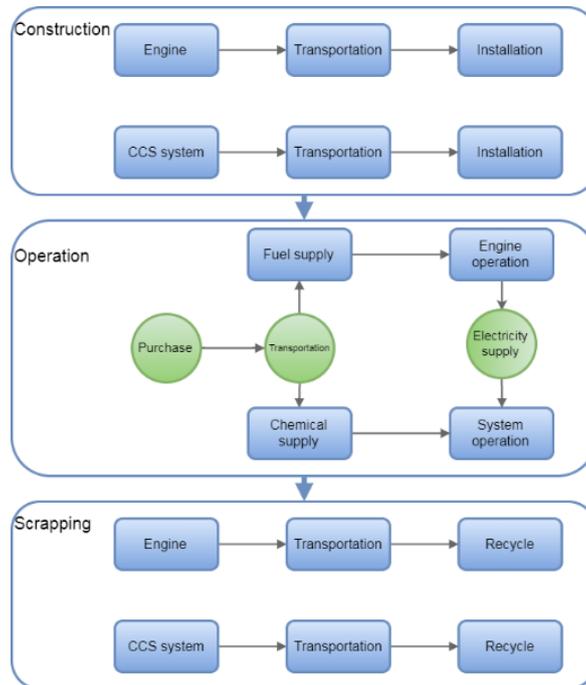


Figure 5 Schematic diagram of LCA scope and processes

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215 **3.1. Goal and scope definition**

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217 The goal of the life cycle assessment is to evaluate the environmental impacts of application of
218 CCS system on ship. The main impact considered is the global warming potential which is used
219 to assess all the energy, emission and material flows on their contributions to the global

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220 warming impact. As the application of CCS system will have an effect on engine output, the
 221 scope of the study is limited to engines and CCS system. The rest parts of the ship and its
 222 activities will not be impacted greatly. To initialize the life cycle assessment, several
 223 assumptions are made due to lack of data and also reduce the model complexity:

- 224 a) Carbon factor of HFO is 3.114 kg CO₂/ kg fuel consumed [26];
 225 b) GWP factor of significant emissions are listed in the following table [21];
 226

227 *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 ₂ O ₃	265
Methane	CH ₄	25

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 229 c) Case ship specification is presented in the following two tables:
 230

231 *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	

232
 233 *Table 4 Engine specification*

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

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 235 d) To consider the scrapping of engines, engine materials are listed in the following table
 236 [27]:
 237

238 *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

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

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Table 6 Energy requirements of engine materials in scrapping phase

<i>Item</i>		Steel and cast iron	Al	Cu	Zn	Pb	
<i>Energy</i>	MJ	Electricity	1.71	0.1	-	0.7	-
		Natural gas	0.62	10.22	-	0.3	-
<i>Emission</i>	kg	CO ₂	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

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- 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 CO₂/ kg fuel consumed. The emission reduction target is 20%. The molar masses of chemicals are listed below:

Table 7 Molar masses of chemicals

<i>Chemical names</i>	Formula	Molar mass (g/mol)
<i>Carbon dioxide</i>	CO ₂	44
<i>Sodium hydroxide</i>	NaOH	40
<i>Calcium oxide</i>	CaO	56

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

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

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

- 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

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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

280 and scrapping phases. The green arrow indicates the flow of nature gas which is only used in
 281 scrapping phase.
 282 To evaluate the Global warming potential, CML 2001 is applied to normalize all the emissions
 283 involved. CML 2001 converts different emissions in to the unit of kg CO2 equivalent applying
 284 different normalization factors.
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CCS system

Process plan:Reference quantities
 The names of the basic processes are shown.

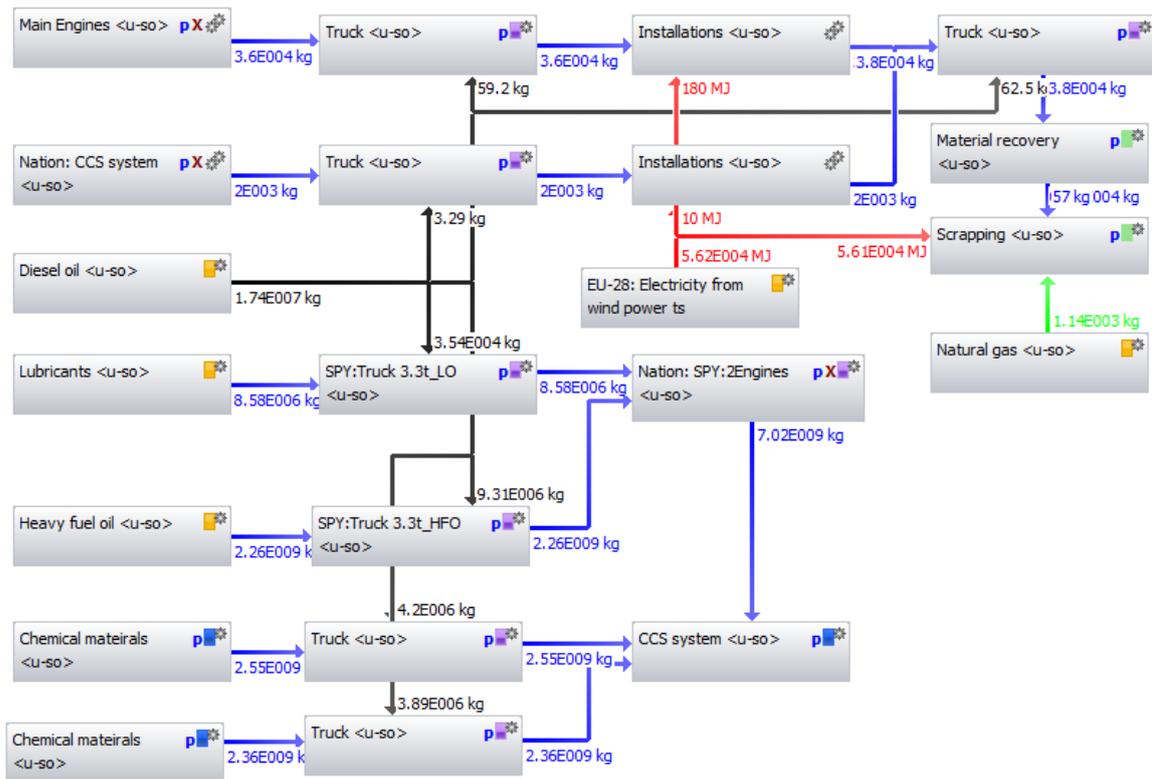


Figure 6 Full LCA model of ship

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

Table 8 Emission inventory

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

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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.

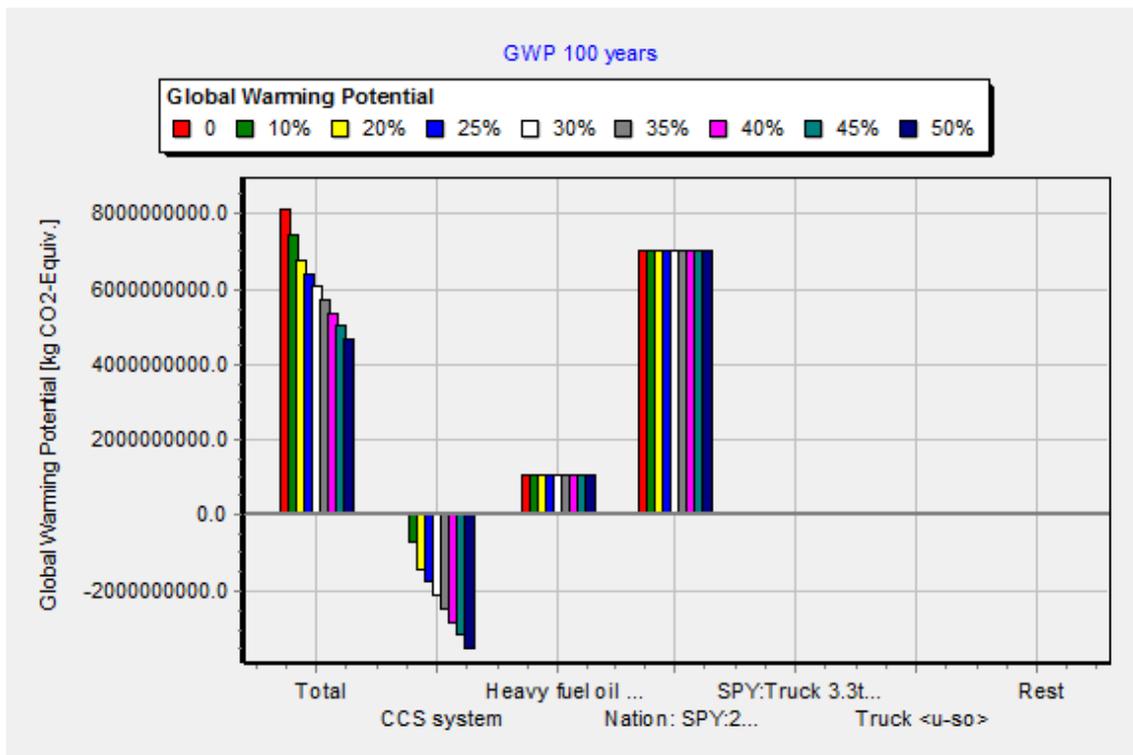


Figure 7 GWP over ship life span (30 year) vs carbon reduction targets

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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 CO ₂ equiv.)	8.13	7.44	6.75	6.41	6.07	5.72	5.38	5.03	4.69
Absorbed GWP (10^9 kg CO ₂ equiv.)	0	0.702	1.4	1.76	2.11	2.46	2.81	3.16	3.51
Total GWP (10^9 kg CO ₂ 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%

<i>Rate difference</i>	0%	1%	3%	3%	4%	5%	6%	6%	7%
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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.

6. Acknowledgment

373

374 Authors are grateful to the Department of Naval Architecture, Ocean and Marine Engineering
375 of University of Strathclyde for the support on the project. We also appreciate the Scottish
376 Environmental Technology Network for providing laboratory facilities and useful advices. We
377 also wish to confirm that there are no known conflicts of interest associated with this
378 publication and there has been no significant financial support for this work that could have
379 influenced its outcome.

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