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A COMPARATIVE LIFE CYCLE ASSESSMENT OF MARINE DESOX SYSTEMS

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ABSTRACT

With new sulphur oxides emission limits carried out in 2020, multiple desulphurisation methods have been proposed. The main desulphurisation scrubber systems were chosen and investigated using life cycle assessment. The whole system life is divided into the construction and operational phases. Three different systems classified by desulphurisers, namely, seawater, NaOH, and Mg-based systems, were modelled in GaBi software. Moreover, environmental, economic and energy aspects (3E model) were introduced for further analysis. Through this study, some conclusions have been drawn. As for the environmental aspect, the seawater system has the most pleasing performance since the primary emissions come from 1.24E+03 kg CO_2 and 1.48E+01 kg chloride. The NaOH system causes 1000 times more emissions than the seawater. The Mg-based system has less pollution than the NaOH system, with 5.86E+06kg CO_2 and 3.86E+03 kg chloride. The economic aspect is divided into capital expenditure (CapEx) and operational expenditure (OpEx) to estimate disbursement. The seawater system also has the most favourable cost appearance, which takes 1.7 million dollars without extra desulphuriser expenses, based on 10MW engine flue gas treatment. The next is the Mg-based system, which cost 2 million dollars in CapEx and $ 1200/year in OpEx for the desulphuriser. NaOH uses about 2.5 million dollars for construction and $ 30000/year in desulphuriser. As for the energy aspect, the seawater and Mg-based systems use less non-renewable energy than the NaOH system in the construction phase. In conclusion, the seawater system shows the best performance and could be an alternative in SOx control technologies. This study sheds light on the comprehensive evaluation of marine environmental protection technologies for further optimisation.

Keywords: life cycle assessment,desulphurization,3E model

INTRODUCTION

With the convenience of shipping transportation, an excess of vessels has caused terrible sulphur dioxide pollution with a negative effect on the ocean environment and human health. 2020 is a watershed in the controlling of marine SO_2 emissions since unprecedentedly strict regulations have taken effect. The International Maritime Organisation (IMO) stipulated that the sulphur content in fuel oil should be less than 0.5% m/m globally, starting from January 1st, 2020 [1], while in emission control areas (ECA), such as the Baltic Sea, below 0.1% m/m was adopted in 2015 [2].

In order to comply with the above standards, multiple SO_2 emission reduction methods have emerged in commercial applications. One is using low sulphur oil, but it has a higher cost with additional CO_2 emissions [3]. Another alternative is liquefied natural gas (LNG). Although LNG combustion emission is cleaner than that of fuel oils mentioned above, the structure of the ship has to be extensively modified, which increases the expenditure of design and implementation [4]. More importantly, the easily flammable property of LNG poses a threat on the operation of marine power plants [5]. Last but not least, exhaust gas cleaning systems (EGCS) have been employed which reduce SO_2 concentrations to the level equivalent to the combustion of low sulphur oil, via wet scrubbing or dry adsorption. Extensive research has been conducted on EGCS, including design, manufacture, installation, and global service. However, seldom does the research focus on the whole process of EGCS operation, that is, the deSOx process, which includes capital expenditure (CapEx) and operational expenditure (OpEx). Moreover, besides economic concerns, environment and energy impact should also be taken into account to appropriately evaluate the deSOx expenditure. Under this framework, different patterns of EGCS could be literally compared and the correct strategy for SO_2 emission control could be made accordingly.

In order to progress this purpose, life cycle assessment (LCA) was introduced into our research. As a tool to synthetically evaluate the process from cradle to grave, LCA has been published in many studies. As early as 1969, Midwest Research Institute (MRI) firstly quantified the resource, the emissions, and the waste by using LCA, helping factories to make decisions [6]. It became the foundation of LCA development. In recent years, LCA has gradually received more attention and is utilised in many fields. Zheng et al. used LCA to evaluate bicycle sharing based on a survey. The results showed that it was friendly to the environment except for metal consumption. However, in the sensitive analysis, the growth of rental fees and quantity of bicycles caused negative impacts [7]. Tomporowski et al. conducted comparison analysis for blade life cycle in land-based and offshore wind power plants, and they arrived at conclusions that land-based blades caused more harmful effects to water, while the offshore blade produced a more negative influence on the atmospheric environment [8]. In the environmental protection field, Wu et al. compared several gaseous pollutant control methods, including limestone-gypsum wet flue-gas desulphurisation (WFGD), selective catalytic reduction (SCR), and electrostatic precipitators (ESP) [9]. Effects such as global warming, acidification, nutrient enrichment, photochemical ozone formation, soot and ashes were taken into consideration. It was found that SCR consumed more energy while more water was used in the WFGD process, and the ESP process possessed excellent performance in environmental and economic aspects. Lopes et al. discussed the environmental performance of the whole wastewater treatment process installed in Bahia State, Brazil and the results showed that the environmental impact in construction also had considerable significance [10]. In the marine field, a comparative study of marine power systems employing LCA was performed [11]. The results showed that a new-build system had a mitigation potential, while a retrofitted one was environmentally benign, due to incorporated emerging technologies. Hwang et al. estimated the environmental impact of ships using MGO, natural gas, and hydrogen. The results showed that the emissions from natural gas in the Well-to-Tank phase were lower than MGO and hydrogen but created more CO_2 than MGO in the Tank -to-Wake phase [12].

The aforementioned studies resorting to LCA tools have comprehensive analysis, but fewer papers concentrate on the whole life of a scrubber including construction and operation. Based on the above experience, our study will compare different marine deSOx systems by means of LCA from the environmental, economic, and energy aspects (3E model).

METHODOLOGY

According to the ISO 14040 issued by International Standard Organisation (ISO), four steps are involved in LCA. First, the goal and scope of the study should be defined [13]; then real data are collected to perform inventory analysis and produce an impact assessment [14]; and the last step is interpretation [15]. It has close-knit relationship between the four steps, as shown in Fig.1.

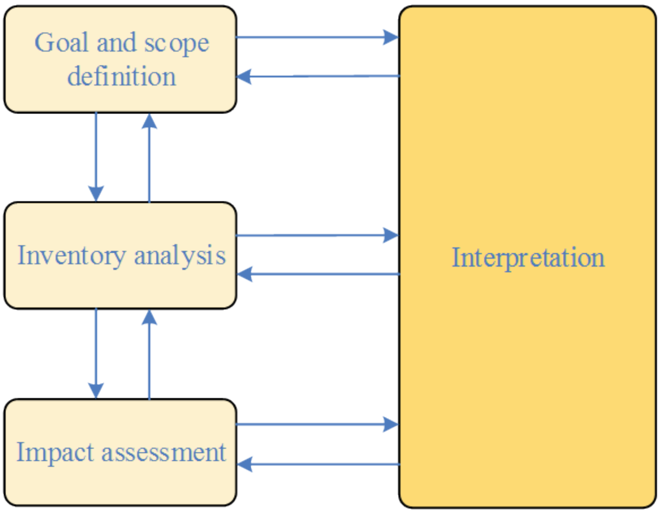

Fig.1. LCA framework

GOAL AND SCOPE DEFINITION

The goal of our study is to compare three deSOx scrubber systems based on LCA and to come up with measures to optimise the system in terms of the results. Before we start to analyse, we need to determine the scope of the system.

For the three systems, we used a 10MW diesel engine as the function unit, from which flue gas emissions could be treated by various systems. In this respect, the performance could be equally assessed and compared. It is assumed that each deSOx system works for 20 years and operates 7000 hours each year [16]. The system boundaries are composed of the input and output flows [17]. The input flows consist of energy and resources, while emissions such as solid waste, waste-water and air pollutants are output flows, which are described in Fig.2.

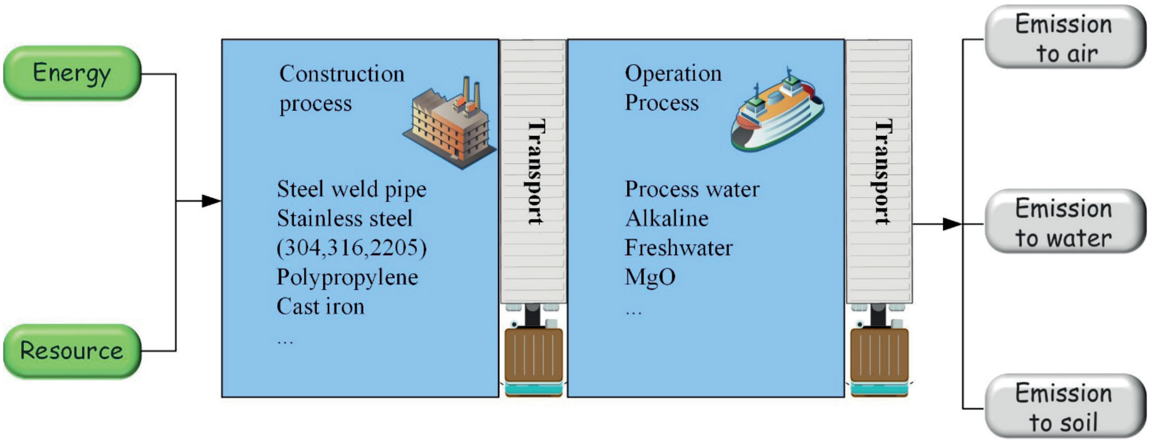

Fig. 2. System boundaries for deSOx process

INVENTORY ANALYSIS

As shown in Fig.1, inventory analysis takes an important role in the whole LCA process, since it is the basis of the interpretation, and needs to set up models for systems. This part also needs to ensure the quality and precision of the practical data, which can help us to gain reasonable results. The following diagram shows the three different deSOx systems investigated. They could be divided into four parts on the basis of types of desulphuriser: the blue part is the all-purpose part; the seawater system consists of the orange part and the all-purpose part. The green part plus the all-purpose part constitute the magnesium-based (Mg-based) system. The last part is the purple part, combined with the all-purpose part, representing the NaOH system.

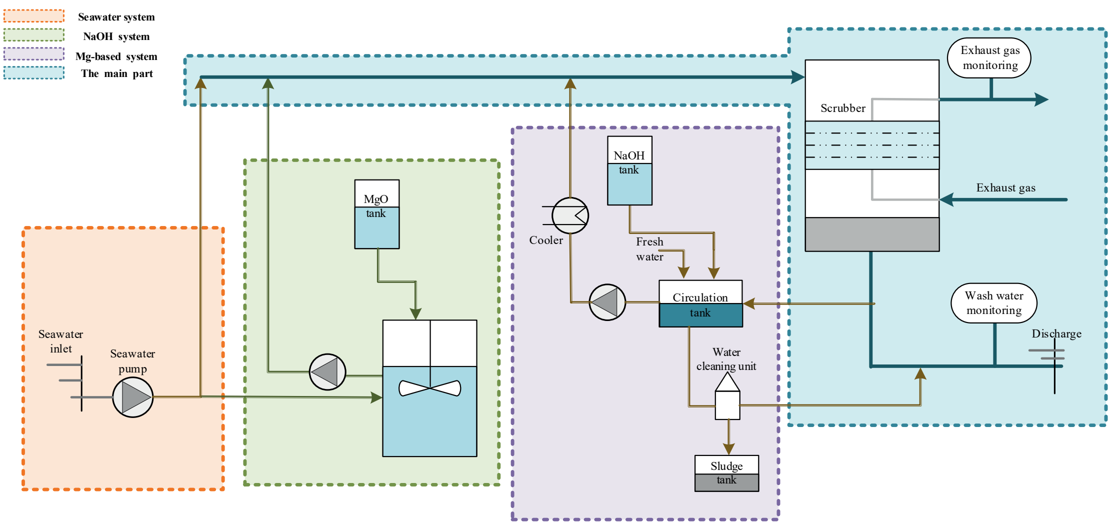

Fig. 3. The desulphurisation scrubber system of our research object

Seawater system

The seawater system, also called the open loop system, uses natural seawater to absorb SO_x and the products are directly or indirectly discharged to the surrounding environment [18]. The seawater is easily acquired while sailing and so the installation is easily fulfilled. The working principle of the seawater system includes SO_x directly absorbed by seawater, which is described by chemical reactions as follows [19]:

$$SO_2(g) \leftrightarrow SO_2(aq) \tag{1}$$

$$SO_2 + H_2O \leftrightarrow HSO_3^- + H_3O^+ \tag{2}$$

$$HSO_3^- + H_3O^+ \leftrightarrow SO_3^{2-} + H_3O^+ \tag{3}$$

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \tag{4}$$

$$H_2CO_3 + H_2O \leftrightarrow HCO_3^- + H_3O^+ \tag{5}$$

$$HCO_3^- + H_3O^+ \leftrightarrow CO_2 + 2H_2O \tag{6}$$

The orange part and blue part describe the subsystems of the seawater system. It can be divided into four main components—flue gas piping, the scrubber, seawater supply, and discharge pipelines. Thanks to basic soluble salts contained in seawater, the exhaust gas accesses the scrubber and could be neutralised repeatedly by seawater until the cleaned gas satisfies the emission standard, as shown above.

NaOH system

The NaOH system, also known as the closed loop system, will operate when the alkalinity of seawater is not sufficient, for example, with pH values below 6.8, or where waste-water discharge is forbidden in some special sea areas. In this case, the deSOx process needs to use stored alkaline solution to absorb SO_X. The system is more complex than the seawater one. The principle of this mode is described as follows [20]:

$$H_2SO_3 + 2NaOH + 1/2\,O_2 \leftrightarrow Na_2SO_4 + H_2O \quad (7)$$

$$H_2SO_4 + 2NaOH \leftrightarrow Na_2SO_4 + 2H_2O \quad (8)$$

The green part and the all-purpose part describe the subsystems of the NaOH system. It can be divided into five main components—flue gas piping, the scrubber, freshwater supply pipelines, lye circulation, and discharge disposal. Fuel gas comes into the scrubber and reacts with NaOH, then the wash water can be reused many times before being further processed and discharged.

Mg-based system

The Mg-based system combines the MgO with seawater to reduce the concentration of sulphur oxides due to the good solubility of seawater for MgO, and the shortage of freshwater on board. Specifically, MgO dissolves in the seawater, which largely depends on the alkalinity of the absorption liquid and then forms $Mg(OH)_2$ to absorb SO_X [21]. The principle of this mode is described as follows [22]:

$$SO_2(g) \leftrightarrow SO_2(aq) \quad (9)$$

$$Mg(OH)_2 + SO_2 \leftrightarrow MgSO_3 + H_2O \quad (10)$$

$$MgSO_3 + H_2O + SO_2 \leftrightarrow Mg(HSO_3)_2 \quad (11)$$

The purple part and the blue part describe the subsystems of the Mg-based system. It consists of four main components—the flue gas piping, the scrubber, magnesium oxide slurry preparation, and washing water discharge. The magnesium oxide slurry is mixed with the seawater to form $Mg(OH)_2$. The mixture is conveyed to the scrubber to reduce the SO_X concentration. After absorption, the product will be directly discharged to the sea owing to the environment-friendly properties of Mg-based materials.

Application

After introducing the three systems, in this part we collect the data from a real working state as our study object. A typical flue gas from a10MW diesel engine was used, with SO_2 concentration equivalent to combustion of 3.5% S containing fuel oil. The whole life cycle is divided into two phases, called the construction and operation phases. The construction phase includes material preparation and transportation, while the operation phase includes desulphuriser preparation and freshwater storage.

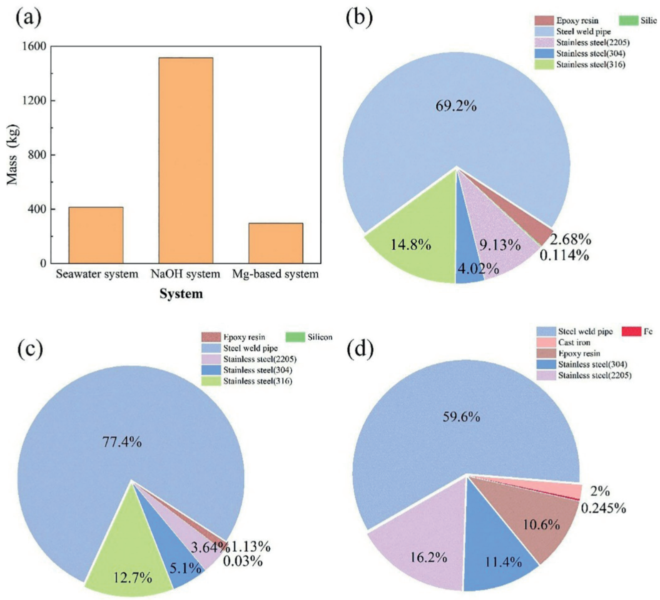

Fig. 4. Material preparation (a)sum mass; (b)seawater system; (c)NaOH system; (d)Mg-based system

Each and every system has a definite architecture utilising a different amount of materials in the construction phase. Fig.4 (a) displays the weight of materials expending each year by three $deSO_X$ systems and the residual pictures show the portion of materials used the in respective systems. The seawater and NaOH system together use diverse stainless steels, steel weld pipe, epoxy resin and silicon, while beyond that, the Mg-based system also uses Fe and cast iron. Different types of stainless steel with various chemical compositions are used for special purposes according to the application. For example, stainless steel (2205) has better corrosion resistance than the others used in the scrubber, as shown in the following picture. Fig.5 presents the disparate stainless steels used in deSOx systems and it is worth mentioning that more epoxy resin was used in Mg-based system instead of stainless steel (316) in construction. After collecting the practical data, the model was established in GaBi software. GaBi was used to obtain the related data, in which the original data are from industry, academia, education, and policy and regulation making departments.

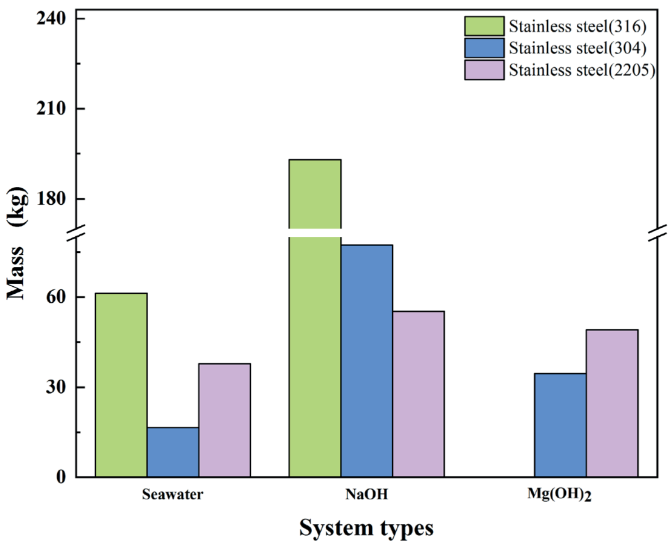

Fig. 5. Amount of different types of stainless steel used in deSOx systems

IMPACT ASSESSMENT

In order to assess the environmental impact, the assessment methodology should be determined. Several methodologies have been published, such as ReCiPe2016, TRACI, PEF and so on. ReCiPe2016 has been chosen to assess the impact through these data in the subsequent statement. ReCiPe2016 is an endpoint assessment model, which consists of CML2001 and Ecoindicator99 and it can be seen as a fusion of the two methodologies, taking the midpoint impact categories from CML2001 and the endpoint impact categories from Ecoindicator99 [23]. The ReCiPe2016 has three perspectives—individualist, hierarchist, and egalitarian, and we chose the hierarchist perspective to investigate the impact mechanism [24].

In more detail, the midpoint impact categories orient to the environment, such as global warming and acidification. The endpoint impact categories are split into three parts, which are human health, biodiversity, and resources. The following picture shows the relation between the midpoint and endpoint indicators in ReCiPe2016 [25].

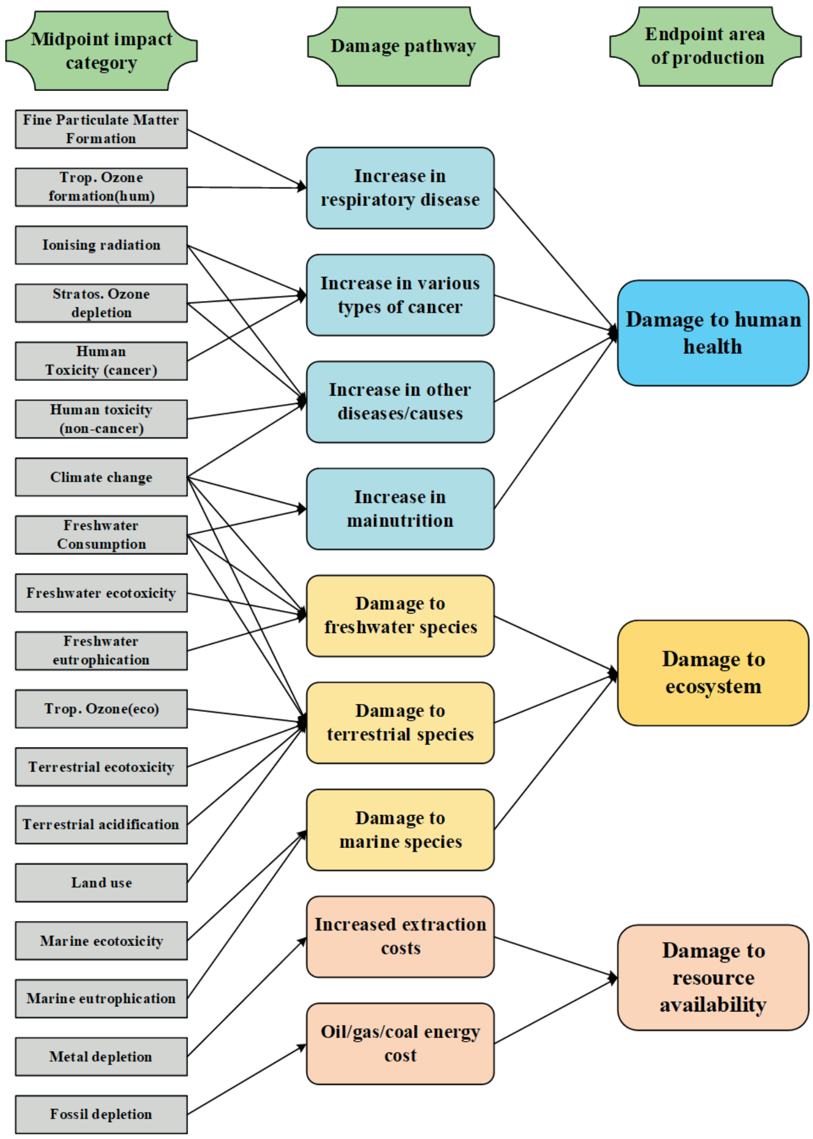

Fig. 6. Relationship between midpoint and endpoint indicators in ReCiPe2016[26]

RESULTS AND DISCUSSIONS

LIFE CYCLE INVENTORY ASSESSMENT

In the construction phase, desired materials for each $deSO_X$ system were prepared based on design. The following operation phase relies on electricity for washing water preparation, in which seawater or freshwater is incorporated into the desulphurising agent. The transporting process is based on the following assumptions: 1) a truck was employed; 2) diesel was used as the fuel; and 3) the average distance was about 100km. As a result, the total consumption of diesel could be estimated. Note that diesel not only provides power to the truck but also delivers an influence on the surroundings during transportation. Table 1 shows the abbreviation and the assessment unit of these category indicators. It simplifies the description of indicators in the subsequent analysis.

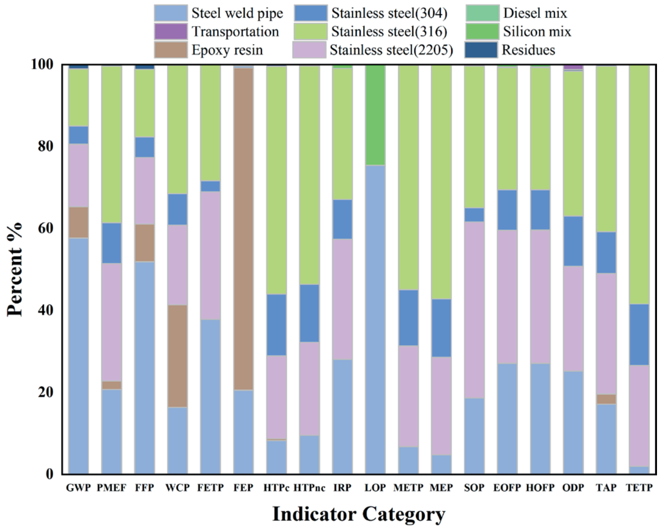

Fig. 7. Seawater system inventory in construction phase

Tab. 1 The abbreviation and the assessment unit of category indicators

Impact category	Abbr.	Unit	Impact category	Abbr.	Unit
Climate change	GWP	kg CO_2	Land use	LOP	m^2 land
Fine Particulate Matter Formation	PMFP	kg PM2.5	Marine ecotoxicity	METP	kg 1,4-DCB
Fossil depletion	FFP	kg oil	Marine Eutrophication	MEP	kg NO_X
Freshwater Consumption	WCP	m^3 water	Metal depletion	SOP	kg Cu
Photochemical Ozone Formation, Human Health	HOFP	kg NO_X	Photochemical Ozone Formation, Ecosystems	EOFP	kg NO_X
Freshwater Eutrophication	FEP	kg PM2.5	Freshwater ecotoxicity	FETP	kg 1,4-DCB
Human toxicity, cancer	HTPc	kg 1,4-DCB	Stratospheric Ozone Depletion	ODP	kg CFC-11
Human toxicity, non-cancer	HTPnc	kg 1,4-DCB	Terrestrial Acidification	TAP	kg SO_2
Ionising Radiation	IRP	kBq Co-60	Terrestrial ecotoxicity	TETP	kg 1,4-DCB

Seawater system inventory

Table 2 shows that part of the emissions in the seawater system and primary air emission is about 1.24E+03kg carbon dioxide, which results in global warming, and the major water emission comes from chloride which is naturally present in the seawater.

Tab. 2 Emissions of the seawater system

Emission to air	Mass(kg)	Emission to water	Mass(kg)
Dust (PM10)	6.04E-01	Nitrate	7.55E-02
Dust (PM2.5)	1.76E-01	Carbonate	1.83E-01
Nitrogen oxides	2.46E+00	Calcium	6.43E-01
Methane	3.93E+00	COD	9.34E-01
Sulphur dioxide	6.70E+00	Sulphate	1.07E+00
Carbon monoxide	7.99E+00	Sodium	4.19E+00
Carbon dioxide	1.24E+03	Chloride	1.48E+01

The seawater system only has a construction phase because it works without an extra desulphuriser. In this system, seawater has a natural alkalinity to cut down the concentration of SO_2 and will be discharged into the sea for disposal. Fig.7 shows the inventory percentage of the seawater system. In general, this system is quasi self-sufficient to reduce the sulphur oxides.

From above, we can see that the steel weld pipe and three types of stainless steel appear in most of the indicator categories. The steel weld pipe plays the leading role in the GWP, FFP and LOP. Three kinds of stainless steel have different distributions in that 316 occupies the most ratios in the indicators, and the least one is 304. Epoxy resin holds over 78.7% parts in the FEP, and no more than 30% has an effect on GWP, PMEP, FFP, WCP and TAP. The silicon mix leads the LOP signal, accounting for 24.6%. As a result, the system is simple to install with environmental-friendly properties. Moreover, due to the seawater being adopted and discharged during sailing, less complexity can be observed in this system.

NaOH system inventory

Table 3 presents the main emissions in the NaOH system. It is obvious that carbon dioxide and nitrogen oxides discharge approximately 1000 times as much to the air as the seawater system. Furthermore, particulate matter is not neglectable, which is the origin of ozone depletion. Although some means are taken to reduce the concentration of sulphur oxides, the inescapable emissions to water show that chloride and calcium are in the majority, followed by sodium, sulphate, and COD (Chemical oxygen demand).

Tab. 3 Emissions of the NaOH system

Emission to air	Mass(kg)	Emission to water	Mass(kg)
Dust (PM10)	1.00E+00	Magnesium	8.74E+01
Hydrogen chloride	4.75E+01	Nitrate	2.71E+02
Dust (PM2.5)	1.04E+02	Iron	6.82E+02
Ammonia	1.15E+02	Fluoride	9.67E+02
Group NMVOC	2.48E+02	COD	1.35E+03
Sulphur dioxide	8.18E+02	Sulphate	2.32E+03
Methane	1.98E+03	Sodium	6.53E+03
Nitrogen oxides	2.33E+03	Calcium	1.28E+04
Carbon dioxide	1.30E+06	Chloride	4.07E+04

As mentioned above, the NaOH system could be evaluated from the construction and operation phases. On the basis of the model in GaBi, the construction phase has a total of 1516 kg materials each year, while the operation phase is composed of 2135 tons of 50% alkaline solution and 7000 tons process water as the solvent. We combine the two processes to see the whole life cycle effect. The NaOH system inventory is described in Fig.8.

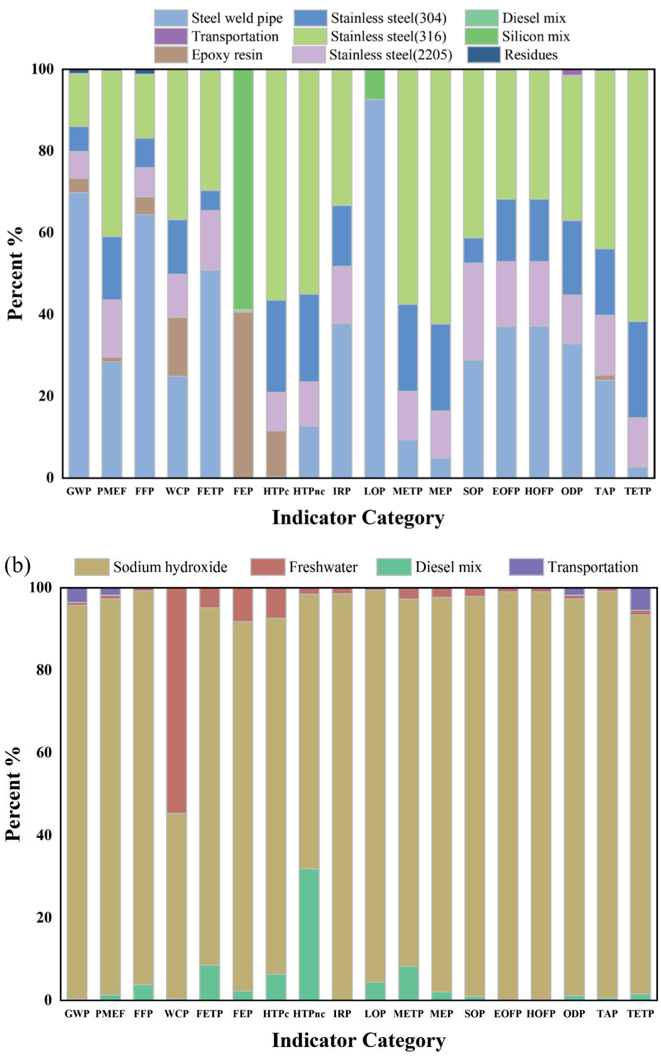

Fig. 8. NaOH system inventory (a)construction phase; (b)operation phase

From the construction phase, steel weld pipe and stainless steels are in the majority of categories except for FEP, which comprises diesel mix, epoxy resin and stainless steel (2205) in decreasing sequence. Silicon also affects LOP, while steel weld pipe and epoxy resin have influences in GWP, PMEP, FFP, WCP and TAP. From the operation phase, sodium hydroxide has an effect on most of the categories, up to more than 70%. It is noticed that WCP not only consist of sodium hydroxide, but also freshwater which has over a 50% ratio. The impact of diesel-mix and transportation become more distinct compared to the construction phase.

The addition of sodium hydroxide increases the absorption of SOx. However, the chemical material has a severely harmful effect on the environment from manufacture to usage. Besides, the NaOH system needs extra freshwater to dilute the alkaline solution, which increases the transport consumption.

Mg-based system inventory

Table 4 shows the main emissions in the Mg-based system. In this system, carbon dioxide occupies about 5.86E+05kg in the contribution to the air, followed by sulphur dioxide, PM2.5 and PM10. Emissions to the water mainly stem from chloride, followed by COD, calcium, sulphate, and sodium.

Tab. 4 Emissions of the Mg-based system

Emission to air	Mass(kg)	Emission to water	Mass(kg)
Tin	4.50E+00	Nickel	6.76E-02
Manganese	7.87E+00	Manganese	2.11E-01
Nitrogen oxides	1.03E+03	Chromium	5.15E-01
Methane	1.25E+03	Magnesium	3.06E+01
Dust (PM2.5)	1.29E+03	Iron	5.98E+01
Dust (PM10)	1.29E+03	Calcium	2.20E+02
Sulphur dioxide	1.29E+03	COD	2.67E+02
Carbon dioxide	5.86E+05	Chloride	3.86E+03

The Mg-based system can be divided into two processes like the NaOH system, as shown in Fig.9. The Mg-based system also uses epoxy resin, steel weld pipe and stainless steels, the same as the NaOH system, with the addition of 122kg cast iron and 14.8kg Fe.

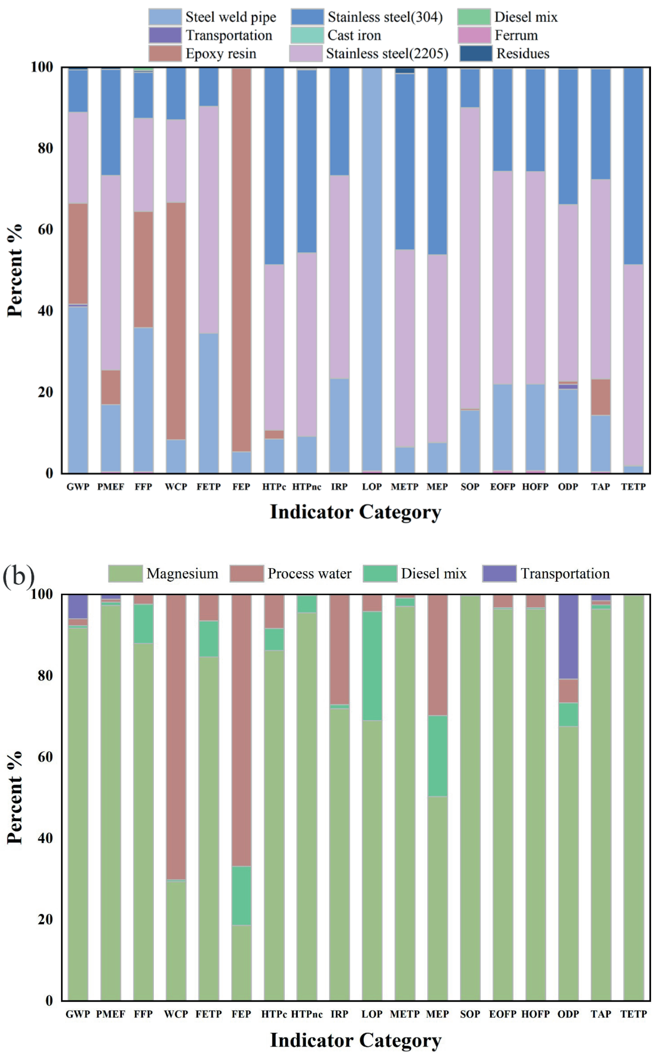

Fig. 9. Mg-base system (a)construction phase; (b)operation phase

From Fig.9 (a), it can be seen that the steel weld pipe and stainless steels play important roles in most of environment indicators. Epoxy resin has a leading role in FEP and a prominent influence in GWP, PMEP, FFP and WCP, while it has slightly less impact in HTPc, MEP and ODP compared with the NaOH system.

The Mg-based system employs seawater because freshwater is scarce when sailing. Moreover, seawater can increase the solubility of MgO. Thus, it will be cleaner and save resources. In the operation phase, magnesium occupies a large part of the affected indicators. Due to the considerable amount of materials that need to be transported, diesel mix, and transportation impacts appear in most of indicators except MEP, SOP, EOFP and TETP.

COMPREHENSIVE EFFECT BASED ON 3E MODEL

Corresponding to the ReCiPe2016 endpoint indicators, we combined the 3E model with the GaBi results for further analysis.

Environmental aspect

The environmental emissions are divided into three main parts, which are emissions to air, emissions to water, and emissions to soil. The important parts in our scope are emissions to air and emissions to water. These damages contact with our daily life and the poor environment results in the growth of disease. The analysis results could further help us to make decision to promote the quality of life. According to the LCIA result, it shows that the Mg-based system is better than the NaOH system in regard to global warming. The seawater system causes less pollution than the others because it uses less materials. More particulate matter was observed in the Mg-based system than the other systems. Chloride tends to have the leading role in emissions to water, while sodium and calcium cannot be neglected.

Above all kinds of materials used, the steel weld pipe and the stainless steel not only show a superior quantity, but also have obvious influences in most of the indicators. The smelting process in metallurgical refinery is known as the origin of abundant pollution. Due to the more radiant molecule produced, they can cause harm to humans and the ecosystem. However, steels have pretty good corrosion and abrasion resistance, and in most cases, they are often the best choice in the industry. The main FEP impact by epoxy resin during fabrication is significant on account of amine and other inactive diluents. In the operation phase, the desulphurisation agent addition causes water consumption and gives rise to the use of freshwater or seawater. Besides, the preparation of the desulphuriser is a prominent reason for the cost of the transportation and diesel mix.

Economy aspect

This part can be assessed by life cycle cost (LCC) in GaBi software, which calculates the spending in the whole life cycle process. Because of the global warming, the ecosystem verges to the poor status, meanwhile the balance is destroyed by reason of over exploitation. However, for ship owners, economy occupies a vital consideration as well as performance, hence analysing synthetically is conducive to saving economic costs. On the assumption that the cost of installation and maintainence are quantified, we primarily compared the cost of the desulphuriser to show the economic effect fairly.

Tab. 5 Expenditure comparation in CapEx and OpEx

	Seawater system	NaOH system	Mg-based system
CapEx ($)	1.69E+06	2.49E+06	1.91E+06
OpEx ($/year)	/	3.00E+04	1.20E+03

According to practical expenditure data incorporated with our project, CapEx and OpEx estimation is shown in Table 5. The major compared objects are the Mg-based system and the NaOH system because without the extra desulphuriser, the seawater system dispenses with OpEx. On the subject of CapEx, NaOH uses about 2.5 million dollars while the Mg-based system costs less than the NaOH system, by approximately two million dollars. As for OpEx, the expenditure of the desulphuriser is taken into consideration. NaOH is about

260$/t and the total cost reaches $ 30000 per year. In the Mg-based system, MgO is about 60$/t and the total cost is no more than $1200 per year. As for the seawater system, it takes about 1.7 million dollars to accomplish construction. In a word, the seawater system is tentatively ascribed as the best choice of the three deSOx systems from an economic aspect.

Energy aspect

Table 6 shows the primary energy used in the deSOx systems during the construction phase. The quantity of the following five kinds of fuels were estimated in the three deSOx systems. From Table 6, it can be found that the NaOH system consumes more fuel than the others. The Mg-based and seawater systems have a similar quantity of materials. These primary energies mainly provoke fossil fuel depletion (FFP) because they can provide high heat values.

Tab. 6 Primary energy consumption estimated in the deSOx systems

Material	System mass(kg)		
	Seawater system	NaOH system	Mg-based system
Crude oil	3.75E+01	1.03E+02	4.30E+01
Hard coal	3.69E+02	1.33E+03	2.77E+02
Lignite	1.86E+01	6.05E+01	1.10E+01
Natural gas	7.33E+01	2.13E+02	9.58E+01
Peat	7.70E-01	2.27E+00	6.88E-01

As the primary energy sources, crude oil, hard coal, lignite, natural gas, and peat have become the focus. They are fundamental to the production of all kinds of materials constituting the system, and also the fundamental input flows in the LCA. With a shortage of primary energy, every part needs to be used efficiently. Moreover, other alternatives are under development, such as wind and solar energy. We prefer to use cleaner energy to protect the natural environment.

CONCLUSIONS

Under established strict standards, efficient marine emissions control has been taken into account. In order to treat the exhaust gas of marine engines, the performance and economy are considered in the first place. So, this study uses LCA tools to estimate the performance of three deSOx systems, from cradle to grave, that is, seawater, NaOH, and Mg-based systems. The results were combined with the 3E model to analyse the construction and operation phases from the environmental, economy, and energy aspects.

In summary, the part we pay more attention to is the environmental effect. The emissions to air and water are predominantly caused by the NaOH system which produced the largest amount of CO_2 and chloride in the construction phase for a 10MW engine flue gas treatment, i.e. 1.30E+06kg and 4.07E+04kg, respectively. Furthermore, the results show that the seawater system seems more cleaner with 1.24E+03kg CO_2 and 1.48E+01kg chloride. Less than 450 times emissions are induced by the Mg-based system, generating 5.86E+05kg carbon dioxide and 3.86E+03kg chloride. From the economic aspect, the least payment of desulphuriser is achieved by the seawater system, which use natural seawater without additional cost, the Mg-based system spends about $1200 per year while the NaOH system costs $30000 per year. From the energy aspect, the most is consumed by the NaOH system which uses more than 10 times the weight of primary energy, except for lignite, compared with the Mg-based and the seawater system in the construction process. In a word, the seawater system has the best performance among all the deSOx systems investigated in this research. However, the efficiency of seawater also needs to be considered in practical use. This work provides valuable opinions for boosting technologies of ocean environment preservation in the future.

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