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Life Cycle and Cost Assessment of a Marine Scrubber Installation

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ABSTRACT

This paper is to provide a guidance as to which scrubber system is applied for marine vessels in both environmental and economic perspectives. It performs a comparative analysis for two different types of wet scrubber systems: they are generally referred as*"open loop"* and *"closed loop"* systems. Those systems are evaluated via life cycle assessment technique, which is further used for evaluating the global warming, acidification and eutrophication potentials. The economic aspect of the scrubber installation will be estimated by establishing the payback time of the installation costs. Sensitivity analysis is performed to determine the effect of various economic scenarios on payback times. Research results reveal that the environmental impacts are higher for the closed loop scrubber than open loop scrubber. The open loop scrubber has a marginally shorter payback time under different scenarios; for No EGCS (MGO) case, it was revealed 3.2 years (with open loop) and 3.6 years (with closed loop), and for No EGCS (VLSFO + MGO) case, 5.4 years (with open loop) and 5.9 years (with closed loop).

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Introduction

Since 1 Januaryst, 2020, IMO regulations only allow a maximum of 0.5 % sulphur content in ship fuels. Even a stricter limit of maximum 0.1 % sulphur content has been applied to Emission Control Areas (ECA) since 2015 (IMO 2020). To comply with the current sulphur limits, there has been a remarkable increase of scrubber installations in the world merchant fleet (Kinch 2020).

Past research on economic benefits

Scrubber technologies for marine vessels are commonly divided into two categories: dry and wet scrubbers. Several studies examining cost-benefit of scrubber systems have come to similar conclusions. The price difference between HFO and MGO, time spent in emission control areas and remaining lifetime of the ship are all deemed as fundamental factors to consider when contemplating a scrubber installation (Abadie, Goicoechea, and Galarraga 2017; Christensen, Jiang, and Kronbak 2014). Gu and Wallace (2017) argue that some of the benefits of using scrubbers to comply with emission regulations are overrated. Their study indicates that if potential route optimisations (to minimise time in ECAs) were to be included when considering a scrubber installation, the investment in a scrubber system may appear less profitable compared to common scenarios presented in other studies.

As part of a large project concerning the practical application of a scrubber system onboard a Stena Line operated ferry, the Swedish Environmental Research Institute conducted an extensive study consisting of several activities. From an emission perspective, the study found that the emission factors of SO_2 and hydrocarbons are lower with a scrubber compared to when operating on VLSFO's (Fridell et al. 2018, p.6). However, from an overall perspective, it was established that operating on LSFO is preferable over having a scrubber system while operating on HFO (Malmaeus et al. 2018, p.7). This argument brings our attention to the necessity of further investigation on whether scrubber systems are truly effective or even harmful from a holistic environmental perspective.

Life cycle assessment

The established measures for marine environmental indicators known as Energy Efficiency Design Index (EEDI) and Energy Efficiency Operational Indicator (EEOI) do not cogitate the emission potentials associated with marine systems (IMO 2014). In other words, there is a lack of measures for estimating holistic environmental impacts. Current practices are no more than determining SO_x reduction levels while disregarding other emission effects pertinent to scrubber systems. This is an obvious area of possible improvement by the life cycle assessment (LCA).

LCA Characteristics

Favi et al (2017, p.1), notices that maritime life cycle management is especially challenging due to the long lifespans and varying operational profiles of vessels. In this context, as expressed by Gediga (2014, p.555), a LCA gives an understanding of how to increase the

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environmental efficiency of a system or product. Blanco-Davis and Zhou (2014) emphasises that LCA is a valuable and useful tool for ship owners and fleet managers, particularly when it comes to choosing and evaluating the environmental performance of retrofit systems. Those research pointed out that the reason for LCAs being important, is that choices and decisions made during the planning and design stage of a product or system will have a significant influence during the whole life cycle. A positive aspect of the all-inclusive nature of an LCA is that environmental impacts cannot be shuffled between life cycle stages to receive a more positive result.

However, some shortcomings concerning the past LCA research can be found on the fact that information regarding energy and material inputs required for a complete LCA may not be available (Chatzinikolaou and Ventikos 2015, p.121). In addition, LCA research do not usually take economic or social effects into consideration (Gediga 2014, p.155). Magerholm-Fet et al (2013, p.8) also touches upon this subject and states that there is a lack of holistic approach in sustainable ship design. They encourage a system engineering-oriented approach for comprehensive and sustainable life cycle management within the maritime industry. For these scenarios, it is reasonable to assume that a wider approach to LCA could be more favourable in terms of social and economic responsibility.

LCA research in marine industry

There are several interesting LCA studies in the marine field. Wang and Zhou (2019) have done a study using LCA as a tool for evaluating carbon reduction techniques in the maritime industry. One of the conclusions from the study is that LCA is both an appropriate and broad tool to use when assessing carbon reduction measures.

A LCA of an offshore wind farm by Baack et al (2011, p.2459) found that the most energy-demanding components were the foundations for the wind turbines and the submarine cables connecting the windfarm to shore. Similar results were found by Blanco et al. (2009). They describe that the foundations, and especially the cement, had the largest environmental impact in a life cycle perspective. Another study on the same subject by Chiueh, Gan, and Huang (2017) conveyed that the main environmental impacts of the examined offshore wind power system all stemmed from the production and installation stage. Materials and electricity consumed when building the wind turbines, as well as fuel consumption and air emissions during transport and installation all fall within this category. Naturally, Chiueh et al (2017, p.104) notes that using less materials during the production phase would lower the environmental impacts of offshore wind systems.

Handler, Mayer, and Rahman (2016) have done an LCA of steel in the recycling industry in Bangladesh, where both environmental and health factors were examined. The study reports that the steel rerolling processes taking place outside the recycling yard have the most negative environmental effects. Due to the emissions and energy consumed when producing steel from iron ore, the use of recycled steel is established as more favourable for the environment.

Two studies closer to the subject of this report is a LCA of an LNG-fuelled ship within the South Korean domestic trade by Jeong et al. (2019) and a partial LCA of a Panamax bulk carrier by Tuan and Wei (2019). According to the study by Jeong et al. (2019), emissions for using LNG as a fuel are substantially lower than sailing on MGO. They note that the supply routes for the bunker fuel will also have an effect on emissions levels. Jeong et al. (2019) concludes that LCA of marine fuels is a beneficial option for a comprehensive overview of emissions levels, and a viable complement in areas where current marine emission indicators are lacking.

Tuan and Wei's (2019) LCA of the bulk carrier covers the stages from material extraction until shipbuilding and sea trials. Comparable to the offshore wind power system studies, Tuan and Wei (2019) reports that the majority of environmental effects are derived from material extraction and the production phase.

An LCCA of marine scrubber technologies by Shu (2013) shows ROI time for a scrubber system is reliant on the number of fuels used, as well as the price spread between HFO and MGO. Shu (2013, p.96) explains that a justifiable ROI time can be achieved when the ship trades within SECA areas for at least 40 % of the time, or when over 5,000 tons of fuel are consumed within the ECA. According to the findings in the study, installing a scrubber system onboard could lead to lower life cycle costs compared with switching over to MGO. However, the results from this study might only be partially applicable today. The scenarios for fuel comparison and payback times were made before the global sulphur cap and thus allowed for a higher sulphur content outside of emission control areas.

The studies coordinated by the Swedish Environmental Institute mentioned in the previous section also included a cradle-to-grave LCA of three different scrubber scenarios. As part of the LCA inventory analysis, material inputs for both an open and closed-loop scrubber system were defined. Copper, glass fibre reinforced epoxy piping and different variations of steel together made up the material types used as inputs for the LCA (Stripple and Zhang 2019, p.38–42).

Research gaps

LCAs for scrubber installation and operation are still in an unsaturated phase, although the instance of LCAs related to scrubbers has increased significantly during the last few years.

From the offshore wind farms LCAs (Baack et al. 2011; Blanco et al. 2009; Chiueh, Gan, and Huang 2017), it is apparent that materials used for construction represent a large part of the total environmental impacts. Therefore, detailed and inclusive material inputs are essential in order to obtain accurate LCA results. Nevertheless, as discussed, the past LCA study does not seem to include a complete inventory of components needed for a scrubber system, Thus, potential environmental impacts may be left out. Given this, a more extensive LCA for an installation of a scrubber unit and its auxiliary systems would have to include other commonly occurring materials in engine room components such as pumps, electrical motors, heat exchangers and control cabinets.

Since there are not many scrubber LCA done focusing on detailed material inputs, an opportunity to contribute to an area in need of further research has been identified. Therefore, it is important to attempt to produce a detailed LCA and investigate as far as possible the environmental impacts of the materials required for a scrubber installation.

Methods

The method for this paper is divided into two stages. The first stage is related to the LCA, which will be done by collecting and analysing data associated with a scrubber installation onboard. The LCA is conducted based on the ISO 14,040–14,044 standards of environmental management. Generally speaking, an LCA consists of four main phases: 1) Goal and scope definition, 2) Inventory analysis, 3) Impact assessment, and 4) Interpretation.

The second stage is to evaluate the payback period of the scrubber installation costs. A case ship with a predefined route will together with system installation costs will serve as the basis for the economic calculations.

Goal and scope definition

According to Figure 1, the LCA is proceeded based on the cradle-to-gate scope; ranged from material manufacturing, transport to the shipyard for installation onboard. However, energy consumption and costs for the actual onboard installation will not be included; collecting accurate data on required welding, cutting and construction activities is challenging but not regarded dominant effects on results. Inputs to the LCA are material mass, energy in form of electricity for material manufacturing and fuel for transportation of materials and components.

Inventory analysis

The inventory analysis has been carried out according to the guidelines in ISO 14,041 (ISO 1998). Preparation for data collection has been done by researching relevant literature to gain insight as to what kind of data would be needed for the LCA model. The data collection process, which is described in detail in the "System Specifics"-section, was carried out by locating information about required scrubber system components and their material composition and weight. The main share of data has been collected from scientific articles, and publicly available data and knowledge from the industry. Validation of data has been implemented by comparing data from several sources to examine their correlation and reliability. Relating data to the unit process and data aggregation are straightforward procedures since the inputs of the LCA are by mass in kilograms, and energy in units of megajoule.

System prerequisites

Based on information from several scrubber manufacturers, it is assumed that scrubber size and material consumption are proportional to engine and scrubber rating. An LCA study by the Swedish Environmental Institute has listed materials and weights which were fed into the production of both an open and closed loop scrubber (see in Table 1 and Table 2). The information has been gathered from a scrubber installation onboard the RoPAX vessel Stena Britannica (Stripple and Zhang 2019). GaBi thinkstep version 9.1.0.53 has been utilised for the modelling and computational part of the LCA for this research.

The case ship of this study has the main engine power of 19,400 kW and the total engine power of Stena Britannica is reported to be 33,600 kW (Asplind 2017, p.19); 58 % of the Stena Britannica engine power. Therefore, this paper presumes that a scrubber installation onboard the case ship will only require 58 % of the materials and energy.

The large amounts of black steel accounted for leads to the notion that auxiliary components such as sludge and holding tanks could be included in the LCA inputs. Since the steel in cold-rolled steel coils are usually too thin to construct ship tanks, it is assumed that steel plates for tank construction needs to be added to the case ship LCA inputs (Nippon Steel Corporation 2020).

Based on Alfa Laval (2018), the Glosten Associates (2011), Lloyd's Register (2012), Shu (2013), and Wärtsilä (2018a; b), information about these components, such as materials, dimensions and weights can be used to conduct the LCA. An inventory of minor components (specific piping, valves, filter systems, gauges etc.), as well as electrical components such as motors, emission monitoring modules, control units and cabling, will not be listed. The same applies to the water treatment unit.

Estimated component weights

Scrubber installations on ships similar to the case ship, and with the case ship engine rating in mind, a suitable

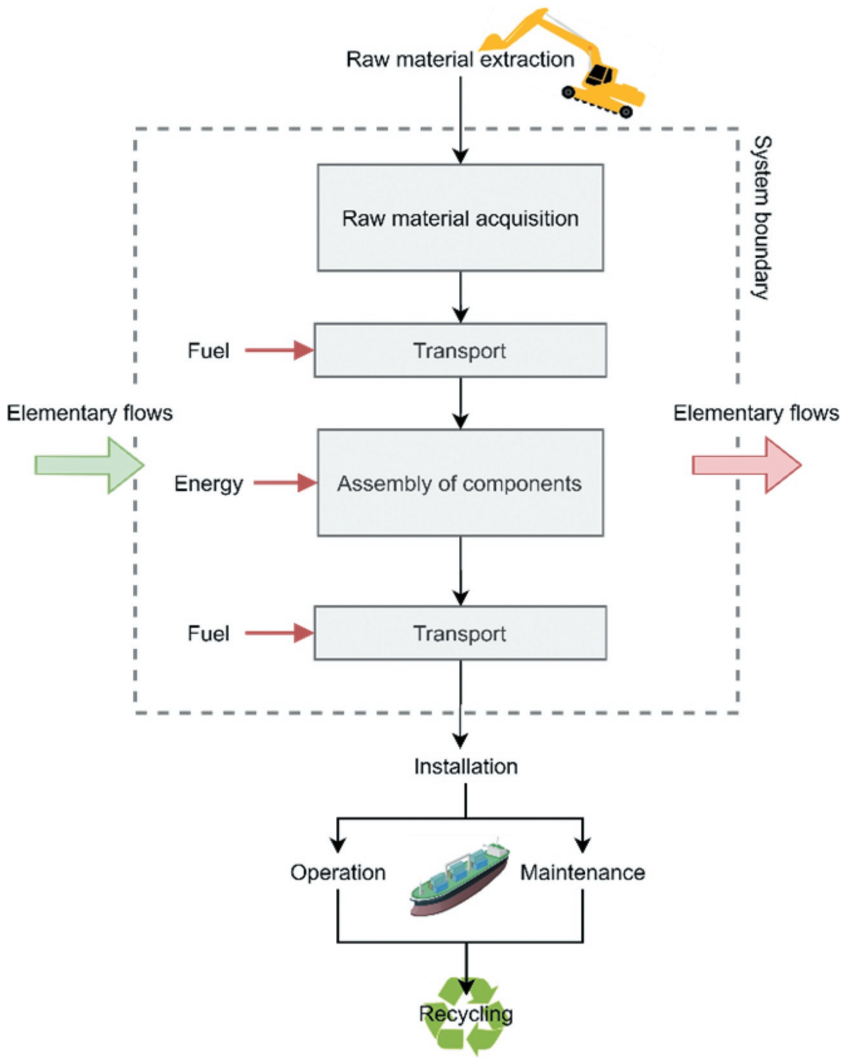

Figure 1. LCA model with system boundaries.

Table 1. Material and supply chain for open-loop scrubber inputs modified based on (Stripple and Zhang 2019, p.42).

Material Input	Dataset used in model	Raw material weight (kg/scrubber)	Transportation (km)	Type of transport
Steel	GLO: Steel sections (ILCD)worldsteel/ELCD	1,470	1,500	TruckTrailer 28–34 t, MPL 22 t, Euro 4
Black steel	GLO: Steel finsished cold rolled coil	78,104	1,500	TruckTrailer 28–34 t, MPL 22 t, Euro 4
Stainless steel	EU-28: Stainless steel sheet (EN15804 A1-A3) ts <p-agg>	28,320	1,500	TruckTrailer 28–34 t, MPL 22 t, Euro 4
GRE	RER: Expoxy resin PlasticsEurope RER: Continuous filament glass fibre (wet chopped strands) APFE/ELCD	36,008	1,500	TruckTrailer 28–34 t, MPL 22 t, Euro 4
Copper	EU-28: Copper sheet (A1-A3) ts	3,308	1,500	TruckTrailer 28–34 t, MPL 22 t, Euro 4
Energy use	Dataset used in model	Energy amount (MJ)	-	-
Electricity	EU-28: Electricity grid mix ts	294,419	-	-
Output		Weight (kg)	Transportation (km)	Type of transport
Closed-loop scrubber		147,209	500	TruckTrailer 28–34 t, MPL 22 t, Euro 4

scrubber for installation is a 20 MW multi stream inlet scrubber (Bentley; Letnes 2013). According to the manufacturer's information, a possible dry and wet weight of our case ship scrubber unit was estimated at 17.5 MT and 23.5 MT.

Scrubber units are mostly made from stainless steel due to the corrosive nature of the wash water. Therefore, it is assumed that part of, or the entire stainless steel would refer to the actual scrubber unit. Adapting these values to the case ship engine power

Table 2. Material and supply chain for closed-loop scrubber inputs modified based on (Stripple and Zhang 2019, p.38).

Material Input	Dataset used in model	Raw material weight (kg/scrubber)	Transportation (km)	Type of transport
Steel	GLO: Steel sections (ILCD)worldsteel/ELCD	1,470	1,500	TruckTrailer 28–34 t, MPL 22 t, Euro 4
Black steel	GLO: Steel finsished cold rolled coil	93,783	1,500	TruckTrailer 28–34 t, MPL 22 t, Euro 4
Stainless steel	EU-28: Stainless steel sheet (EN15804 A1-A3) ts <p-agg>	31,956	1,500	TruckTrailer 28–34 t, MPL 22 t, Euro 4
GRE	RER: Expoxy resin Plastics Europe RER: Continuous filament glass fibre (wet chopped strands) APFE/ELCD	42,439	1,500	TruckTrailer 28–34 t, MPL 22 t, Euro 4
Copper	EU-28: Copper sheet (A1-A3) ts	3,308	1,500	TruckTrailer 28–34 t, MPL 22 t, Euro 4
Energy use	Dataset used in model	Energy amount (MJ)	-	-
Electricity	EU-28: Electricity grid mix ts	345,913	-	-
Output		Weight (kg)	Transportation (km)	Type of transport
Closed-loop scrubber		172,967	500	TruckTrailer 28–34 t, MPL 22 t, Euro 4

(multiplying with 0.58) the stainless steel mass for closed and open loop scrubber units are 18.5 MT and 16.4 MT. It is evident that these values correspond well to the case ship scrubber unit weight explored in the previous section.

For a closed loop scrubber of 20 MW, ABS (2019, p.30) suggests a process water tank volume of 30 m^3. Regarding the holding tank, Wärtsilä advices that it should be dimensioned by 0.17 m^3/MWh when running on 3.5% sulphur. Since the case ship might operate on 3.5% sulphur HFO in the future, the Wärtsilä sizing rate will be kept unaltered. Calculation of case ship holding tank volume is 39 m^3.

A compilation of estimated sludge generation from open and closed loop scrubber system by various sources can be seen: for open loop, 0.1–0.4 kg/MWh (Shu 2013), 0.1 g/kWh (Wärtsilä 2012); for close loop, 2.5 litres/MWh (Lahtinen 2016), 3.3 litres/MWh (Wärtsilä 2018a), 2 litres/MWh (Wärtsilä 2012).

An average of the closed loop values has been used to calculate the case ship sludge production: open loop for 23 kg and closed loop for 602 litres. The open loop value from Wärtsilä is assumed to be the most accurate one due to Wärtsilä being a well-known scrubber manufacturer. Therefore, that value has been used for the open loop sludge calculations.

The values for engine power and running hours are based on the engine daily log for the case ship and company information. The average load for the case ship is around 65% and the average operating hours during a three-year period are circa 6,500 hours. Reasonable predicted volumes for open and closed loop sludge tanks for 30 days of continuous service (with a 15% extra margin) are approximated to 0.8 m^3 and 21 m^3.

The sodium hydroxide consumption is relative to both engine power and HFO sulphur content, and is usually dosed in a 50% aqueous solution (Wärtsilä 2018a). According to Bak et al (2014, p.48), a NaOH tank can be dimensioned for 40 days of service at normal operation speed and with a HFO sulphur content of 3.5%. A formula suggested by Wärtsilä (2018a) to calculate the sodium hydroxide consumption to bring the sulphur content in the exhaust gas down to 0.1% is presented. Lloyd's Register (2012, p.18) estimates that to scrub 2.7% sulphur fuel to 0.1% sulphur, the sodium hydroxide dosing rate should roughly be around 15 litres/MWh of scrubbed engine power.

As stated in bunker delivery notes from the same period as the average engine power and running hours were gathered from, the case ship has been operating on 2.1% sulphur HFO. With these values, the sodium hydroxide consumption for the case ship is estimated to 150 litres per hour, and 2,672 litres per day. Since the case ship will only have to scrub its exhaust to 0.5 % sulphur when operating outside emissions control areas it is assumed that a sodium hydroxide storage tank volume of 75 m^3 will be sufficient for a 30-day supply.

Unfortunately, a technical specification of an alkali feed module has not been able to be acquired. Česnauskis et al (2014, p.43) mentions that a feed module typically has two pumps and a total estimated weight of 200–300 kg (in operating condition). According to Wärtsilä (2018a, p.10), a feed module for a 21 MW scrubber system is equipped with 3 pumps made from chemically resistant materials, and the whole module weighs 450 kg: Cast iron (110 kg, 24.4%); Copper (35 kg, 7.8%), Stainless steel (25 kg, 5.6%), Steel (280 kg, 62.2%).

The material and energy consumption required to produce the feed module might not seem to be of big importance to the overall outcome of the LCA. The reason for adding the NaOH feed module manufacturing into the LCA inputs is to highlight the fact that even small components will most likely need several stages of transport before being installed and operational onboard. The ambition is to emphasise that it might all add up to a considerable environmental impact in the end.

To select appropriate pumps and heat exchangers for the scrubber system the water flow through the system must be established. An example by ABS (2019, p.30) reports a cooling water flow of 900 m^3/h and 480 m^3/h for open loop and closed loop systems. Two other examples of scrubber water flows are shown in Table 3. The water flow in an open loop system onboard the case ship is assumed to be 45 m^3/MWh, and roughly 900 m^3/h. The closed loop scrubber water flow is assumed to 22 m^3/MWh and 440 m^3/h. These estimates seem to match well with the earlier mentioned examples from ABS. Resting on available technical data for the scrubber installation onboard Stena Britannica (Asplind 2017, p.20), and a technical specification of a scrubber installation onboard a containership with a similar engine power as the case ship (Wärtsilä 2018a, p.10–11), assumed pump quantities and capacities for an open and closed loop scrubber system are presented.

In the open loop system, two seawater and wash water pumps are intended to be in continuous service, with the third pump as a standby. Since the water flow is lower in the closed loop system, only two pumps are estimated to be needed, one pump in service and one in standby. As mentioned earlier, suitable materials for pump parts that are in contact with the process medium (such as casing and impeller) are nickel aluminium bronze or stainless steel.

The pump type selected for our case ship scrubber system is a centrifugal pump with a 570 m^3/h capacity, the same kind that is already in use as main seawater-cooling pumps onboard the case ship. A specification and drawing of the pump type can be found. The pump assembly is made up from various materials such as bronze, stainless steel, cast iron, zinc, resin and rubber. The total pump weight is 460 kg. An assumption is made that the casing and the impeller together make up 85 % of the total pump weight. It is also assumed that the distribution of weight between impeller and casing is 65 and 35 %. The other parts of the pump will not be included in the LCA since their weights and sizes are deemed too negligible to have an impact on the overall outcome of the LCA. Based on these assumptions, a specification of pump weights is given in the table.

Based on the information given about scrubber system water flows in the previous section, a plate heat exchanger with a flow of circa 330 m^3/h on the fresh water side, and 380 m^3/h one the sea water side has been selected for the case ship. Since the case ship will not run at full speed for extended periods of time, 2 pieces of plate heat exchangers are considered enough for both the open and closed loop systems. As described in the pump section, smaller quantity materials such as rubber gaskets, valves and gauges will not be included in the LCA inputs.

The value for energy consumption is obtained from the Swedish Environmental Research Institute study (Stripple and Zhang 2019, p.37) where an estimated value of 2 MJ is required for manufacturing every kilogram of scrubber and scrubber system materials.

Also derived from the same study are the assumed transportation distances. A presumption for the LCA is that all scrubber materials are manufactured in Europe, and that the scrubber installation process takes place at a Polish shipyard. The transportation distance of raw materials to manufacturing facilities is assumed to 1,500 km, which according to Stripple and Zhang (2019, p.37) is roughly the average distance between European countries. It is also assumed that the transportation distance of manufactured components to the ship yard installation site is 500 km (Stripple and Zhang 2019, p.37).

System inputs

Tank volume requirements presented in the previous section has been used to appraise the raw material mass needed for tank constructions. Based on the tank volumes, the length, height and width of the tanks has been assumed to calculate the material mass. Tank thickness information has been taken from General Industries (2020). Stainless steel density is from Euro Inox (2007), and density for all other materials are from Evans (2015). Material calculations for the open and closed loop scrubber systems and a complete list of the inputs to the LCA in the GaBi thinkstep software are shown in Table 4 and Table 5.

As discussed earlier, the inputs to the GaBi software are based on the study by Stripple and Zhang (2019) but with additional components to provide a more

Table 3. Scrubber water flows, scrubber system pump capacity and dimensions.

System	(Lloyd's Register 2012)	(Wärtsilä 2012)	Sea water pumps		Wash water pumps	
			Quantity	Capacity [m^3/h]	Quantity	Capacity [m^3/h]
Open Loop	45 m^3/MWh	45 m^3/MWh	3	500	3	500
Closed Loop	20 m^3/MWh	24 m^3/MWh	2	500	2	500

scrubber pump weights

- Plate 265 (Q'ty), Titanium 952.0 kg
- Plate 265 (Q'ty), Titanium 952.0 kg
- Plate 265 (Q'ty), Titanium 952.0 kg
- Flame 2 (Q'ty), Mild steel 1,372.7 kg
- Flame 2 (Q'ty), Mild steel 1,372.7 kg
- Flame 2 (Q'ty), Mild steel 1,372.7 kg

Table 4. Closed loop scrubber inputs.

Materials	Type	Dataset used in model	Total material weight [kg]	Transport distance 1 [km]	Transport distance 2 [km]	Type of transport
Scrubber unit	Steel	GLO: Steel sections world steel	853	1,500	500	Truck, Euro 5, up to 7.5 t GW
	Black steel	GLO: Steel finished cold rolled coil	54,446	1,500		Truck-trailer, Euro 5, 34–40 t GW
	Stainless steel	EU-28: Stainless steel cold rolled coil (304)	18,534	1,500		Truck-trailer, Euro 5, 34–40 t GW
	GRE	DE: Glass fibres ts & RER: Epoxy resin Plastics Europe	24,615	1,500		Truck-trailer, Euro 5, 34–40 t GW
	Copper sheet	DE: Copper mix	1,919	1,500		Truck, Euro 5, up to 7.5 t GW
Tanks	Steel	EU: Steel plate world steel	2,111	1,500		Truck, Euro 5, up to 7.5 t GW
	Stainless steel	EU-28: Stainless steel cold rolled coil (304)	9,785	1,500		Truck, Euro 5, 14–20 t GW weight
Heat exchanger	Titanium	* Replaced with EU-28: Stainless steel cold rolled coil (304)	1,904	1,500	500	Truck, Euro 5, up to 7.5 t GW
	Mild Steel	EU: Steel plate world steel	2,745	1,500		Truck, Euro 5, up to 7.5–12 t GW
Pumps	Ni Al Br	*Bronze material mix	1,017	1,500	500	Truck, Euro 5, up to 7.5 t GW
	Stainless steel	EU-28: Stainless steel cold rolled coil (304)	547	1,500		Truck, Euro 5, up to 7.5 t GW
NaOH feed module	Cast iron	Cast iron part (automotive) ts	110	1,500	500	Truck, Euro 5, up to 7.5 t GW
	Copper	DE: Copper mix	35	1,500		Truck, Euro 5, up to 7.5 t GW
	Stainless steel	EU-28: Stainless steel cold rolled coil (304)	25	1,500		Truck, Euro 5, up to 7.5 t GW
	Steel	EU: Steel plate world steel	280	1,500		Truck, Euro 5, up to 7.5 t GW
Total:			118,926		-	
Other	Type	Dataset used in model	Amount [MJ]			
Energy usage	Electricity	EU-28: Electricity grid mix ts	23,7852			

Table 5. GaBi open loop scrubber inputs.

Materials	Type	Dataset used in model	Total material weight [kg]	Transport distance 1 [km]	Transport distance 2 [km]	Type of transport
Scrubber unit	Steel	GLO: Steel sections world steel	853	1,500	500	Truck, Euro 5, up to 7.5 t GW
	Black steel	GLO: Steel finished cold rolled coil	45,300	1,500		Truck-trailer, Euro 5, 34–40 t GW
	Stainless steel	EU-28: Stainless steel cold rolled coil (304)	16,426	1,500		Truck-trailer, Euro 5, 34–40 t GW
	GRE	DE: Glass fibres ts,RER: Epoxy resin Plastics Europe	20,885	1,500		Truck-trailer, Euro 5, 34–40 t GW
	Copper sheet	DE: Copper mix	1,919	1,500		Truck, Euro 5, up to 7.5 t GW
Tanks	Steel	EU: Steel plate world steel	243	1,500		Truck, Euro 5, up to 7.5 t GW
Pumps	Ni Al Br	*Bronze material mix (see p. 25)	1,525	1,500	500	Truck, Euro 5, up to 7.5 t GW
	Stainless steel	EU-28: Stainless steel cold rolled coil	821	1,500		Truck, Euro 5, up to 7.5 t GW
Total:			87,971		-	
Other	Type	Dataset used in model	Amount [MJ]			
Energy usage	Electricity	EU-28: Electricity grid mix ts	175,942			

comprehensive LCA of a scrubber system installation. Glass reinforced epoxy pipes (GRE) are not available as a material in the GaBi software, therefore the same ratio of epoxy resin and glass fibre mix as used by Stripple and Zhang (2019) has been utilised to simulate a manufacturing process.

The nickel aluminium bronze required for the scrubber water pump casings were also not available in GaBi database, instead a model for a nickel aluminium bronze mix were made based on a specification by National Bronze (2020). The reported percentage shares of metals that constitute a nickel aluminium bronze alloy (National Bronze 2020) were used to calculate pump casing material weights, which were then subsequently added to the LCA model. In Table 6 calculations for open and closed loop pump casings are showed. Nickel was not available in the GaBi database, therefore the 4 % nickel share was added to the copper percentage instead. Total weight for the closed loop is 1,017 kg and for the open loop is 1,525 kg.

Table 6. Calculation of Ni Al Br pump casing (unit: %).

Type	Make up	Materials						
		Copper	Aluminium	Cast iron	Manganese	Silicon	Tin	Zinc
Closed loop	Percentage (%)	86.8	9.0	2.0	1.5	0.3	0.2	0.3
	Weight[kg]	882	92	20	15	3	2	3
Open loop	Percentage (%)	86.8	9.0	2.0	1.5	0.3	0.2	0.3
	Weight[kg]	1,323	137	31	23	4	3	5

As titanium was also not a part of the GaBi educational database, for the heat exchanger model, the titanium was replaced with stainless steel to not leave the slot for potential emissions from material construction and transportation empty. Regarding transportation distances, all materials except the steel for tank manufacturing were connected to two legs of transport. However, it is assumed that the tank steel would only need to be transported from the steel manufacturing site directly to the shipyard.

Impact assessment and interpretation

According to ISO 14,042, the mandatory elements of a life cycle impact assessment are; selection of impact categories, category indicators and characterisation models, assignment of LCI results and calculation of category indicator results (ISO 2000a, p.4). The impact categories, which was presented in the introduction and the category indicators are listed below: GWP: kg CO2 eq.; AP: kg SO_2 eq.; EP: kg PO_4^{3-}; HTP inf: kg DCB eq.

Assignment of the LCI results to the impact categories and calculation of the category indicator results are computed by the GaBi thinkstep software and will be discussed in the Results section. As described by ISO (2000b, p.2), the purpose of the interpretation phase is to analyse the results, reach conclusions, explain limitations and provide recommendations.

Payback time

The payback time calculations will be done by gathering information about open and closed loop scrubber installation costs and evaluating these in relation to the case ship route and current fuel prices. Cost assumptions will be taken from literature, and when available, real-life examples.

For this report, four theoretical scenarios will be made where the case ship is trading on a predefined route:

- Case 1: Case ship operating on HFO with closed loop scrubber
- Case 2: Case ship operating on HFO and MGO with open loop scrubber
- Case 3: Case ship operating on MGO without any scrubber system.
- Case 4: Case ship operating on VLSFO and MGO without any scrubber system.

The case ship route, trade pattern and fuel prices are all expected to affect the outcome of the payback period assessment. As an example, a ship with an open loop scrubber system must switch over to MGO before entering areas where wash water discharge is prohibited (unless the ship has a special arrangement for storing vast amounts of wash water). Depending on the fluctuation of fuel prices, a scenario like this could prove troublesome for a ship owner, or barely noticeable.

Case ship particulars and route

The case ship is a 74,258 GRT car carrier with a main engine power of 19,040 kW, built in 2011. Length of the ship is 228 m, and the beam stretches 32-m wide. The payback time calculations of this project are based on real fuel consumption data from the case ship. Both the fuel data and the ship's trading route have been collected from 12 months' worth of entries in the engine daily log.

The basic outline of the route is illustrated in Figure 2. Time spent in emission control areas and areas where washwater discharge is prohibited has been counted in full days: 105 days/year (Days spent in emission control areas); 27 days/year (Days spent in areas where washwater discharge is prohibited).

Exclusions and limitations of method

In addition to the described LCA system boundaries, the case ship's auxiliary engines are not included within the theoretical scrubber installation for the main engine. Which means that materials and components that would be required for such an installation are not a part of the LCA or the cost assessment. Instead, the assumed scenario is that the ship's auxiliary engines will continue to operate on low sulphur MGO, as has been the previous practice.

The focus of this paper is solely on scrubber systems and the reduction of SO_X in ship's exhaust gases. Regulations, methods, and systems for NO_X reduction will not be considered or discussed.

Naturally, there will be limitations and shortcomings of any chosen method. Instead of using information from a case ship as the foundation of this project,

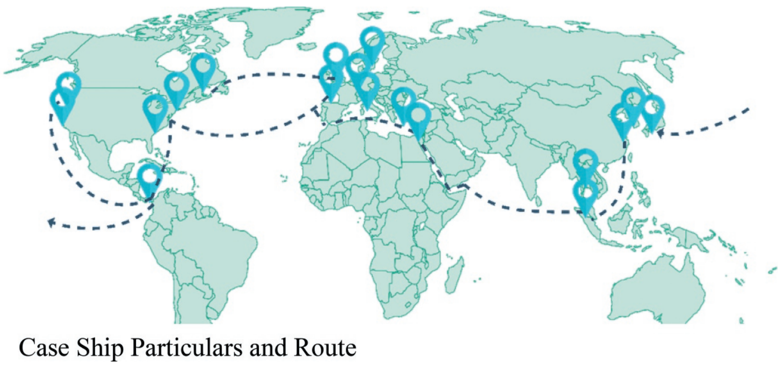

Figure 2. General outline of case ship route.

statistical data about several ship's operating profiles may perhaps have contributed to a wider application of the study. However, the application of an actual case ship scenario provides more detail and a stronger link to real-life operating conditions.

In replacement of the payback time period investigation, a complete LCCA could have been done alongside the LCA. Although, cost specifications regarding specific components such as plate exchangers, water treatment modules etc, are difficult to attain. As a result, assumptions within these areas are likely to affect the study's reliability.

The restricted data selection within the GaBi educational database poses an obvious limitation. Access to a larger database would have increased the accuracy of emission potential results. Nevertheless, as discussed in the inventory analysis, methods have been employed to mitigate these shortcomings. Access to specific industry data from a real scrubber installation is certain to have improved the quality and reliability of the project.

A greater amount of inputs, such as energy consumption during material extraction and onboard installation could have improved the LCA. However, potential areas of improvement and inclusion must be weighed against the available time at hand. To realize a finalisation of the project, the project scope must be defined and limited to a certain extent.

Results

LCA

The main closed and open loop LCA models designed with GaBi thinkstep are shown in Figure 3 and Figure 4.

The summary of each impact category for the open and closed loop scrubber systems are provided in Figure 5 and Figure 6. The total amount for each emission potential is summarized by the leftmost bar of each chart. The remaining bars indicate the contribution to emission potential by each sub-project of the GaBi model, such as scrubber material, pumps, heat exchangers, and so on.

The emission potential for the closed loop system are higher across all categories, which is expected since the closed loop system requires a greater total material mass than the open loop system. For both systems, the main contributor to all emission potentials are the materials needed for the scrubber unit. The second-most contributing factor for the closed loop system

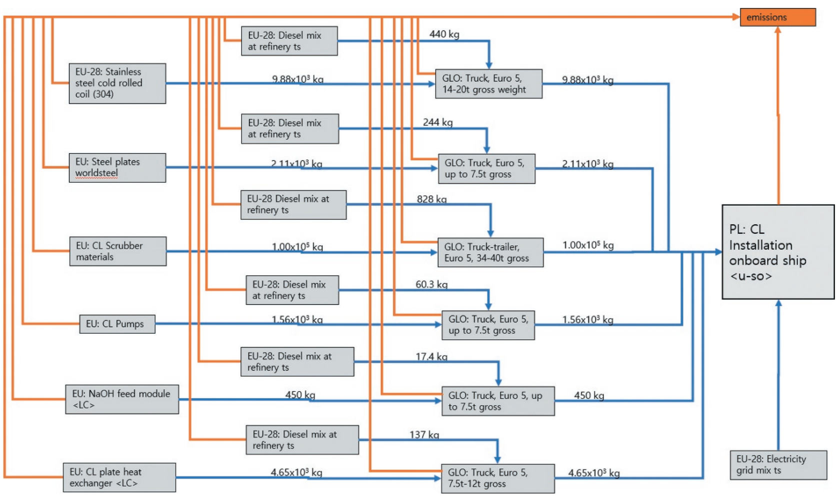

Figure 3. Closed loop scrubber Gabi model.

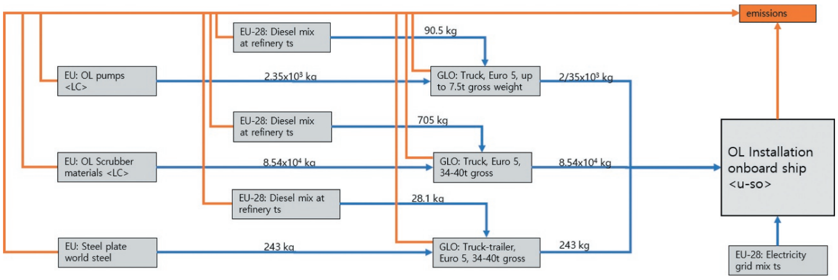

Figure 4. Open loop scrubber GaBi model.

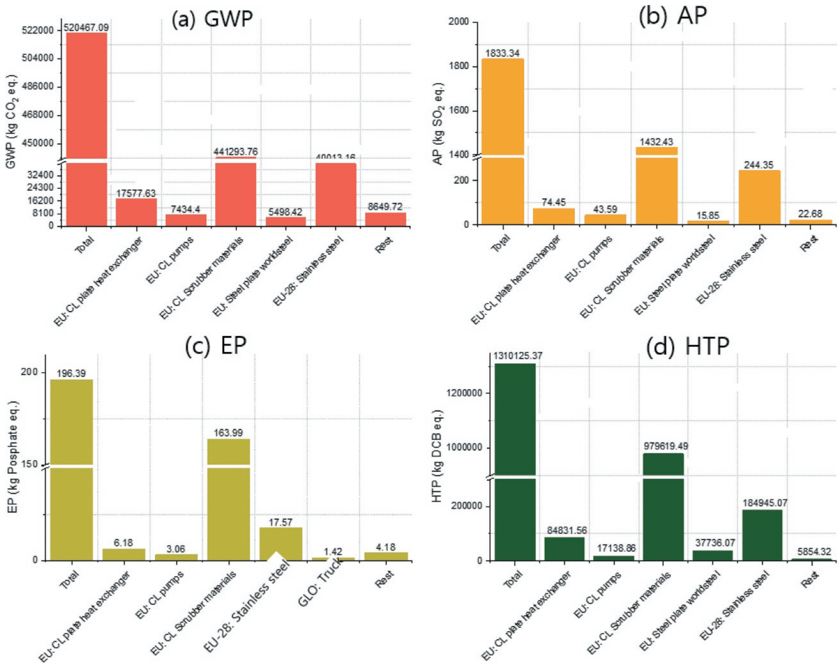

Figure 5. Closed loop emission potentials.

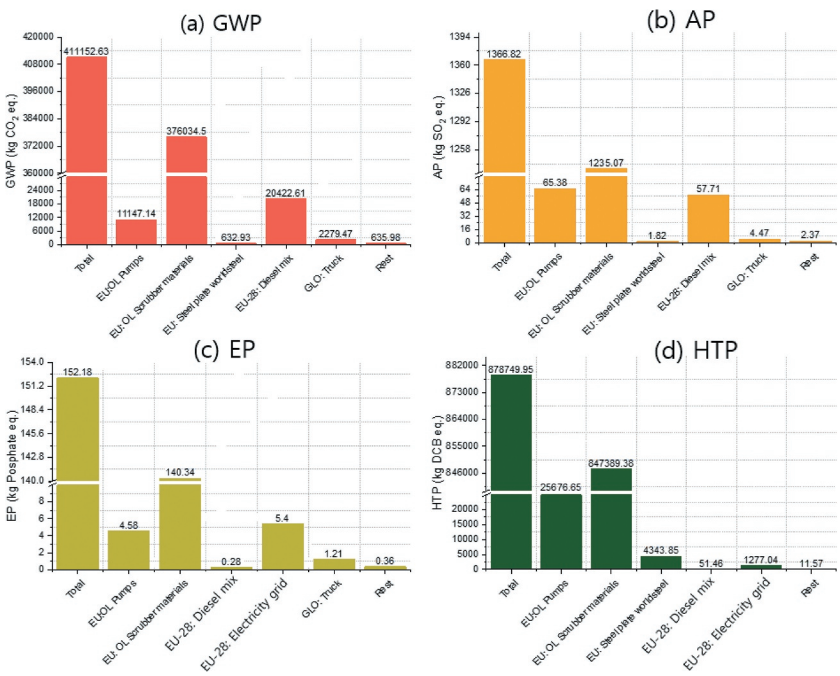

Figure 6. Open loop emission potentials.

are the regular and stainless steel required for tank construction. Since the open loop system requires less tanks than the closed loop, the second-most category across all impact categories (except HTP) is the electricity used for component and material assembly.

Considering that material usage results in higher emission potentials than transportation and electricity, there is certainly room for improvement of scrubber designs. To lessen the environmental impact scrubber systems could be optimised by reducing the amount of materials needed. This could be achieved by choosing lighter and stronger materials (as long as their environmental impact is not significantly larger) and by strategic placing of scrubber components and piping in the engine room.

Cost assessment

Scrubber Costs

Scrubber system investment costs have been gathered from various sources and compiled in Table 7.

All the reported scrubber costs fall within the interval 3–4 million US dollars. The values from the Glosten Associates (2011) will be used for the payback time calculations, mainly since reference values for both closed loop and open loop has been given.

Fuel costs

Fuel consumption values for the four payback time scenarios have been calculated according to the ship voyage profiles. The results of the monthly fuel consumption values for the different scenarios (see Table 8).

Bunker fuel prices was estimated: IFO 180 Huston ($375); IFO 380 Global ($295); VLSFO Global ($351); MGO Global ($420) as of 14 August 2020. (Ship & Bunker 2020)

the yearly fuel costs for four case ship fuel scenarios are shown in Table 9. Since the case ship normally operates on IFO 380, that heavy fuel oil will be used for the payback time comparisons.

Payback time

The yearly savings in fuel costs with an open and closed loop scrubber system, compared to a scenario where no scrubber is installed are presented in Figure 7. The payback times are: No EGCS (MGO) was 3.2 years (in open loop) and 3.6 years (in closed loop), and No EGCS (VLSFO + MGO) was 5.4 years (in open loop) and 5.9 years (in closed loop).

The payback times for the open and closed loop scrubber systems only differ marginally. Although it must be mentioned that the operating costs for the closed loop systems are expected to be significantly higher than for the open loop, due to the NaOH consumption. Prices for liquid NaOH average at US 350 per tonne (Alibaba.com 2020). Depending on the operational profile, the yearly NaOH cost is estimated to at least US 360,000 USD (Asplind 2017, p.18).

Companies supplying scrubber equipment, like Wärtsilä (HoSik 2017, p.16) and Alfa Laval (2018) generally gives examples of payback time periods between 1 and 3 years. However, the payback time is dependent on the engine and ship size, and tends be significantly longer for smaller vessels (Alfa Laval,, n.d., p. 15; Lahtinen 2016, p.113). Lahtinen (2016, p.113) concludes that a three year payback time is only reasonable for larger ships, and not applicable to smaller vessels (Alfa Laval,, n.d.). It should be noticed that companies supplying scrubber equipment are probably keen to advertise short payback times in order for their products and solutions to seem like profitable investments. In all, from the information discussed, the suggested payback times for the case ship scenario seems reasonable.

As mentioned in literature review, time spent in emission control areas and areas where wash water discharge is prohibited has slight effect on the payback time. Based on the same data and calculation methods explained in the inventory analysis, Figure 7 illustrates how the payback time is affected by an increase of time spent in emission control areas and areas where wash water discharge is prohibited.

As reported by other studies cited throughout this report, payback times are heavily influenced by fuel prices. For the case ship, both open loop and closed loop installation payback times seems feasible considering the ship has at least 16 years left of its service life. Although the payback time of the open loop system is slightly shorter (4 months), there could be a negative effect if the price spread between HFO and MGO is changed. The figure also illustrates how an increase of MGO and HFO prices could affect the payback time of the scrubber installation. Higher HFO prices equal longer payback periods for both scrubber systems. Increased MGO prices will on the contrary lead to a reduction of payback times.

Discussion

Since less material is used for the open loop system, the environmental impact is slightly smaller

Table 7. Scrubber investment costs ($ US).

Source	Open loop	Closed loop	Scrubbed engine power	Notes
(Bak et al. 2014, p.20)	-	$ 3,199,000	5 x 8 MW	*Design for 5 × 8 MW engines*
(Eefsen et al. 2012, p.19)	-	$ 5,840,000	9,48 MW	-
(Glosten Associates 2011, p.15)	$ 4,611,000	$ 5,724,000	16 MW	-
(Lee, 2019, p.6)	$ 4,500,000	$ 4,500,000	-	*Values are for Handymax bulk carrier. System type not specified*

Table 8. Case ship monthly fuel consumption scenarios.

	Open Loop		Closed Loop		No EGCS (1)		No EGCS (2)	
Month	HFO [MT/ month]	MGO [MT/ month]	Total HFO [MT/ month]	Total DO [MT/ month]	Total HFO [MT/ month]	Total DO [MT/ month]	Total VLSFO [MT/ month]	Total DO [MT/ month]
1	590	247	731	106	-	837	472	365
2	929	118	962	86	-	1048	513	535
3	810	165	897	78	-	975	694	281
4	999	167	1106	60	-	1166	1035	132
5	1242	145	1331	56	-	1387	754	632
6	679	146	726	100	-	825	538	287
7	1194	106	1235	65	-	1300	741	559
8	1074	156	1148	82	-	1230	926	304
9	955	88	955	88	-	1043	924	120
10	1235	77	1280	31	-	1311	91	1220
11	782	167	836	113	-	949	728	221
12	1175	230	1356	49	-	1405	1310	95
	11,663	1813	12,562	914	-	13,476	8726	4750
Total	**13,476**		**13,476**		**13,476**		**13,476**	

Note:

- For Open Loop: Monthly HFO = $HFO_{monthly}$ – (HFO_{day} * R_{ww}); Monthly MGO = (R_{ww} * HFO_{day}) + $AUX_{monthly}$
- For Open Loop: Monthly HFO = $HFO_{monthly}$ – (HFO_{day} * R_{ww}); Monthly MGO = (R_{ww} * HFO_{day}) + $AUX_{monthly}$
- For Closed loop: Monthly HFO = $HFO_{monthly}$; Monthly MGO = $AUX_{monthly}$
- For Closed loop: Monthly HFO = $HFO_{monthly}$; Monthly MGO = $AUX_{monthly}$
- No EGCS (1): MGO = $HFO_{monthly}$ + $AUX_{monthly}$
- No EGCS (1): MGO = $HFO_{monthly}$ + $AUX_{monthly}$
- No EGCS (2): Monthly VLSFO = ($HFO_{monthly}$ – (HFO_{day} * R_{ECA}); Monthly MGO = (HFO_{day} * R_{ECA}) + $AUX_{monthly}$
- No EGCS (2): Monthly VLSFO = ($HFO_{monthly}$ – (HFO_{day} * R_{ECA}); Monthly MGO = (HFO_{day} * R_{ECA}) + $AUX_{monthly}$
- No EGCS (2): Monthly VLSFO = ($HFO_{monthly}$ – (HFO_{day} * R_{ECA}); Monthly MGO = (HFO_{day} * R_{ECA}) + $AUX_{monthly}$

$HFO_{monthly}$ = Monthly HFO consumption
HFO_{day} = Average daily HFO consumption
R_{ww} = Days in area where wash water discharge is prohibited
R_{ECA} = Days in area with restricted wash water discharge
$AUX_{monthly}$ = Monthly MGO consumption for auxiliary engines and boilers

Table 9. Yearly savings in fuel costs compared with no EGCS (US $).

Fuel combination	Open Loop	Closed Loop	No EGCS
IFO 180 + MGO	$5 135 101	$5 094 667	-
IFO 380 + MGO	$4 202 047	$4 089 730	-
VLSFO + MGO	-	-	$5 057 851
MGO	-	-	$5 659 944

compared to the closed loop systems. However, the use of liquid NaOH could further increase the environmental impact of the closed loop scrubber. A ships' lifetime supply of NaOH is likely to have a real effect on emissions.

Infrastructure and bunkering of NaOH is another crucial factor. With the estimate NaOH consumption of the case ship, and the need to bunker once a month, coordinating delivery of NaOH in various ports around the world might prove challenging. There is also a question as to how frequent bunkering of NaOH might affect cargo operations and crew rest hours for vessels with short turn-around times in port. Normal practice onboard the case ship, is to bunker fuel and lube oil ever second to two months. Bunkering NaOH from several tank trucks at least once a month takes up valuable onboard resources (at least one crewmember required to supervise the process) and may reduce the estimated cost effectiveness of a closed loop scrubber system.

An area of concern regarding the open loop scrubber system is the wash water discharge. The wash water is reported to have a negative environmental effect when released back into the ocean without any treatment (Aakre et al. 2012). Due to the environmental effects from open loop scrubbers, some critics propose that new installations of open loop scrubbers should be prohibited and existing open loop system to be converted to closed loop instead (Comer 2020).

Taking areas of wash water discharge restrictions into consideration for an economic perspective, open loop scrubbers might become a less beneficial choice if more countries decide to adopt stricter local regulations for wash water discharge.

Suggestions for future research

Based on the previous section, recommended areas for future research has been identified. A majority of the recommendations propose a continuation on the same path as this report, except with an extended scope.

To investigate the future of scrubbers, and especially the prospects of open loop systems an examination of trends in shipowners and operators' attitudes towards environmental friendliness versus costs could prove interesting. Focus could lie on exploring how the relationship has changed during the last 50-years, and if environmental aspects are considered more important today when choosing systems for retrofit and building new vessels.

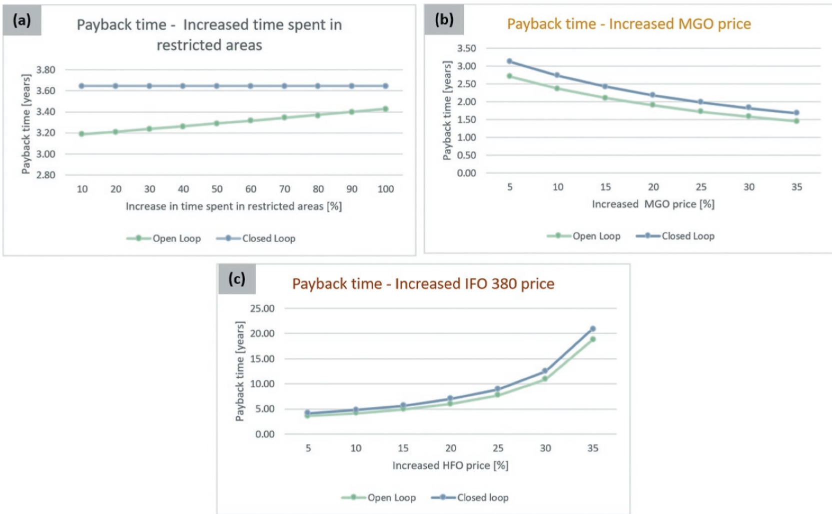

Figure 7. Payback time: (a) as a result of increased IFO 380 price; (b)more time spent in restricted areas; (c) increased MGO price.

As the significance of transportation routes has been discussed, a comparative LCA and LCCA study of scrubber installations in different locations and with contrasting transportation distances of construction materials could be insightful and perhaps highlight the importance of supply chain optimization.

Finally, the strongest recommendation is to carry out an extensive and detailed cradle-to-grave LCA and LCCA study of open and closed loop systems, encompassing crucial factors such as the environmental effects of NaOH consumption and wash water discharge from open loop systems. For the LCCA, aspects such as additional costs for scrubber maintenance and operation (e.g. crew wages and spare parts) would be essential to include. Perhaps then, the eternal question as to which system is preferable might be closer to an answer.

Limitations

From the results of the LCA and the discussed literature, there is an apparent advantage in using less materials, and if possible-recycled materials, to reduce the environmental impact of a scrubber installation.

The system inputs of the case ship LCA does not encompass the entire array of components and materials used for a scrubber installation. Due to practical reasons, only the main components have been included. The LCA is likely to have been more comprehensive and reliable with additional material and component inputs in the life cycle inventory phase. However, accurate specifications of certain components and systems (such as water treatment units) have proven to be hard to acquire.

Electricity usage during the installation process at the shipyard has not been included in the LCA, instead only the electricity needed for the manufacturing process of the scrubber component are incorporated to the LCA. This is due to the lack of proven data of energy and time consumption for this instance. As the electricity consumption for material and components manufacturing were not the main contributor in any of the emission impact categories, it is believed that the electricity during installation would significantly affect the LCA results.

Compared to the LCA by Stripple and Zhang, individual truck and trailer capacities have been added for materials and components based on their weights. The purpose is to both to make the model more realistic, and to highlight the benefits of environmental efficiency. The transportation inputs of the LCA brings up another area of discussion, transportation routes. It is likely that by setting the installation site to another part of the world, transportation emissions are expected to constitute a larger share of the environmental impacts. Although, a scrubber installation in a country with lower labour costs than in the EU, could instead lead to monetary savings and a shorter payback time.

A potential limitation of this study is the exclusion of the energy required to power the scrubber system onboard from the payback time estimates. Lloyd's Register (2012, p.29) estimates that an open loop system and closed loop system consumes 1–2% and 0,5–1% of the scrubbed engine power. Based on these values, the increased fuel consumption as a result of the scrubber power demand is deemed to not have a substantial effect on the outcome of the study.

Conclusion

1)Based solely on the environmental impact of the materials required for an installation, an open loop scrubber system is to prefer since less materials and components are required compared to a closed loop scrubber system. However, potential environmental impacts of the closed loop scrubber NaOH consumption and wash water discharge from open loop scrubbers might offset this relationship.

2)As the yearly savings in fuel costs only differ marginally between the two system there is no certain winner. However, changes in the price spread between HFO and MGO are certain to affect the payback times and favour one system.

3)It has shown that there is a possible grey area regarding detailed material inputs for scrubber installation LCAs. To rectify this, an attempt has been made to provide specific material inputs for the life cycle inventory analysis phase. From the results of the study, there is clear benefit of using less materials, and recycled materials as far as possible. It is also recommended that scrubber design should be optimised at an initial stage to reduce environmental impacts and increase the energy efficiency of the system.

4)There is currently no absolute saying as to which system is the more superior one from both an environmental and economic perspective. Instead, the conviction of the client ordering the scrubber will serve as a deciding factor. A ship owner concerned about the environment and perhaps eager to collect PR goodwill might lean towards a closed loop scrubber system. While a ship owner not willing to compromise on profits is more likely to install an open loop scrubber system.

Abbreviations and Terms

AP	Acidification Potential
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EGCS	Exhaust Gas Cleaning System
EMSA	European Maritime Safety Agency
EP	Eutrophication Potential
GRE	Glass Reinforced Epoxy
GWP	Global Warming Potential
IMO	International Maritime Organization
HFO	Heavy Fuel Oil
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Assessment
LSFO	Low Sulphur Fuel Oil
MARPO	LInternational Convention for the Prevention of Pollution from Ships
MGO	Marine Gas Oil
MEPC	Marine Environment Protection Committee
m/m	mass by mass
NaOH	Sodium Hydroxide
NO_X	Nitrogen Oxides
PAH	Polycyclic aromatic hydrocarbons
PO_4^{3-}	Phosphate
ROI	Return On Investment
RoPax	Roll-On-Roll-Off-Passenger ship/ferry
SECA	Sulphur Emission Control Area
SO_X	Sulphur Oxide
SO_2	Sulphur Dioxide
SO_3	Sulphur Trioxide
VLSFO	Very Low Sulphur Fuel Oil

Disclosure statement

No potential conflict of interest was reported by the authors.

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