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# Assessing Wärtsilä's exhaust gas abatement solution

Life cycle assessment of a SOx scrubber system

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**ABSTRACT :**

Wärtsilä offers competent technical solutions for complying with the sulphur content regulations set by the IMO. Wärtsilä's exhaust gas cleaning systems are a viable option for ship owners and operators that prefer to continue operating their vessels with fuels with a sulphur content of over 0,5% m/m. As the number of environmental regulations on maritime traffic and related industries is likely to increase in the near future, a proactive approach can yield beneficial results for companies looking to offset the impact of potential future restrictions.

In this study, a life cycle assessment of a Wärtsilä V-SOx hybrid scrubber system was conducted. The used methodology followed the principles and framework demonstrated in the ISO 14040 standard. The main objective of the study was to generate information about the environmental impacts of the scrubber system throughout its life cycle. The results were to be used to initiate the process of developing environmental KPIs to monitor and improve Wärtsilä's environmental performance. Also, the study was conducted to support Wärtsilä's efforts to decarbonize its own operations by 2030.

The studied scrubber system was installed on a tanker vessel in 2019. The life cycle inventory for the LCA was built using data from Wärtsilä's internal databases, scientific literature and documentation provided by the customer. The impacts were assessed with the ILCD 2011 midpoint+ method, which contains the impact categories recommended by the European Joint Research Centre.

Most of the potential environmental impacts occurred during the operational phase. The raw material extraction & manufacturing of components phase produced the second highest potential impacts. These phases combined produced more than 98% of the potential impacts in each measured impact category except for the freshwater ecotoxicity category.

The system had been operated mostly in open loop mode, and therefore an additional scenario analysis was conducted to get an overview of the potential environmental impacts of operating the system in closed loop mode. Although contributing less to marine eutrophication, closed loop operation was found to produce a significant number of indirect impacts in all the other impact categories. For example, the production of sodium hydroxide used in closed loop operation multiplied the potential $CO_2$ emissions in both additional scenarios.

In addition to direct environmental impacts, the LCA produced significant insight to the indirect impacts behind the processes that are connected to the system's life cycle. As the responsibility of mitigating environmental burden through regulations will likely extend to affect more operators in supply chains, Wärtsilä is taking proactive steps to find various ways of improving its environmental performance.

**KEYWORDS:** Life cycle assessment, Maritime sustainability, Exhaust gas scrubbing

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**TIIVISTELMÄ :**

Wärtsilä tarjoaa tehokkaita teknisiä ratkaisuja IMO:n asettamien rikkipitoisuusmääräysten noudattamiseen. Wärtsilän pakokaasunpuhdistusjärjestelmät ovat pätevä vaihtoehto laivanomistajille ja operaattoreille, jotka haluavat jatkaa alustensa toimintaa polttoaineilla, joiden rikkipitoisuus on yli 0,5% m/m. Koska meriliikennettä ja siihen liittyviä toimialoja koskevien ympäristömääräysten määrä todennäköisesti lisääntyy lähitulevaisuudessa, ennakoiva lähestymistapa voi tuottaa hyödyllisiä tuloksia yrityksille, jotka haluavat lieventää mahdollisten tulevien määräysten vaikutuksia.

Tässä työssä suoritettiin elinkaariarviointi Wärtsilän V-SOx hybridijärjestelmälle. Käytetty metodologia noudatti ISO 14040 – standardin toimintaperiaatteita ja viitekehystä. Tutkimuksen päätavoitteena oli tuottaa tietoa järjestelmän ympäristövaikutuksista koko sen elinkaaren ajalta. Tuloksia käytettiin käynnistämään ympäristöindikaattoreiden kehitysprosessi, joiden tarkoituksena on seurata ja auttaa parantamaan Wärtsilän ympäristötehokkuutta. Työn tarkoituksena oli myös tukea Wärtsilän vuodelle 2030 asettamaa hiilineutraalisuustavoitetta.

Tutkimuksen kohteena ollut pesurijärjestelmä asennettiin erääseen säiliöalukseen vuonna 2019. Elinkaari-inventaario rakennettiin käyttäen Wärtsilän sisäisiä tietokantoja, tieteellistä kirjallisuutta ja asiakkaan toimittamaa dokumentaatiota. Ympäristövaikutukset arvioitiin ILCD 2011 midpoint+ menetelmällä, joka sisältää Euroopan yhteisen tutkimuskeskuksen suosittelemat vaikutusluokat.

Valtaosa potentiaalisista ympäristövaikutuksista syntyi käyttövaiheen aikana. Raaka-aineiden louhinta & komponenttien valmistusvaihe tuotti toiseksi eniten potentiaalisia ympäristövaikutuksia. Nämä vaiheet tuottivat makean veden ekomyrkyllisyysluokkaa lukuunottamatta yli 98% potentiaalisista vaikutuksista jokaisessa mitatussa vaikutusluokassa.

Järjestelmää oli käytetty pääosin avoimen kierron tilassa, minkä vuoksi suoritettiin ylimääräinen skenaarioanalyysi yleiskuvan saamiseksi suljetun kierron käytön mahdollisista ympäristövaikutuksista. Vaikka suljetun kierron toiminnalla oli vähemmän vaikutusta merialueiden rehevöitymiseen, sen havaittiin aiheuttavan huomattavan määrän epäsuoria vaikutuksia kaikissa muissa mitatuissa vaikutusluokissa. Suljetun kierron operaatiossa käytettävän natriumhydroksidin tuotanto esimerkiksi moninkertaisti potentiaaliset $CO_2$ päästöt molemmissa lisäskenaarioissa.

Suorien ympäristövaikutusten lisäksi työ tuotti merkittävää näkemystä järjestelmän elinkaareen liittyvien prosessien taustalla olevista välillisistä vaikutuksista. Koska vastuu ympäristöstä tulee todennäköisesti koskettamaan yhä useampaa toimijaa tulevaisuudessa, Wärtsilä tekee ennakoivia toimenpiteitä löytääkseen erilaisia tapoja parantaa ympäristötehokkuuttaan.

**AVAINSANAT:** Elinkaariarviointi, Kestävä merenkulku, Pakokaasun puhdistus

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## Abbreviations

| | |
|---|---|
| AE | Auxiliary engine |
| CCS | Carbon capture and storage |
| CEMS | Continuous emission monitoring system |
| $CH_4$ | Methane |
| CL | Closed loop |
| $CO_2$ | Carbon dioxide |
| ECA | Emission control area |
| EFP | Environmental footprint |
| EGC | Exhaust gas cleaning |
| EoL | End-of-life |
| FU | Functional unit |
| GHG | Greenhouse gas |
| GW | Gigawatt |
| GWP | Global Warming Potential |
| HC | Hydrocarbon |
| HFO | Heavy fuel oil |
| ILCD | International Life Cycle Data System |
| IMO | International Maritime Organization |
| ISO | International Organization for Standardization |
| JRC | European Joint Research Centre |
| KPI | Key performance indicator |
| kW | Kilowatt |
| kWh | Kilowatt-hour |
| LCA | Life cycle assessment |
| LCIA | Life cycle impact assessment |
| LNG | Liquefied natural gas |
| MCR | Maximum continuous rating |
| ME | Main engine |
| MGO | Marine gas oil |
| $Mg(OH)_2$ | Magnesium hydroxide |
| MW | Megawatt |
| m/m | Mass by mass |
| NaOH | Sodium hydroxide |
| NOx | Nitrogen oxide |
| OFB | Oil-fired boiler |
| OL | Open loop |

| | |
|---|---|
| PAH | Polycyclic aromatic hydrocarbon |
| PM | Particulate matter |
| ppm | Parts per million |
| SCR | Selective catalytic reduction |
| SOx | Sulphur oxide |
| STH | Sustainable Technology Hub |
| Tkm | Tonne-kilometre |
| VOC | Volatile organic compound |

# 1 Introduction

The volume of maritime transport in global trade has increased substantially in the past decades. Between 1992 and 2012, the global maritime traffic grew by 400%, showing a slight period of stagnancy only during the 2008-2009 economic crisis (Tournadre, 2014, p. 7929). In the past 30 years, the global maritime trade has been growing annually by 3.3% on average and today more than 80% of the global merchandise trade is transported by sea (UNCTAD, 2022, pp. 17, 24). According to forecasts based on varying scenarios of economic development, the global maritime traffic is expected to grow between 240-1200% by 2050 (Sardain et al. 2019, p. 276).

Along with the positive impacts that the growing maritime traffic will likely have on global economic prosperity, concerns have also risen on its impacts on human health and the environment (Li et al. 2020, p. 1). In addition to the global maritime sectors significant amount of direct greenhouse gas emissions such as methane ($CH_4$) and carbon dioxide ($CO_2$), it is also a major source for sulphur oxide (SOx), nitrogen oxide (NOx) and particulate matter (PM) emissions (Wang & Wright, 2021, p. 456). These emissions are regulated by The International Maritime Organization (IMO), which is an agency of the United Nations that is specialized in the development and maintenance of the regulatory framework in the shipping industry (IMO, n.d. -a).

Although the shipping industry emissions are being investigated and regulated holistically by the IMO, a special focus has been targeted on SOx emissions in the recent years. SOx emissions are harmful to human health and the marine environment and can adversely impact air quality hundreds of kilometres away from the source of the emissions (Fan et al. 2021, pp. 1, 2). To tackle these impacts, the IMO has limited the sulphur content of the fuel used in ships down to 0.5% m/m (mass by mass) globally and 0.1% m/m in the specifically defined emission control areas (ECAs) (IMO, n.d. -b). However, the use of low-sulphur marine fuel is not the only solution to meet the requirements of the regulations.

Currently, there are two regulation abiding, technologically and economically feasible alternative solutions to using low-sulphur fuel: using alternative nonpetroleum-based fuel such as liquefied natural gas (LNG) or methanol or installing an exhaust gas cleaning (EGC) system that removes the sulphur from the exhaust gas (Solakivi et al. 2019, p. 339). The decision for choosing one of these solutions is often based on the operating profile of the vessel, its operating routes, and thorough comparative cost assessment.

Currently, the environmental responsibility regarding maritime traffic is in most parts shared between ship owners and operators through regulations regarding the operation of the vessel. However, given the political pressure on environmental issues and growing environmental awareness amongst the public, it is reasonable to assume that in the future this responsibility will be extended to affect each party involved in the life cycle of a vessel. Should such extension unfold, the operators involved in the marine industry supply chains might have to examine their own operations more precisely in terms of environmental and social sustainability. As in many other industries, in the marine industry as well, the life cycle assessment method has been proven effective in forming a comprehensive view of the environmental impacts of a product or a process during its life cycle (Jang et al. 2020, p. 3).

## 1.1 Purpose of the study

This study is commissioned by Wärtsilä Finland Oy. Wärtsilä is the market leader for exhaust gas cleaning systems in the global commercial shipping industry and has been a major contributor in engineering and designing ship engines and parts for over 60 years (Wärtsilä, n.d. -a, n.d. -b). Wärtsilä offers a wide range of EGC systems for being compliant with the IMO SOx regulations and is also developing carbon capture and storage (CCS) technology to answer to the increasing focus on reducing $CO_2$ emissions in the shipping industry.

In addition to ensuring that their customers are compliant with the current and upcoming IMO regulations, Wärtsilä has set environmental targets regarding their own operations. The company has committed to being carbon neutral in their own operations by 2030 and by then also providing a product portfolio that is compatible with the use of carbon-free fuels (Wärtsilä, 2021). The fulfilment of these commitments requires Wärtsilä to increase environmental awareness amongst the employees and to find feasible solutions to mitigate the environmental impacts of its operations.

The main purpose of this study is to evaluate the environmental footprint of a Wärtsilä V-SOx hybrid scrubber system throughout its life cycle. The study is conducted to gain insight about the most significant environmental impacts that the system produces both directly and indirectly during its lifetime. In addition, the purpose of the study is to evaluate and determine the difference in the magnitude and quality of environmental impacts between different operating modes of the system.

The studied scrubber system is designed to remove SOx and other pollutants such as PM from the exhaust gas. In the V-SOx design, a single or multiple venturis are used as the inlet for the exhaust gas, depending on the configuration of the system (Suopanki, 2021, p. 428). A Wärtsilä V-SOx scrubber body and venturi design is shown in figure 1. The operating principles of the hybrid system and other Wärtsilä SOx scrubber systems are described in chapter 2.1.2.

By commissioning this study, Wärtsilä has also expressed interest in developing and determining key performance indicators for enhancing environmental performance in its EGC business. This study also has potential to help Wärtsilä to develop their EGC systems, identify new business opportunities and to make more sustainable decisions regarding the EGC supply chain.

**Figure 1.** Wärtsilä V-SOx scrubber body with a venturi (Suopanki, 2021, p. 429)

## 1.2 Structure of the study

The study is divided into six parts. The first part introduces the topic and purposes behind of the study. The second part introduces the history of Wärtsilä as a company, Wärtsilä Exhaust Treatment business unit and Wärtsilä's SOx scrubber systems. The third part is the theoretical background, which describes the IMO regulatory framework, the LCA methodology, and previous scrubber system LCA studies. The fourth part is the methodology, which focuses on data collection and building the life cycle inventory using the LCA method. The fifth part is the impact assessment, in which the results of the LCA are presented and interpreted, and the KPI development is discussed. The sixth and final chapter is conclusions, which contains discussion about the results, recommendations for mitigating environmental impacts and conducting future research, and limitations of the study.

# 2 Wärtsilä

Wärtsilä was founded in Tohmajärvi, Finland in 1834 (Wärtsilä, n.d. -b). The company started as a sawmill, but quickly adopted ironworks to its operations. In 1935, Wärtsilä acquired a majority holding of Kone- ja Siltarakennus Oy (Machine and Bridge Construction Ltd), which manufactured paper machines and locks among other products (Wärtsilä, n.d. -b). The acquisition gave Wärtsilä control for the Hietalahti shipyard in Helsinki and the Crichton-Vulcan shipyard in Turku. In 1938, Kone- ja Silta group was fully merged with Wärtsilä. During the same year, Wärtsilä signed a licence agreement with Friedrich Krupp Germania Werft AG which led to the manufacturing of Wärtsilä's first diesel engine in 1942 (Wärtsilä, n.d. -b).

In the following decades, Wärtsilä focused on designing and manufacturing its own diesel engines. Wärtsilä started its international manufacturing operations in 1978, after acquiring the majority of the NOHAB diesel business from a Swedish company called Bofors (Wärtsilä, n.d. -b). In 1986, Wärtsilä and a Finnish industrial company Valmet joined their marine resources together and as a result, Wärtsilä Marine Oy was formed (Wärtsilä, n.d. -b). In exchange for Valmet's marine resources, Wärtsilä's paper machines were transferred to Valmet. By the year 2002, Wärtsilä had expanded its diesel and gas engine operations and gained a foothold in the biopower field through acquiring a Finnish boiler plant manufacturing company Sermet Oy (Wärtsilä, n.d. -b).

Between 2003-2010, Wärtsilä expanded its operations globally and entered into several joint ventures that included the production of propellers, the production of dual-fuel engines for LNG carriers, and the integration of biopower operations with heat and power businesses (Wärtsilä, n.d. -b). From 2010 to 2020, Wärtsilä continued developing its marine and energy businesses towards more sustainable direction. In 2016-2017, Wärtsilä entered into the solar energy business with solar photo-voltaic solutions and successfully tested remote control ship operating capability and wireless induction charging system in the marine environment (Wärtsilä, n.d. -b).

In 2018, Wärtsilä launched a major investment in building a new innovation and technology hub in Vaasa, Finland (Wärtsilä, n.d. -b). The building is named Sustainable Technology Hub (STH) and its construction was completed in 2022. The hub acts as a centre for research, product development and production, and its main purpose is to contribute to marine and energy decarbonization (Wärtsilä, n.d. -b). The electricity produced in engine test runs at STH is fed into the power grid and residue heat is stored and used in the building, thus contributing to Wärtsilä's sustainable development targets (Wärtsilä, n.d. -d).

In 2021, Wärtsilä committed to being carbon neutral in its own operations by 2030 and introduced a new strategic framework called "The Wärtsilä Way" (Wärtsilä, n.d. -b). The new strategic framework defines the company's core values as customer success, passion, and performance, and its purpose as "enabling sustainable societies through innovation in technology and services" (Wärtsilä, n.d. -c). The framework also defines the company's target position as "shaping the decarbonization of marine and energy", which according to the framework can be achieved by following and implementing Wärtsilä's strategic priorities (Wärtsilä, n.d. -c). These strategic priorities are exceling in creating customer value, developing high performing teams that make a difference, driving decarbonization in marine and energy, capturing growth in services, and continuously improving Wärtsilä's end-to-end value chain (Wärtsilä, n.d. -c).

## 2.1 Wärtsilä businesses

Wärtsilä has 17,500 employees in 79 countries and the company's net sales were 5,8 billion euros in 2022 (Wärtsilä, n.d. -e). In 2023, Wärtsilä is operating in the energy and marine markets with four different businesses: Wärtsilä Energy, Wärtsilä Marine Power, Wärtsilä Marine Systems, and Wärtsilä Portfolio Business (Wärtsilä, n.d. -e).

Wärtsilä Energy develops and produces energy storage technology and balancing power plants that can be run with low-emission fuels such as synthetic carbon-neutral methanol, methane, and hydrogen (Wärtsilä, n.d. -f). Currently, Wärtsilä has delivered over 110 energy storage systems to 180 countries and the company’s power plant capacity is over 76 GW (Wärtsilä, n.d. -f). Wärtsilä Energy also provides lifecycle services such as delivering spare parts, field service, and power plant lifecycle upgrades (Wärtsilä, n.d. -f).

Wärtsilä Marine Power has a wide product and service portfolio including marine engines, propulsion systems, hybrid technology, and integrated powertrain systems (Wärtsilä, n.d. -g). Wärtsilä Marine Power delivers products and services for a variety of marine applications including passenger, offshore, merchant, and special purpose vessels such as fishing vessels and tugs (Wärtsilä, n.d. -g). Marine Power also provides lifecycle services, spare parts, technical support, and maritime cyber security services (Wärtsilä, n.d. -g).

Wärtsilä Marine Systems consists of three business units: Exhaust Treatment, Gas Solutions, and Shaft Line Solutions (Wärtsilä, n.d. -h). Exhaust Treatment delivers technological solutions to reducing emissions and achieving compliance with environmental regulations (Wärtsilä, n.d. -h). Gas Solutions provides cargo handling systems, gasification and liquefaction systems, fuel systems, and alternative engine configuration systems (Wärtsilä, n.d. -h). Shaft Line Solutions provides end-to-end marine shaft line products such as seals, bearings, and hydraulic equipment (Wärtsilä, n.d. -h). All three business units also provide lifecycle services.

Wärtsilä Portfolio Business consists of three business units that aim to enhance performance and create value by managing divestments and other strategic measures (Wärtsilä, n.d. -e). The businesses that are divested often do not have strong connections to other Wärtsilä products or services or are no longer in line with Wärtsilä’s strategy. Currently, the business units in Wärtsilä Portfolio Business are Automation, Navigation & Control Systems (ANCS), Marine Electrical Systems, and Water & Waste (Wärtsilä, n.d. -e).

ANCS offers dynamic positioning systems, sensors, and navigation & automation systems to increase vessel efficiency and safety, while being compliant with regulations (Wärtsilä, n.d. -e). Marine Electrical Systems specializes on electrical integration services on complex vessels, military vessels, and yachts (Wärtsilä, n.d. -e). Water & waste business unit provides environmental products such as wastewater management systems, ballast water management systems, as well as freshwater generation solutions and vacuum collection systems (Wärtsilä, n.d. -e).

### 2.1.1 Wärtsilä Exhaust Treatment

Wärtsilä Exhaust Treatment, is a business unit under Wärtsilä Marine Systems, that designs exhaust gas abatement solutions and products for the shipping industry (Wärtsilä, n.d. -i). The unit also provides lifecycle services including spare parts and field services for its abatement products. Exhaust Treatment's product portfolio consists of scrubber technology that reduces SOx and PM emissions and onboard CCS technology (Wärtsilä, n.d. -i). Wärtsilä Exhaust Treatment currently employs over 200 employees in nine countries in Europe and Asia (Wärtsilä, n.d. -i).

The environmental regulations set by the IMO are one of the main business drivers for Wärtsilä Exhaust Treatment. The SOx and NOx emission regulations in MARPOL Annex VI and the IMO's increasing focus on $CO_2$ emissions create the market in which Wärtsilä Exhaust Treatment operates. Wärtsilä Exhaust Treatment is the market leader for EGC systems with over 800 installed exhaust gas treatment systems (Wärtsilä, n.d. -i).

### 2.1.2 Wärtsilä Exhaust Treatment SOx abatement solutions

Wärtsilä Exhaust Treatment's scrubber portfolio consists of five different designs, as illustrated in figure 2. The design family includes both inline and venturi scrubber designs.

The designs have different capabilities and features such as capacity and energy consumption, which together with vessel type and layout, are important factors when acquiring a scrubber system for a vessel (Wärtsilä, n.d. -i). For example, inline designs such as the Wärtsilä I-SOx system require less space but have less capacity and require a higher water flow compared to the venturi designs such as Wärtsilä V-SOx. Wärtsilä scrubbers can be operated in open loop, closed loop, or hybrid mode.

**Figure 2.** Wärtsilä Exhaust Treatment scrubber design family (Wärtsilä, n.d. -j).

In a Wärtsilä open loop scrubber system, seawater is sprayed to the exhaust gas in three different stages (Wärtsilä, n.d. -k). The sprayed seawater reacts with the sulphur oxide in the exhaust gas and forms sulphuric acid, which is neutralized by the natural alkalinity of the seawater (Wärtsilä, n.d. -k). The neutralized wash water is discharged to the sea after ensuring that it complies with the environmental regulations. Wash water is monitored at the inlet and outlet points of the system to ensure compliance and to record system operations (Wärtsilä, n.d. -k). Wärtsilä open loop SOx scrubber system is illustrated in figure 3.

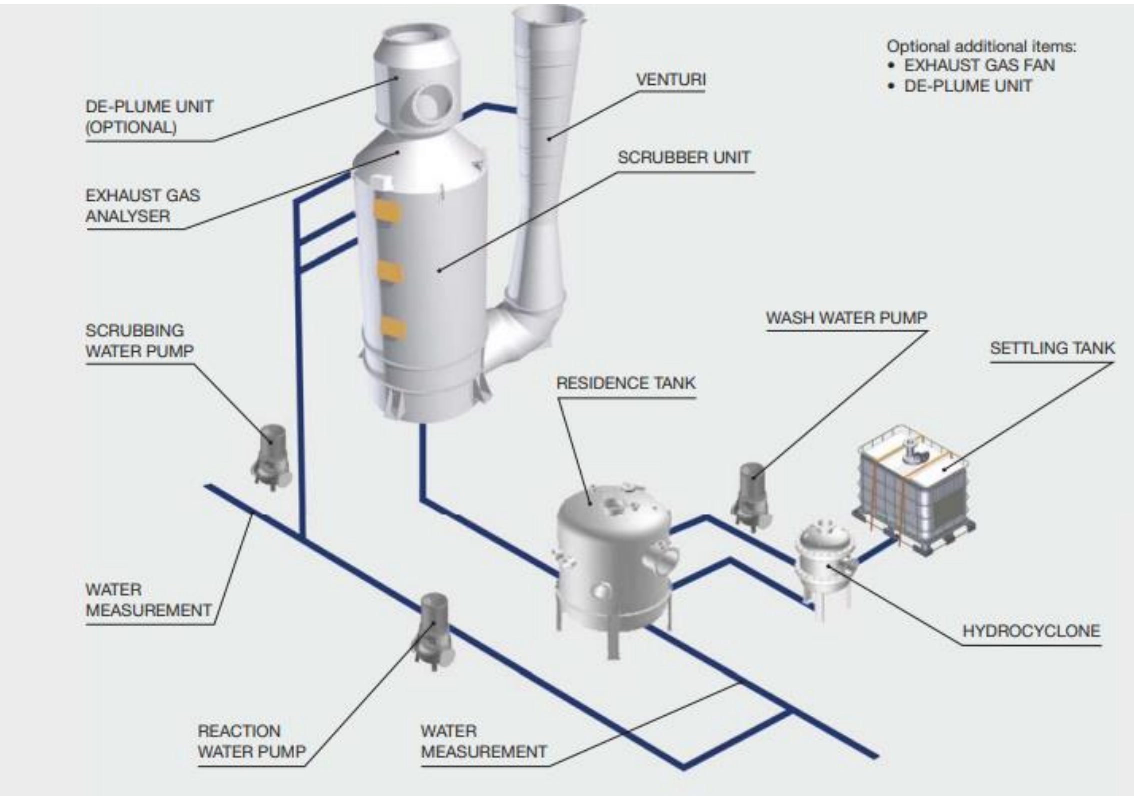

**Figure 3.** Wärtsilä open loop scrubber system (Wärtsilä, 2017, p. 4)

In a Wärtsilä closed loop scrubber system, the sulphur oxide in the exhaust gas is neutralized by spraying it with a mixture of scrubbing water and alkali such as sodium hydroxide (Wärtsilä, n.d. -k). Instead of discharging the wash water to the sea, the closed loop system circulates the washing mixture in the scrubber and only a small bleed-off is extracted from the system, which is replaced with fresh water and alkali (Wärtsilä, n.d. -k). The accumulated impurities in the wash water are removed from the loop with the extracted bleed-off, which is then fed to the water treatment unit where it is filtered for PM, PAH, and other harmful particles (Wärtsilä, n.d. -k). The cleaned effluent is then discharged or led to a holding tank if discharging is prohibited (Wärtsilä, n.d. -k).

The pH levels of the washing mixture are constantly monitored and controlled with alkali dosing to ensure maximum cleaning efficiency and proper functioning of the system. The closed loop system is useful in areas where the natural alkalinity of the water is low and discharging is limited or prohibited (Wärtsilä, n.d. -k). Wärtsilä closed loop system is illustrated in figure 4.

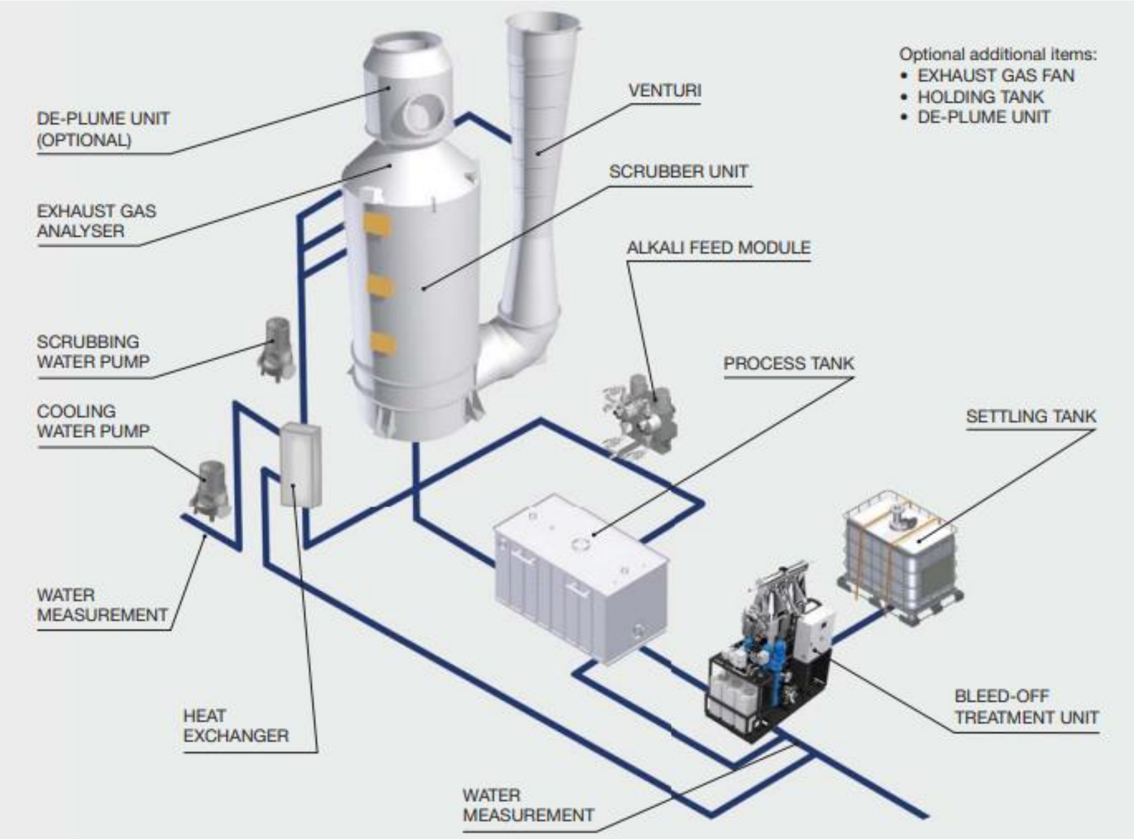

**Figure 4.** Wärtsilä closed loop scrubber system (Wärtsilä, 2017, p. 5).

The Wärtsilä hybrid scrubber system combines the open and closed loop systems, allowing the vessel to operate in low alkaline waters as well as in the open sea (Wärtsilä, 2018, p. 6). The system can be switched run closed or open loop at any given time, which increases the vessels operational flexibility and is therefore suitable for vessels with variable operational routes. Wärtsilä hybrid scrubber system is illustrated in figure 5.

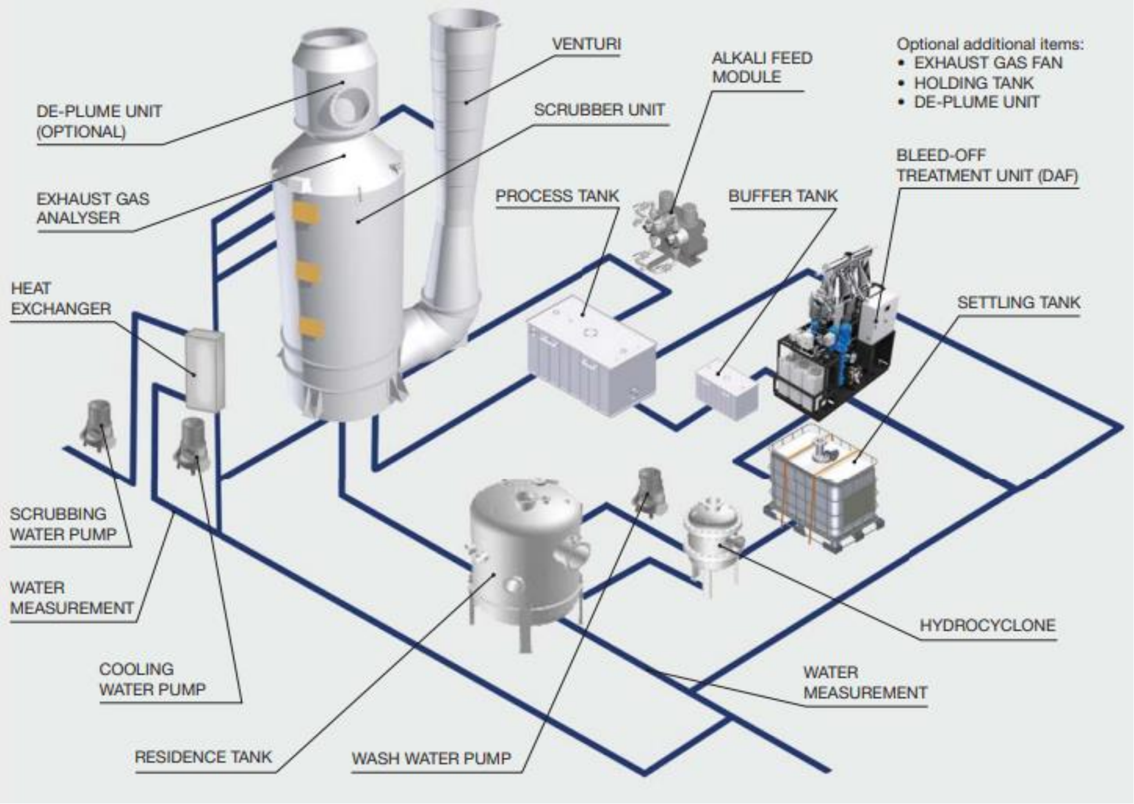

**Figure 5.** Wärtsilä hybrid scrubber system (Wärtsilä, 2017, p. 6)

# 3 Theoretical background

This chapter introduces the history of IMO regulatory framework, the life cycle assessment method, life cycle of a Wärtsilä SOx scrubber system, and prior LCA studies in the field. The chapter therefore covers the key theories behind the drivers of the SOx abatement product business, the units of analysis used in this study, and the used methodology.

## 3.1 IMO regulatory framework

The convention for the establishment of IMO was formed in 1948 at the international maritime conference of the United Nations and entered into force in 1958 (IMO, n.d. -c). The organization was established initially to improve maritime safety and efficiency of navigation and to control marine pollution caused by ships (IMO, n.d. -c). Since its inception, IMO has created a broad regulatory framework around the safety and sustainability of the maritime industry that does not conflict with the needs of global economy (Joseph & Dalaklis, 2021, p. 1).

One part of the regulatory framework is the International Convention for the Prevention of Pollution from Ships, referred to as MARPOL. MARPOL was adopted in 1973 and entered into force in 1978 (IMO, n.d. -c). Today its main responsibilities are to counter accidental and operational oil pollution, as well as chemical, sewage, and air pollution caused by maritime traffic (IMO, n.d. -c). The convention has been updated many times since its inception and today it includes six (I-VI) technical Annexes (IMO, n.d. -d). These Annexes, especially Annex VI, are one of the main drivers for Wärtsilä’s EGC system business.

### 3.1.1 Annex I

MARPOL Annex I was adopted in 1983 and its main objective is to ensure that oil tankers are built and operated in a manner that minimizes oil pollution during normal operation or in the event of accident (IMO, n.d. -e). Annex I introduced regulations for the fitting out and construction of new oil tankers, such as ballast tanks to separate the ballast water from the cargo to prevent oil spills in the event of an accident (IMO, n.d. -e). In 1992, Annex I was revised, and an amendment was added stating that all new oil tankers must built with a double hull to prevent leakage if the vessel is damaged (IMO, n.d. -e). This amendment replaced the requirements for separate ballast tanks. The amendment also stated that existing oil tankers were also to be scheduled for the fitting of double hulls (IMO, n.d. -e).

In addition to cargo oil and its potential for pollution, fuel oils and discharged water are also addressed in Annex I. The oil content of bilge water discharged from ships over 400 gross tons was limited to 15 ppm in Annex I and since then the limitations have become more stringent in certain waters around the world (McLaughlin et al. 2014, p. 5638). To comply with the limitations, the oil is separated from the bilge water in an oily water separator, and the oil content is monitored to ensure compliant discharge (IMO, n.d. -e).

Construction and operational regulations introduced in Annex I combined with traffic separation schemes and other safety regulations have greatly contributed to the decrease of sea pollution (IMO, n.d. -e). However, given the forecasted growth in marine traffic and the increasing focus on sustainability, stricter measures regarding discharging of bilge water and other harmful liquids can be expected. One possible solution for reducing oil pollution is the development of advanced combustion technologies that utilize e.g., methane or hydrogen instead of traditional petroleum.

### 3.1.2 Annex II

MARPOL Annex II entered into force in 1983 and addresses pollution from noxious liquid substances carried in bulk (Arslan et al. 2018, p. 358). Annex II includes a categorization system for noxious and liquid substances and their impacts on human health, environment, and amenities (IMO, n.d. -f). The categories are named X, Y, Z and other substances and they are presented in table 1.

**Table 1.** Categorization system for pollution caused by noxious and liquid substances (IMO, n.d. -f).

| Category | Definition |
|---|---|
| X | Noxious Liquid Substances which, if discharged into the sea from tank cleaning or de-ballasting operations, are deemed to present a major hazard to either marine resources or human health and, therefore, justify the prohibition of the discharge into the marine environment |
| Y | Noxious Liquid Substances which, if discharged into the sea from tank cleaning or de-ballasting operations, are deemed to present a hazard to either marine resources or human health and, or cause harm to amenities or legitimate uses of the sea and therefore justify a limitation on the quality and quantity of the discharge into the marine environment |
| Z | Noxious Liquid Substances which, if discharged into the sea from tank cleaning or de-ballasting operations, are deemed to present a minor hazard to either marine resources or human health and therefore justify less stringent restrictions on the quality and quantity of the discharge into the marine environment |
| Other substances | Substances which have been evaluated and found to fall outside category X, Y or Z because they are considered to present no harm to marine resources, human health, amenities, or other legitimate uses of the sea when discharged into the sea from tank cleaning or de-ballasting operations. The discharge of bilge or ballast water or other residues or mixtures containing these substances are not subject to any requirements of MARPOL Annex II |

In addition to the categorization system, Annex II defines rules and requirements for discharging, carriage, and stripping procedures for the noxious liquids (Arslan et al. 2018, p. 347). By way of example, Annex II prohibits the discharge of noxious substance residue within 12 nautical miles of the nearest shore (Arslan et al. 2018, p. 358).

### 3.1.3 Annex III

MARPOL Annex III was adopted in 1992 and addresses the pollution caused by harmful substances in packaged form (Arslan et al. 2018, p. 348). According to the Annex, each vessel carrying harmful substances in packaged form should store documentation for the stowage plan of the ship until the substances are discharged or stored ashore (Arslan et al. 2018, p. 348). In addition to substances in packaged forms, the Annex addresses the stowage plans for harmful substances carried in freight containers, tanks, and wagons (Arslan et al. 2018, p. 348).

The Annex includes marking and labelling regulations which state that each package containing harmful substances should be marked durably and with the correct technical name (Arslan et al. 2018, p. 348). Stowage documents combined with correct marking and labelling of harmful substances are effective in reducing the risks of accidents harmful to human health or the environment.

### 3.1.4 Annex IV

MARPOL Annex IV addresses the pollution caused by sewage and it entered into force in 2003 (Arslan et al. 2018, p. 349). In Annex IV, sewage is defined as wastewater from lavatories, medical facilities, spaces containing living animals, and other wastewater containing waste from these premises (Şahin et al. 2020, p. 49). Among other chemicals, sewage contains high amounts of nitrogen and phosphorus, which are harmful to the marine environment (Arslan et al. 2018, p. 349).

Annex IV regulates the discharging of untreated sewage and requires governments to provide sewage reception facilities in ports (IMO, n.d. -g). Vessels certified to carry over 15 persons and are of 400 gross tonnage or above are required to have a sewage treatment plant, sewage disinfecting system, or a sewage holding tank (IMO, n.d. -g). Discharging of sewage is prohibited unless the vessel is equipped and operating with a sewage treatment plant. Discharging of disinfected sewage is allowed if the vessel is located more than three nautical miles away from the nearest shore (IMO, n.d. -g). Untreated sewage can be discharged if it is approved by administration or if the vessel is more than 12 nautical miles away from the shore and moving at a speed of at least four knots (IMO, n.d. -g).

### 3.1.5 Annex V

MARPOL Annex V entered into force in 1988 and contains regulations for the prevention of pollution by garbage from ships (Arslan et al. 2018, p. 350). The regulations in the Annex apply to all ships but do not contain any certification or approval requirements. Despite the lack of these requirements, over 150 countries have ratified the Annex (IMO, n.d. -h). The Annex prohibits discharging any type of garbage into the sea unless they comply with the regulations included in the Annex related to food waste, cargo residues, cleaning agents, or animal carcasses (IMO, n.d. -h).

Annex V also requires a garbage management plan to be stored on all ships and floating or fixed platforms that are of 100 gross tonnage or more or certified to carry 15 or more persons (Arslan et al. 2018, p. 350). All ships and fixed or floating platforms that are certified to carry 15 or more persons and are of 400 gross tonnage or above are required to keep a garbage record book on board (Arslan et al. 2018, p. 350). The intent of the garbage record book is to keep track of the amount of incinerated and discharged waste produced in the ship, and the location and date of the waste management procedures (IMO, n.d. -h). The garbage record book can be a useful tool for ship operators to avoid penalties when upon inspection. Keeping an up-to-date record book of waste management is an approved proof of complying with the waste regulations and ensuring that waste is handled properly in allowed locations.

### 3.1.6 Annex VI

MARPOL Annex VI, also called Regulations for the Prevention of Air Pollution was introduced by the IMO in 1997 and entered into force in 2005 (Čampara et al. 2018, p. 3). Annex VI regulations limit SOx, NOx, PM, VOC, and other ozone depleting emissions from shipping operations and define specific ECA's in which some of the emission regulations are more stringent (IMO, n.d. -d). The currently established ECA's are the Baltic Sea area, North Sea area, the North American area, and the United States Caribbean Sea area, as presented in figure 6 (Fagerholt et al. 2015, p. 58). In addition to these areas, the Mediterranean Sea area has been adopted as the next SOx and PM emission-controlled area under Annex VI (IMO, n.d. -i). The amendment is expected to enter into force in 2024.

**Figure 6.** Emission Control Areas (Rymaniak et al. 2018, p. 2).

Annex VI regulations limit the SOx content in marine fuel oils to improve air quality and to prevent environmental damage. The marine fuel oil SOx content limitations have progressively tightened over time, as illustrated in figure 7. SOx and PM emissions are harmful to human health and have been linked to asthma, heart attacks and premature death (Tokuslu et al. 2020, p. 150). Compliance with the latest SOx regulations can be achieved by using fuel oil that meets the SOx content limits, natural gas, or biofuels (Boviatsis, 2022, p. 393). Exhaust gas cleaning systems, also called scrubbers, are also a viable alternative for achieving compliance. Scrubbers remove sulphur oxides and particle matter from engine exhaust gases and can achieve the strictest 0,1% m/m SOx limitation (Boviatsis, 2022, p. 393).

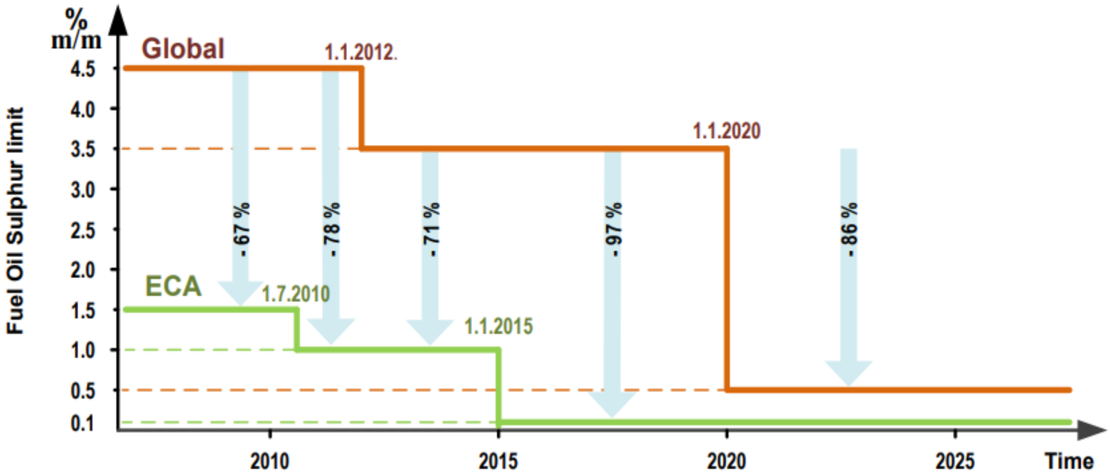

**Figure 7.** Annex VI fuel oil SOx content limitations over time (Čampara et al. 2018).

SOx and NOx emissions cause acidification and eutrophication in oceans resulting in changes in water pH levels and increase in anoxic and hypoxic water areas (Omstedt et al. 2015, p. 242). Annex VI introduced NOx control levels for all marine diesel engines with a power output of more than 130 kW and that are installed on ships built on or after 1 January 2000 (Čampara et al. 2018, p. 4). Today, these control levels are defined as Tiers I, II, and III. The three Tiers are based on the construction date of the vessel and their NOx limitations are defined as g/kWh, which is proportional to the engine's rated speed (Čampara et al. 2018, p. 4). Tier III is the most stringent and applies to ships built after 2016 and only when operating in ECA's. Operating elsewhere requires compliance with Tier I or Tier II depending on the age of the vessel (Čampara et al. 2018, p. 4). The Tier specific NOx limitations are illustrated in figure 8.

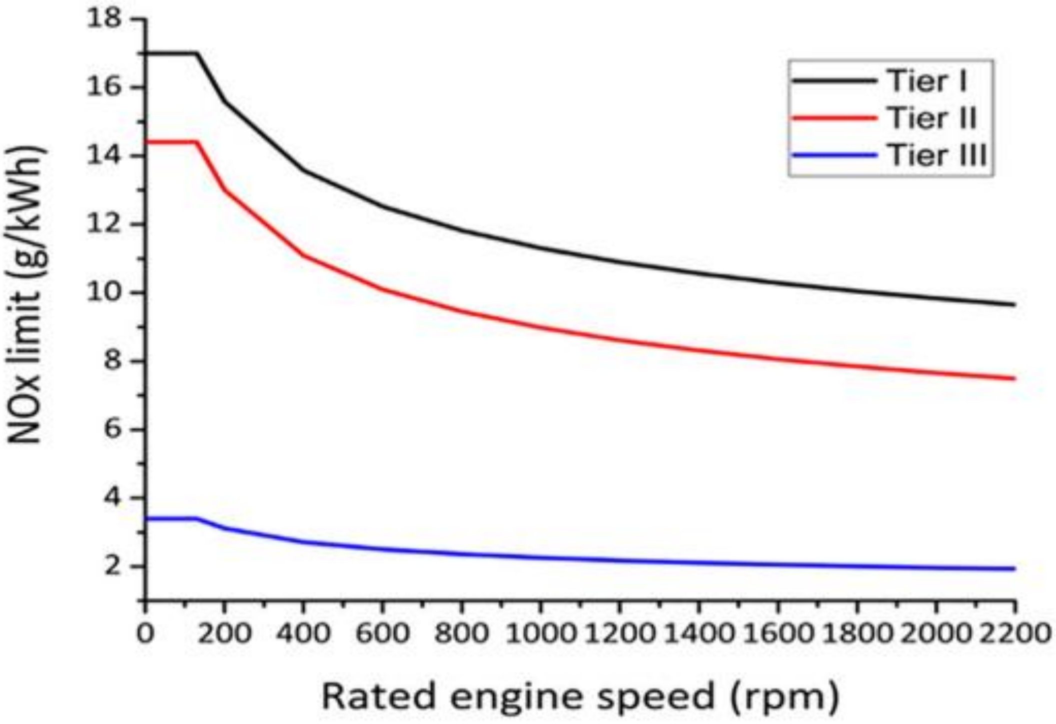

**Figure 8.** MARPOL Annex VI NOx emission limits (Deng et al. 2021, p. 4)

NOx emission reduction methods are often categorized as primary or secondary methods (Rymaniak et al. 2018, p. 2). Primary methods aim to reduce the formation of NOx inside the engine during the combustion process and they are often sufficient for Tier II limitations. Primary methods are, for example, modifying the fuel injection into the combustion chamber or lowering the temperature of the combustion air (Rymaniak et al. 2018, p. 3). Secondary methods aim to reduce NOx from the exhaust gas and the most common method for this is the use of SCR technology (Rymaniak et al. 2018, p. 2). SCR produces chemical reactions using ammonia and a catalyst, the most dominant of which converts nitrogen monoxide, oxygen and ammonia into nitrogen and water (Aakko-Saksa & Lehtiranta, 2019, p. 21). SCR technology is often used in vessels operating in areas that require Tier III compliance due to its high NOx reduction efficiency (Rymaniak et al. 2018, p. 5).

In 2011, Annex VI was complimented with new regulations concerning energy efficiency requirements. These regulations state that all vessels must have an energy efficiency management plan which includes plans to improve voyage planning, increase frequency of cleaning underwater parts, and implement new technical measures for increasing energy efficiency (Boviatsis et al. 2022, p. 394). The regulations also state that the Energy Efficiency Design Index (EEDI), which is a measure of ship's energy efficiency, must be calculated for all new ships. The calculation is to be done using a formula developed by the IMO and the results represent the minimum required energy efficiency of the vessel (Čampara et al. 2018, p. 8).

## 3.2 Life cycle assessment

Life cycle assessment (LCA) is an ISO-standardized quantitative method for identifying the environmental impacts of a product or a process throughout its lifecycle (Hellweg & Canals, 2014, p. 1109). LCA can be used in many ways, for example to optimize the environmental performance of a product or a process, to benchmark and compare environmental impacts of products or processes, to design production and consumption policies, or to market a product or a process (Hellweg & Canals, 2014, p. 1109). Wärtsilä has commissioned this LCA study to initiate the process of developing environmental KPIs for their scrubber business and to contribute to the company's target of being carbon neutral by 2030.

ISO has developed two standards for life cycle assessments and how they should be conducted. These standards are ISO 14040, which defines LCA principles and framework, and ISO 14044, which defines requirements and guidelines for conducting a life cycle assessment. As shown in figure 9, the LCA framework is an iterative process that consists of four phases: defining goal and scope, inventory analysis, impact assessment, and interpretation of results (ISO, 2006).

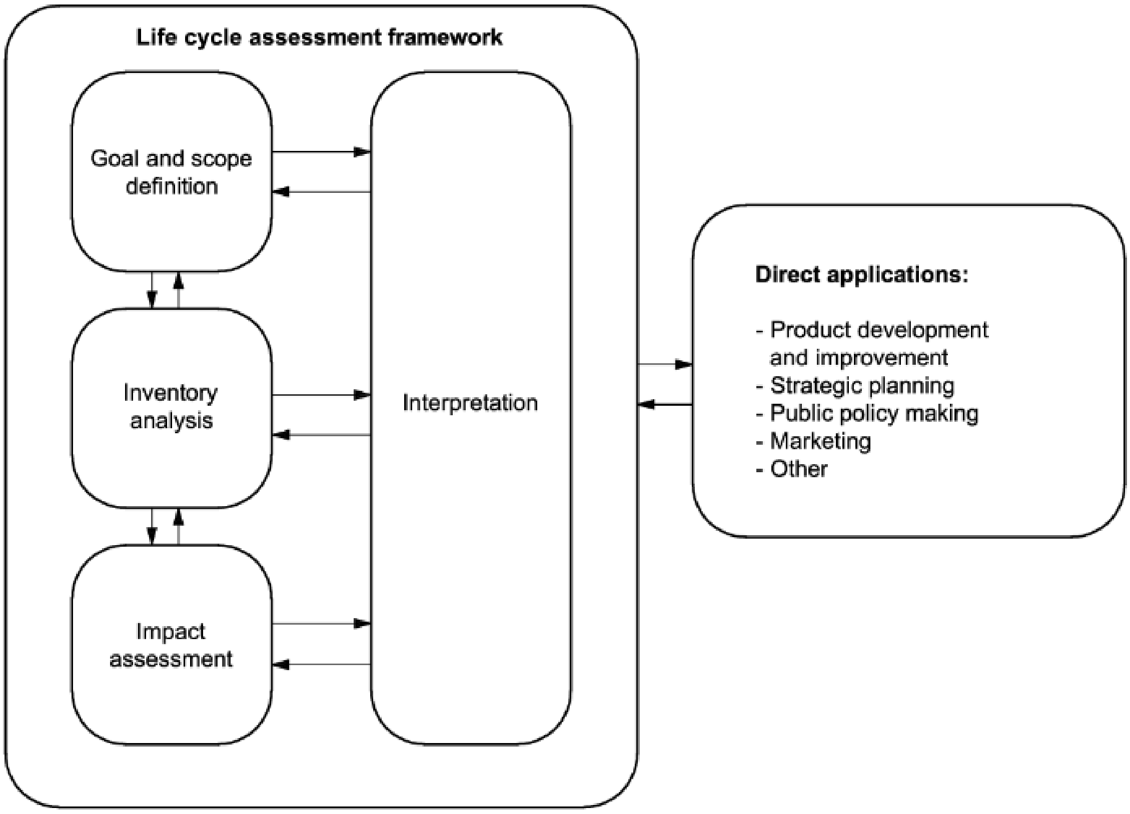

**Figure 9.** Stages and example applications of LCA (ISO, 2006).

In the first phase of an LCA, the goal and scope of the study are defined. The goal definition of the study must include four statements for the LCA to be compliant with the ISO standards. These statements are the intended application of the study, reasons for conducting the study, to whom the results are to be presented, and whether the results will be used in comparative public assertions (Matthews et al. 2015, p. 85). The scope of the study should include a specific explanation of what is included in the study and how the assessment is going to be conducted. ISO 14044 standard defines clear instructions for 12 items that are required to be described in the scope. These items include for example the studied system, the functional unit of the system, system boundaries, and the impact assessment methodology used in the study (Matthews et al. 2015, p. 86).

The second phase of an LCA is the inventory analysis. In this phase, the input and output data for the studied system is collected in accordance with the predefined goal and scope of the study (Matthews et al. 2015, p. 101). The input data generally is the materials, electricity consumption, logistics, and other resources that are needed to produce the studied system. The output data refers to the product system itself, co-products, and release outputs such as GHG emissions that are produced in creating the product system (Matthews et al. 2015, p. 101). The ISO 14044 guidelines state that the data collected for the inventory analysis needs to be validated and related to the functional unit that is defined in the goal and scope (Matthews et al. 2015, p. 101).

The third phase of an LCA is the impact assessment, in which the environmental impacts of the life cycle inventory are assessed in accordance with the chosen impact assessment methodology. The goal of the impact assessment is to transform the results of the inventory analysis into a form that serves the goal and purpose of the study (Matthews et al. 2015, p. 366). There are several impact assessment methodologies that track different impact categories and therefore different impacts on ecosystems, natural resources, and human health (Matthews et al. 2015, p. 366).

The fourth and final phase of an LCA is the interpretation of the results. In this phase, the results all previous phases are studied in order to make conclusions and to recommend actions based on the purpose of the study (Matthews et al. 2015, p. 113). The interpretation phase is often complemented with a sensitivity analysis, although it is not mandatory for achieving compliance with the ISO standards (Matthews et al. 2015, p. 113). The sensitivity analysis is often performed by modifying the output and input parameters and the used methodology to see how much the results are affected (Matthews et al. 2015, p. 114). The purpose of the sensitivity analysis is to test if the conclusions are affected by changing the quantitative parameters (Matthews et al. 2015, p. 114).

### 3.2.1 Life cycle of a Wärtsilä V-SOx scrubber

A Wärtsilä SOx scrubber system consists of hundreds of different components, which makes it difficult to estimate the service life of the system as an entity. The scrubber towers are given a service lifetime expectancy of 20-25 years, during which some other components may have had to be replaced several times. In this research, the operational lifetime of the system is estimated to be 20 years, and replaceable components are considered and included in the life cycle assessment.

Wärtsilä does not manufacture its SOx scrubbing systems in-house. Wärtsilä designs and delivers the systems, hence the manufacturing is outsourced to different suppliers. The company uses different suppliers to acquire most of the necessary components which are then ordered to the shipyard in which the system is assembled and installed to the vessel. After the system is installed and the vessel is ready to sail, a sea trial is performed to ensure that the scrubber operates in compliance with the IMO regulations. After passing the sea trial, the scrubber system is ready to be used as part of the ship's operation.

This study assesses a V-SOx hybrid scrubber system that is installed on a certain type of tanker. The operational lifetime of these type of tankers is generally 20 to 25 years (Ozguc, 2018, p. 33). Therefore, if the scrubber system is inspected and maintained regularly, it should be able to operate throughout the lifetime of the tanker. Once the operational lifetime of the vessel and scrubber has come to an end, the scrubber is scrapped and disposed of or recycled, thus ending the lifecycle of the system.

### 3.2.2 Prior works

Although the latest sulphur content regulations were introduced in 2020 and the widespread use of marine SOx scrubber systems is relatively new, several LCA studies have been conducted in the field. Many of the studies are comparative and contain cost assessments for comprehensive comparison between the different options of complying with the sulphur content regulations.

Andersson et al. (2020) compared 20 MW open and closed loop marine SOx scrubber systems in terms of environmental impacts and installation cost payback time. They conducted the LCA following the framework in the ISO 14040 standard and built the life cycle inventory using material from scientific articles and other publicly available data. The results were used to evaluate global warming, acidification, and eutrophication potentials. Andersson et al. (2017, p. 175) concluded that the impacts generated by the open loop system are slightly smaller due to less material needed for installation and operation. However, open loop discharge water and closed loop NaOH consumption were not considered in the study. Andersson et al. (2017, p. 174) suggested further research to address these limitations, as they may have significant potential for impacting the environment. They also concluded that compared to closed loop system, the open loop system had a marginally shorter payback time regardless of the type of fuel used.

Cui et al. (2021) conducted a comparative LCA and cost assessment study on an open loop system, closed loop system utilizing NaOH, and a system utilizing $Mg(OH)_2$ as the alkali. The LCA consisted of the construction and operational phase and the impacts were assessed with the ReCiPe2016 method, which combines midpoint and endpoint impact categories. Cui et al. (2021, p. 113) found that the NaOH system produced the most environmental impacts out of the three systems. The open loop system was found to produce significantly less impacts compared to the other two systems. However, open loop wash water discharging was not modelled in the LCA, which likely contributed to the gap between the impacts of the systems. The NaOH and $Mg(OH)_2$ systems were also more expensive according to the results obtained in the cost assessment due to the cost of the alkali over the life cycle (Cui et al. 2021, p. 113).

Martínez-López et al. (2022) introduced an environmental assessment model and compared the environmental performance of different marine sulphur mitigation methods. The studied methods were open and closed loop scrubber systems using varying sulphur content HFOs, running the main engine on MGO and running the engine in dual mode using LNG. They applied the model to a container vessel operating in a shipping line between the Canary Islands and the Iberian Peninsula.

Martinez-Lopez et al. (2022) evaluated the environmental performance of the different sulphur mitigation methods with climate change, marine ecotoxicity, and marine eutrophication impact categories. They included the scrubber wash water discharge in the study and modelled it to contain average concentrations of 16 different PAHs, nitrate and ten different metals. The introduced model quantified the environmental performance of the different methods in monetary terms, determining a cost for each environmental characterization factor (Martinez-Lopez et al. 2022).

Martinez-Lopez et al. (2022) concluded that regardless of the operating mode, the scrubber system was the most efficient sulphur mitigation method in terms of environmental performance. In terms of air emissions, they found that the dual engine LNG operation was the most suitable option. However, the total pollution impact was the lowest for the scrubber systems. MGO operation was found to be the least suitable option in comparison to the other methods.

Martinez-Lopez et al. (2022) also concluded that there was no significant difference between the total pollution impact between open and closed loop scrubber systems. They highlighted that although the volume of discharge water in closed loop operation is significantly lower, the marine eutrophication results were nearly the same. According to Martinez-Lopez et al. (2022), this phenomenon is the result of the significantly higher nitrogen concentration in closed loop discharge water. They suggested further research on the marine eutrophication caused by closed loop scrubber system operation.

# 4 Methodology

This chapter demonstrates the data collection and research methodology used in the study. The goal and scope of the life cycle assessment are covered in chapters 4.1, followed by inventory analysis and an explanation of uncertainties in inventory data in chapter 4.2.

## 4.1 Goal and scope

The goal of the life cycle assessment was to determine the environmental impacts of a certain Wärtsilä V-SOx hybrid scrubber system throughout its complete lifecycle. The reason for conducting the LCA study was to initiate the process of developing KPIs for future monitoring of environmental performance in the manufacturing, logistics and installation phases of the lifecycle. Also, assessing the environmental impacts of the operational and end-of-life phases of the system provides the company with information that can be used in benchmarking and product development activities. The results of the LCA were to be presented internally in Wärtsilä and as part of a master’s thesis seminar at the University of Vaasa.

The system studied in the life cycle assessment is an Wärtsilä V-SOx hybrid scrubber system. The studied system was installed on a tanker in 2019 and at the time of conducting the study, it had been in operation for four years and two months. The function of the system is to remove sulphur oxides and other contaminants from the exhaust gas produced by the combustion engines on the tanker.

In LCA studies, the function of the system should be expressed as a functional unit which acts as a reference point for all inputs and outputs in the scope (Panesar et al. 2017, p. 1969). Using the functional unit as a reference point allows the results of the LCA to be compared to other LCA studies of different processes or products with the same function (Panesar et al. 2017, p. 1969). The exhaust gas produced by the combustion processes in the vessel is directed into the scrubber where it is treated. The functional unit used in this LCA was determined as 1 kg mass of exhaust gas entering from the engine to the scrubber system. The exhaust gas mass flows were obtained from Wärtsilä's technical documentation.

The system boundary defines the boundaries within which the life cycle assessment is performed (ISO, 2006). In this study, the system boundary includes four life cycle stages, 27 specifically chosen components, raw materials and transportation, and other inputs of the V-SOx system life cycle. The system components were selected based on their mass and function in the system, with the aim of selecting the most critical components in terms of system functionality. The system boundary is outlined in figure 10.

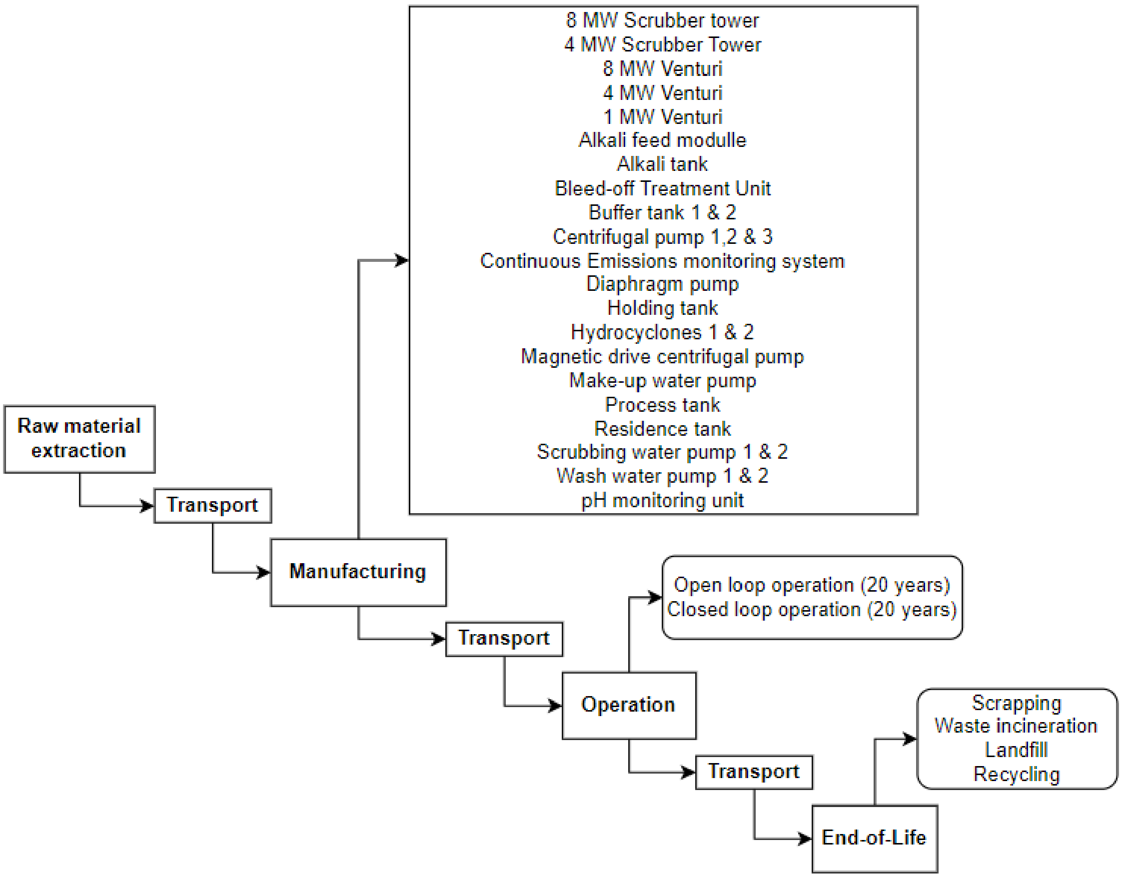

**Figure 10.** LCA System boundary

The LCIA method used in the study was ILCD 2011 Midpoint+. Midpoint LCIA methods assess category indicators for selected impact categories that are in the middle of the pathway between life cycle inventory results and endpoints (Sharaai et al. 2012, p. 1392). Midpoint methods convert the category impacts into real environmental phenomenon such as eutrophication, acidification, and climate change (Sharaai et al. 2012, p. 1392). Endpoint LCIA methods assess category indicators that are in the end of the pathway of the environmental impact (Sharaai et al. 2012, p. 1392). Endpoint methods assess the impact of the environmental system to human health, ecosystem diversity, or resource availability, thus measuring damage on the societal value these entities produce (Sharaai et al. 2012, p. 1392). The general framework for LCIA pathways is illustrated in figure 11.

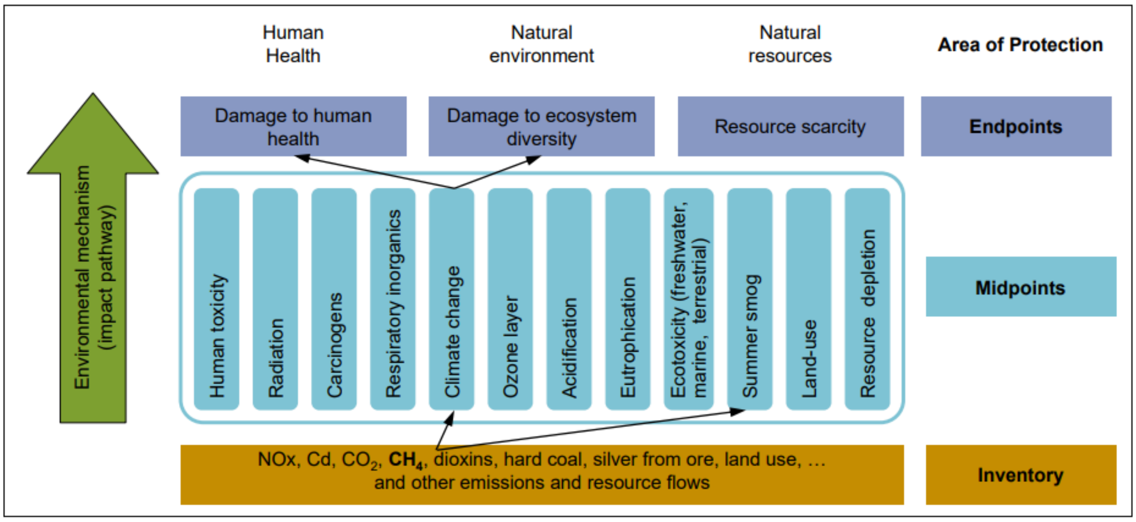

**Figure 11.** LCIA steps from inventory to category endpoints (JRC, 2010a, p. 108)

The ILCD handbook recommends ten midpoint impact categories and three areas of protection to be checked for relevance by default in LCIA's (JRC, 2010a, p. 109). These impact categories and areas of protection are all included in the ILCD 2011 midpoint+ LCIA methodology. The ILCD handbook also recommends methods and characterisation factors for the impact categories, as illustrated in table 2. The characterisation factors are classified as level I, II, or III. Level I is defined in the ILCD handbook as recommended and satisfactory, level II as recommended but in need of some improvements, and level III as recommended but to be applied with caution (JRC, 2010b, p. 3). In addition to these classifications, a separate classification category for methods that are considered best of the analysed methods but still considered deficient, is called “interim” (JRC, 2010b, p.3).

The ILCD 2011 midpoint+ LCIA methodology and the ILCD handbooks were developed by the European Joint Research Centre in effort to enhance consistency and quality when applying LCA within the ISO 14040 and 14044 standards. ILCD 2011 midpoint+ uses the methods and characterisation factors recommended in the ILCD handbooks, which is the reason for choosing it as this study’s LCIA methodology. The same methodology has previously also been used by Järvinen (2021) in an LCA performed on a Wärtsilä marine diesel engine. The LCIA in this study was calculated using OpenLCA version 1.11.0 software.

**Table 2.** Recommended methods and their classification at midpoint (JRC, 2010b).

| **Impact category** | **Recommended default LCIA method** | **Characterisation factor** | **Classification** |
|---|---|---|---|
| Climate change | Baseline model of 100 years of the IPCC | Radiative forcing as Global Warming Potential (GWP100) | I |
| Ozone depletion | Steady-state ODPs 1999 as in WMO assessment | Ozone Depletion Potential (ODP) | I |
| Human toxicity, cancer effects | USEtox model (Rosenbaum et al. 2008) | Comparative Toxic Unit for humans ($CTU_h$) | II/III |
| Human toxicity, non-cancer effects | USEtox model (Rosenbaum et al. 2008) | Comparative Toxic Unit for humans ($CTU_h$) | II/III |
| Particulate matter/Respiratory Inorganics | RiskPoll model (Rabl and Spadaro, 2004) and Greco et al. 2007 | Intake fraction for fine particles (kg PM2.5-eq/kg) | I |
| Ionising radiation, ecosystems | Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al, 2000) | Human exposure efficiency relative to $U^{235}$ | II |
| Ionising radiation, ecosystems | No methods recommended | | Interim |
| Photochemical ozone formation | LOTOS-EUROS (Van Zelm et al. 2008) as applied in ReCiPe | Tropospheric ozone concentration increase | II |
| Acidification | Accumulated Exceedance (Seppälä et al. 2006, Posch et al. 2008) | Accumulated Exceedance (AE) | II |

| Impact category | Recommended default LCIA method | Characterisation factor | Classification |
|---|---|---|---|
| Eutrophication, terrestrial | Accumulated Exceedance (Seppälä et al. 2006, Posch et al. 2008) | Accumulated Exceedance (AE) | II |
| Eutrophication, aquatic | EUTREND model (Struijs et al. 2009b as implemented in ReCiPe | Fraction of nutrients reaching freshwater end compartment (P) or marine end compartment (N) | II |
| Ecotoxicity (freshwater) | USEtox model, (Rosenbaum et al. 2008) | Comparative Toxic Unit for ecosystems ($CTU_e$) | II/III |
| Ecotoxicity (terrestrial and marine) | No methods recommended | | |
| Land use | Model based on Soil Organic Matter (SOM) (Milá I Canals et al. 2007b) | Soil Organic Matter | III |
| Resource depletion, water | Model for water consumption as in Swiss Ecoscarcity (Frischknecht et al. 2008) | Water use related to local scarcity of water | III |
| Resource depletion, mineral, fossil, and renewable | CML 2002 (Guinée et al. 2002) | Scarcity | II |

The LCA conducted on this study includes assumptions on each phase of the systems life cycle. The assumptions and uncertainties in each phase are outlined in chapter 4.2.5. The assumptions in the study create limitations to the interpretation of the environmental impacts of the systems lifecycle, which are discussed in chapter 6. The results of this LCA study were not to be used in a comparative assertion, and therefore a critical review for the study was not performed.

## 4.2 Inventory analysis

The life cycle inventory analysis includes the input and output data for each life cycle phase of the studied product system. The input data was collected from Wärtsilä's internal databases, documentation sent by the ship's operator and secondary sources i.e., scientific literature and Ecoinvent database if internal data was not found to be sufficient. The life cycle phases of the system were defined as raw material extraction and manufacturing of the components, transportation to shipyard, operational phase, and end-of-life phase.

As stated in chapter 3.2.1, the studied V-SOx hybrid scrubber system consists of hundreds of different components. The components for the LCA were selected from the bill of materials of the delivery project of the system based on their mass and functionality in the system. Out of the 27 selected system components, six were not supplied by Wärtsilä, but instead by the shipyard. Although not being in Wärtsilä's scope of supply, the components are crucial for the function of the system and contribute significantly to meeting the mass-specific requirements of the LCA. The total weight of the system was estimated to be 35 tons. The combined weight of the selected components without packaging materials was 30,3 tons, giving the weight-based cut-off range for the LCA of 86,7%. The data collection methods for each phase of the life cycle are illustrated in table 3.

**Table 3.** Data collection methods and data quality in each life cycle phase.

| Life cycle phase | Data quality | Data Source |
|---|---|---|
| Raw material extraction & manufacturing of components | Primary & secondary data | Wärtsilä internal databases, Ecoinvent database v3.8, Literature |
| Transportation to shipyard | Primary data & secondary data | Wärtsilä internal databases, Ecoinvent database v3.8 |
| Operational phase | Primary & secondary data | Wärtsilä internal databases, customer documentation, Ecoinvent database v3.8 |
| End-of-Life | Secondary data | Ecoinvent database v3.8 |

### 4.2.1 Raw material extraction and manufacturing of components

The first life cycle phase of the studied system consists of the extraction and manufacturing of the materials used in the selected components, and their delivery to the component manufacturers and suppliers. Packaging materials, for which data were acquired from Wärtsilä's shipping documents were also included in the material inputs of this phase. The material compositions of the selected components were collected from Wärtsilä's internal tools and databases and scientific literature. All 6 components delivered by the shipyard were tanks and were assumed to be made of carbon steel based on

Wärtsilä's documentation. Wärtsilä has delivered similar tanks in the past and has documentation of their typical material composition and mass.

The data for extraction and production of the raw materials was collected from Ecoinvent database version 3.8 market processes. The transportation data from extraction to supplier was based on average distances and transportation methods and was also collected from the Ecoinvent database. The material composition of the selected components consisted mostly of different grades of stainless and carbon steel, copper, cast iron, and aluminium. Some of the components also included metal coating, synthetic rubber, brass, polyvinylchloride, glass reinforced plastic, carbon reinforced plastic, or electronic systems such as displays, for which input data were collected from the Ecoinvent database. For coated components, an assumption was made that the coating material accounted for 3% of the components total mass. In OpenLCA, the coating materials were modelled with a market process for epoxy resin liquid obtained from Ecoinvent database v3.8.

Carbon steel was the most dominant material in the system, attributing for 75% of the total mass of the system. Stainless steel accounted for 10% of the systems mass and cast iron for 9%. The remaining 6% of the mass was accounted by all other materials mentioned on page 35. The components were delivered in wooden boxes, and rigid foam made of polyurethane was assumed to be the protective material for the delivery. The mass of the protection material was assumed to be 0,5% - 5% of the total package mass, depending on the size and fragility of the component. The volume of wood used in the packaging materials was calculated using the dimensions of the packages, which were obtained from the shipping documents.

Wärtsilä did not manufacture the components on the scope of this LCA. The manufacturing data was collected from Ecoinvent database version 3.8 due to the vast number of different manufacturers and difficulties in acquiring data from them.  Majority of the components in the scope were given an estimated lifetime of 15-20 years. Four replaceable components during the lifetime of the system were identified and their processes were duplicated in the OpenLCA model. The Ecoinvent database contains processes containing average inputs and outputs for steel, copper, aluminium, and other metal product manufacturing, which were utilized in simulating the manufacturing of the components in the scope.

### 4.2.2 Transportation from supplier to shipyard

The second life cycle phase of the system consists of transportation from the supplier to the shipyard, where the system is installed on the vessel. The transportation data including transportation methods and delivery address information were collected from shipping documents and Wärtsilä's internal databases. The six components in the scope delivered by the shipyard were assumed to be transported 500 km with 7.5-16 metric ton lorries that operate in compliance with the EURO VI exhaust gas emission standard.

The EURO emission standards were created by the European Commission to regulate the GHG emissions produced by light-duty and heavy-duty vehicles. The EURO VI standard is the latest and most stringent emission standard for heavy-duty vehicles set by the commission, and it regulates, for example $CO_2$, NOx, HC, and PM contents in exhaust gas emissions (Grigoratos et al. 2019, p. 348).

The system was installed on the vessel in a shipyard located in South Korea. The components in the scope were delivered to the shipyard from various locations in East Asia and Europe. The freight was transported with lorries, aircrafts, and cargo ships. In the OpenLCA software, the transportation was modelled using a tonne-kilometre (tkm) as the unit of measure. The unit represents the transport of one tonne of goods including packaging materials for a distance of one kilometre with the given transport method (Eurostat, 2023). The tkm value for each delivery was calculated using equation 1:

$$tkm = \frac{Mass\ (kg)\ of\ transported\ goods}{1000} \times Distance\ (km)\ of\ transport, \quad (1)$$

The transportation distances were calculated using road, seaport and airport distance calculators that were found on the internet. For road transport, 3.5-7.5 metric ton and 7.5-16 metric ton lorry processes obtained from Ecoinvent v3.8 were used to model the transport. The lorries were assumed to operate in compliance with the EURO VI in South Korea and Europe and EURO V in some parts of East Asia. For sea transport, bulk carrier and container ship processes were obtained from the Ecoinvent database and used in the model. Air transport was modelled with a process for generic air freight obtained from the Ecoinvent database. In total, the components were transported by three air deliveries, four ship deliveries, and 18 road deliveries.

### 4.2.3 Operational phase

The operational data of the system was collected from Wärtsilä's technical documentation of the system, Wärtsilä's databases and documentation and other information provided by the operator of the vessel. The operator was unable to attend meetings regarding the operation of the system, which led to an increased number of assumptions in the modelling of the operational phase.

The V-SOx scrubber system was installed in 2019 on a tanker and had been in operation for 50 months at the time of conducting the LCA. The tanker has one main engine that is connected to an 8 MW scrubber, three auxiliary engines that are connected to a 4 MW scrubber and an oil-fired boiler that is connected to a 1 MW venturi tube. The systems running hours were provided by the operator and used to calculate an estimate for total running hours for the duration of the operational phase. The main engine scrubber was estimated to be in operation for 142 560 hours, auxiliary engine scrubber for 87 840 hours and the oil-fired boiler scrubber for 4392 hours during the 20-year operational phase.

The installed scrubber system is a hybrid and can thus be operated in both open and closed loop modes. The ratio of open to closed loop usage was provided by the operator and was used in modelling the operational phase. The vessel had mostly operated in sea areas and ports where discharging of the wash water is allowed. Therefore, the scrubber system had been operated in open loop mode for 99% and in closed loop for 1% of the running hours since installation. The closed loop operation was assumed to be in port running two auxiliary engines and the oil-fired boiler. The baseline scenario shown in table 4 was modelled using the scrubber mode usage ratio provided by the operator.

An additional analysis for two more operational phase scenarios was calculated to provide more results on the environmental impacts of closed loop operation in comparison to open loop operations. In the first additional scenario, the system was assumed to be operated in manoeuvring closed loop mode for 10% of the time and in the second scenario for 30% of the time. In both additional scenarios, the system was assumed to be run on port closed loop operating mode for 5% of the time. For rest of the running hours, the system was assumed to be run on open loop seagoing mode. The operational profiles and scrubber running configuration for each scenario are presented in table 4, in which the running time of different configurations are described as percentages of the systems total running hours.

**Table 4.** Scrubber operating modes as percentages of total system running hours.

| **Scenario** | **Seagoing** | **Manoeuvring** | **Port** |
|---|---|---|---|
| Baseline scenario | OL, 70% | OL, 25% | OL 4% / CL 1% |
| Additional scenario 1 | OL, 70% | OL, 15% / CL 10% | CL 5% |
| Additional scenario 2 | OL, 65% | CL, 30% | CL 5% |

The estimated fuel consumption of the vessel in 2022 was obtained from Wärtsilä’s internal database. Running the scrubber system typically increases the ships fuel consumption approximately between 1% to 3% depending on the characteristics of the system, used fuel type, and operating mode (Zis et al. 2022, p. 1101). The estimated fuel consumption for 20 years of operating the scrubber was calculated based on the tankers fuel consumption estimate from 2022 and Wärtsilä’s technical documentation on the systems energy consumption. An estimation was made that different operating modes increase fuel consumption between 0,8% to 2,9%. Open loop operation typically increases the fuel consumption more compared to closed loop operation because more water is needed in the scrubbing process, which increases the use of scrubbing water pumps and therefore energy consumption.

Based on the estimates on fuel consumption increase, assumptions were made that the vessels fuel consumption due to scrubber use in the baseline scenario was increased by 2,7%, in the first additional scenario by 2,4% and in the second additional scenario by 2%. The energy consumption of the system was modelled to be embedded in the fuel consumption increase of the vessel. The tanker was assumed to operate on heavy fuel oil with a sulphur content of 3,5% m/m throughout the operational phase. On all scenarios, the scrubber was assumed to operate to clean the exhaust gas to a level equivalent to using a fuel with a 0,1% sulphur content.

The data on scrubbing water consumption in open and closed loop operations was obtained from Wärtsilä's technical documentation and is described in table 5. The water supply values in the documentation were based on operating modes that are permitted for complying with MARPOL Annex VI regulations. The operating modes are described in table 6.

**Table 5.** Water consumption on different operating modes.

| **Utility** | **Seagoing** | **Manoeuvring** | **Port** |
|---|---|---|---|
| EGC operating mode | Open loop | Closed loop | Closed loop |
| Total scrubbing water supply ($m^3/h$) | 540 | 405 | 160 |
| Cooling water supply for closed loop operation ($m^3/h$) | - | 265 | 225 |
| Sea water intake ($m^3/h$) | 540 | 300 | 260 |

**Table 6.** Operating modes.

| **Ship operating mode** | **Seagoing** | **Manoeuvring** | **Port** |
|---|---|---|---|
| EGC operating mode | Open loop | Closed loop | Closed loop |
| ME1 load (% MCR) | 86 | 75 | 0 |
| AE1 load (% MCR) | 91 | 80 | 80 |

| **Ship operating mode** | **Seagoing** | **Manoeuvring** | **Port** |
|---|---|---|---|
| EGC operating mode | Open loop | Closed loop | Closed loop |
| AE2 load (% MCR) | 91 | 80 | 80 |
| AE3 load (% MCR) | 91 | 80 | 0 |
| OFB1 load (% MCR) | 0 | 0 | 100 |

Closed loop operation of the system requires the use of sodium hydroxide to control the pH levels of the washing mixture. The consumption of sodium hydroxide in the closed loop operation is directly proportional to the operating power of the vessel and sulphur content of the fuel. The recommended solution was sodium hydroxide 50% solution, in which the chemical is mixed with equal amount of water. The consumption of the chemical was obtained from Wärtsilä’s technical documentation.

The closed loop operation of the system, specifically the use of the bleed-off treatment unit also requires the use of coagulation and flocculation chemicals. Flocculation chemicals are used to clump small particles in the effluent together so that they are easier to remove. Coagulation chemicals are used to remove the particles and impurities such as heavy metals, oil, suspended solids and turbidity from the effluent (Abujazar et al. 2022). The estimated consumption of coagulation and flocculation chemicals during the systems operational phase on the different scenarios was based on consumption averages obtained from Wärtsilä’s technical documentation. In the OpenLCA model, the use of flocculant was modelled as aluminium sulfate input and use of coagulant as polyaluminium chloride input. Both flows were obtained from the Ecoinvent database version 3.8.

The combustion process in the ships engines creates non-water-soluble content that is typically referred to as sludge. In closed loop operation, the sludge in the effluent is separated in the bleed-off treatment unit and collected in a sludge tank. The collected sludge cannot be incinerated on-board but must be brought to port where it is removed from the tank and transported to a treating facility for disposal. The estimated sludge generation for the closed loop operation was 35 litres/ton fuel and the sludge was assumed to be treated in a dewatering unit. The dewatering unit removes the water of the mix and therefore reduces the final amount of generated sludge. The final amount of sludge was assumed to be 0,6 times the mass of the generated sludge in the closed loop operation. In OpenLCA, the sludge generation was modelled with a market process for fly ash and scrubber sludge, which includes the transportation of the sludge to the treatment facility and the treatment process. The process was obtained from the Ecoinvent database.

In open loop operation, the amount of discharging water is the same as sea water intake for the scrubbing process. In closed loop operation, only a small bleed-off is discharged, after it has been cleaned in the bleed-off treatment unit. The capacity of the bleed-off treatment unit in the system was 5 $m^3$ per hour, which was assumed to be fully utilized during the manoeuvring closed loop operation hours. In port closed loop operation, the used capacity was assumed to be 4 $m^3$ per hour. The amount of discharged effluent on closed loop operations were calculated by multiplying the running hours with the given used capacity of the bleed-off treatment unit.

The open loop wash water and closed loop effluent are constantly measured for PAH, turbidity and pH-level to ensure compliant running of the scrubber. However, the discharged water also contains other substances, such as nitrates, arsenic, chromium, nickel, mercury, and zinc (Teuchies et al. 2020, p. 3). In modelling the discharge water, only PAHs and nitrates were used as emission categories. This was due to lack of data on the discharging water quality and the difficulty of calculating reliable averages for the specific system configuration. The PAH and nitrate concentrations of the discharge water were obtained from Wärtsilä’s technical documentation and data logs provided by the operator.

### 4.2.4 End-of-Life

Wärtsilä does not have documentation on recommended procedures for the end-of-life activities of the scrubber system. The lifetime of the scrubber system was estimated to be 20 years, which is close to the average operational lifetime of tankers, as described in chapter 3.2.1. Therefore, the scrubber system is likely to be scrapped and disposed or recycled along with the tanker. Ships are scrapped mostly in Bangladesh, Pakistan, India, China and Turkey and the industry can recycle up to 90-95% of the scrapped materials (Barua et al. 2018, p. 30880).

The operator of the studied system was not able to provide plans for the end-of-life activities for the system. The studied system consists of materials that are for the most part recyclable, such as stainless steel and copper. However, the Ecoinvent database only contained material recovery processes suitable for the electronic equipment and iron in the system. Therefore, the end-of-life activities for the rest of the materials were modelled in OpenLCA with Ecoinvent waste incineration and landfill processes that included transportation to the facilities. The used processes for each material are described in table 7.

**Table 7.** End-of-life activity processes for each material.

| Material | End-of-life process |
|---|---|
| Scrap aluminium | Waste incineration |
| Scrap copper | Waste incineration |
| Scrap steel | Inert material landfill / waste incineration |
| Scrap tin sheet | Waste incineration |
| Waste iron | Recycling via sorting facility |
| Waste plastic | Waste incineration |
| Waste polyvinylchloride product | Unsanitary landfill / waste incineration |
| Waste rubber | Waste incineration |
| Waste electric and electronical equipment | Recycling via shredder facility |

### 4.2.5 Inventory data uncertainties

The life cycle inventory contains assumptions in the inputs in each phase of the life cycle. In the first life cycle phase, the raw material extraction and manufacturing of the components was modelled with processes from Ecoinvent using the data on material composition of the components. The geographical location of the extraction and manufacturing was set based on the location of the supplier. The used processes contained average transportation methods and distances, which might deviate from the actual transportation operations in the supply chains first phase. There was no primary data on the raw material extraction or component manufacturing phases apart from the materials and supplier locations, which increases the uncertainty of the reliability of the cradle-to-gate part of the life cycle.

The transportation to shipyard phase was modelled using primary data from Wärtsilä's internal databases which contained accurate data on the delivery of the components from supplier to shipyard. Transportation of the six components in the scope that were delivered by the shipyard were modelled using assumptions on both transportation distances and methods which might deviate from the actual logistical processes. The capacities and emission standard of the lorry transport processes were assumed based on the weights and dimensions of the delivered components. Data for padding or other protective material for the deliveries was not available, and therefore rigid polyurethane foam was assumed to be used in each delivery.

The operational phase was modelled using operational information provided by the case customer and Wärtsilä's technical documentation. The customer provided the systems running hours since installation and open loop and closed usage ratio, which were used to calculate average running hours for the whole operational phase. The vessel was assumed to run on heavy fuel with a 3,5% sulphur content throughout the phase, since no data on actual used fuel types was available. The fuel consumption due to scrubber use was calculated using an assumption for the vessel's fuel consumption in 2022, which was obtained from Wärtsilä's internal database. The fuel type and consumption assumptions inputs have major uncertainties, and therefore the created model might deviate significantly from the actual operation of the vessel and scrubber.

The usage ratio of different operating modes in the operational phase was based on the assumption that the operating company aims to minimize time spent in ports. No data was available on the actual operation on different modes, which creates uncertainty to the model. The scrubber's water consumption in different modes depends on many factors such as the engine loads, fuel type, and whether the exhaust gas is to be scrubbed to a level equivalent to 0,1% or 0,5% m/m sulphur content. The model was created using constant values for water consumption on different modes, which were obtained from Wärtsilä's documentation. These values were based on certain constant engine loads and fuel type. In actual operation the factors determining the consumption change constantly, which makes it difficult to accurately model the entire operational phase. The consumption of sodium hydroxide, coagulant and flocculant chemicals also depends on operating power and required cleaning efficiency and hence assumptions on the operational use of the system affect the calculation of these values.

The discharge water and its contents were based on the data logs sent by the customer and Wärtsilä's documentation of the system. The amount of discharge water is directly proportional to the scrubbing water use and therefore uncertainties in water consumption data affect also affect the accuracy of the discharge water data. The PAH and nitrate concentration of the discharged water in different use modes were modelled as averages calculated from the data or other estimates based on the compliant operation of the system. The discharge water quality is also dependent on many factors including those described on page 44. The most significant factor in the uncertainty of the discharge water modelling was the lack of data on heavy metals and other contaminants.

The end-of-life phase was modelled as waste treatment and recycling activities using the material inputs from the manufacturing phase as basis for inputs for the treatment activities. Therefore, any uncertainties in the first phase inputs affect the quality of results in the last phase. Regarding the end-of-life activities, the system has potential to be recycled in most parts, which deviates from the approach and model built in this study.

# 5 Impact assessment and interpretation of results

This chapter demonstrates the impact assessment of the LCA, scenario analysis for the different operational use scenarios, and the KPI development based on the results. Unless otherwise stated, the results are presented as per functional unit, which was determined as 1 kg mass of exhaust gas entering the scrubbing process. The LCIA is demonstrated and interpreted in chapter 5.1, and scenario analysis in chapter 5.2. Chapter 5.3 contains discussion on completing the objective of initiating the process of developing KPIs to improve Wärtsilä's environmental performance during the first two phases of the system's life cycle.

## 5.1 Environmental impacts of life cycle phases

The LCIA was calculated using the ILCD 2011 midpoint+ method in the OpenLCA software. Table 8 demonstrates the environmental impacts per functional unit based on the impact categories. The table also contains the percentage contributions of each life cycle phase to each environmental impact. The column for the operational phase in the table includes separate percentages for open and closed loop operations and their contribution to the impacts.

As was described in chapter 4.2.3, the ME scrubber was estimated to be operated for 142 560 hours, AE scrubber for 87 840 hours and the OFB scrubber for 4392 hours during the operational phase. The exhaust gas mass flows at MCR load were 60480 kg per hour for the ME, 9360 kg per hour for the AEs, and 1800 kg per hour for the OFB. The hourly mass flows were used to estimate the total exhaust gas mass flow for the whole operational phase using the running hours provided by the customer.

Since in real operation the engines are not operated on MCR loads constantly, the flow values were multiplied with estimated factors to generate more realistic exhaust gas mass flows for the operational phase. For seagoing mode operation hours, the exhaust gas mass flow for the ME was multiplied with by a factor of 0,86 and for the AEs by a factor of 0,91. For manoeuvring operation hours, the exhaust gas flows for the ME and AEs were multiplied by 0,8. For port operation hours, the exhaust gas mass flows for the two AEs in use were multiplied with 0,8. The exhaust gas mass flow for the OFB was assumed to be 100% in port operation.

Based on the calculations, the total exhaust gas mass flow for the operational phase in the baseline scenario was 9,39E+09 kilograms. This equals to an average of 53,59E+03 kilograms of exhaust gas mass flow every operating hour or approximately 14,89 kilograms every operating second. The generated results in the LCIA are based on the exhaust gas flows and represent the total potential environmental impacts per 1 kg of exhaust gas flow entering the scrubber system. Thus, the total potential environmental impacts of the studied system would be calculated by multiplying the generated results in each impact category by the total exhaust gas mass flow for the operational phase.

The V-SOx scrubber system removes particulate matter and sulphur oxides from the exhaust gas. The treated exhaust gas is continuously monitored with a CEMS to ensure compliance with the IMO Annex VI sulphur regulations. The scrubber system is designed to be able to reduce over 97% of the SOx content in the exhaust gas. As described in chapter 4.2.3, the scenarios were built assuming a SOx reduction from 3,5% SOx content HFO to a level equivalent to using 0,1% sulphur content fuel.

The results of the impact assessment are from the use profile that was created based on the running hours provided by the customer. Based on the provided data, in the baseline scenario the system is assumed to run on different open loop modes for 99% of the time and on closed loop port mode for 1%. The scenario analysis in chapter 5.2 contains results with increased closed loop operation.

It should be noted that the LCIA only addresses the data that was entered into the life cycle inventory based on the scope of the study (ISO, 2006). Therefore, the results do not represent the total environmental impacts of the V-SOx system throughout its lifetime. Complementing the scope of the LCA and LCI data are discussed more in chapter 6.

**Table 8.** Impact assessment results per functional unit.

| **Impact category** | **Total / FU** | **Unit** | **Raw mat. & manufacturing** | **Transportation** | **Operation** | **EoL** |
|---|---|---|---|---|---|---|
| Freshwater ecotoxicity | 0,0085 | CTUe | 70,62 % | 0,04 % | OL 5,07 %<br>CL 1,47 % | 22,80 % |
| Land use | 0,0021 | kg C deficit | 1,88 % | 0,23 % | OL 96,65 %<br>CL 1,22 % | 0,03 % |
| Climate change | 0,00014 | kg $CO_2$ eq | 30,08 % | 1,32 % | OL 63,19 %<br>CL 5,38 % | 0,03 % |
| Water resource depletion | 7,88E-05 | $m^3$ water eq | 61,15 % | 0,11 % | OL 28,70 %<br>CL 10,03 % | 0,01 % |
| Ionizing radiation HH | 5,72E-05 | kBg U235 eq | 8,56 % | 0,21 % | OL 88,74 %<br>CL 2,49 % | 0,01 % |
| Marine eutrophication | 5,01E-05 | kg N eq | 0,11 % | 0,01 % | OL 99,64 %<br>CL 0,24 % | 0 % |
| Terrestrial eutrophication | 2,53E-06 | molc N eq | 23,39 % | 1,43 % | OL 71,35 %<br>CL 3,84 % | 0,03 % |
| Acidification | 1,53E-06 | molc H+ eq | 18,83 % | 0,62 % | OL 77,21 %<br>CL 3,33 % | 0,02 % |
| Photochemical ozone formation | 9,38E-07 | kg NMVOC eq | 17,64 % | 1,01 % | OL 78,31 %<br>CL 3,02 % | 0,03 % |
| Particulate matter | 1,25E-07 | kg PM2.5 eq | 36 % | 0,34 % | OL 58,09 %<br>CL 5,53 % | 0,03 % |
| Freshwater eutrophication | 5,89E-08 | kg P eq | 79,69 % | 0,07 % | OL 14,64 %<br>CL 5,59 % | 0,01 % |
| Mineral, fossil, ren. Resource depletion | 2,06E-08 | kg Sb eq | 80,56 % | 0,06 % | OL 18,14 %<br>CL 1,24 % | 0 % |
| Ionizing radiation E (interim) | 3,77E-10 | CTUe | 4,63 % | 0,21 % | OL 93,38 %<br>CL 1,77 % | 0 % |
| Ozone depletion | 1,60E-10 | kg CFC-11 eq | 2,47 % | 0,21% | OL 93,82 %<br>CL 3,50 % | 0 % |
| Human toxicity, non-cancer effects | 8,14E-11 | CTUh | 83,41 % | 0,29 % | OL 13,24 %<br>CL 2,99 % | 0,07 % |
| Human toxicity, cancer effects | 2,48E-11 | CTUh | 73,38 % | 0,12 % | OL 23,5 %<br>CL 2,98 % | 0,02 % |

As shown in table 8, the operational phase produces the most potential environmental impacts in ten different impact categories. In these categories, specifically the open loop operation is the most dominant cause for potential environmental impacts. This phenomenon is unsurprising due to the length of the phase and the overwhelming number open loop running hours compared to closed loop running hours.

The potential environmental impacts for the remaining six impact categories are dominated by the raw material extraction & manufacturing of components phase of the life cycle. The end-of-life phase has significant contribution in the freshwater ecotoxicity impact category but does not significantly affect other potential impacts in other categories relative to other phases. Transportation to shipyard phase has no significant contribution in any of the categories relative to other phases but it is taken into further consideration in chapter 5.3 as it is a process that is under Wärtsilä’s control. Figure 12 illustrates the results as contribution percentages for each phase of the life cycle.

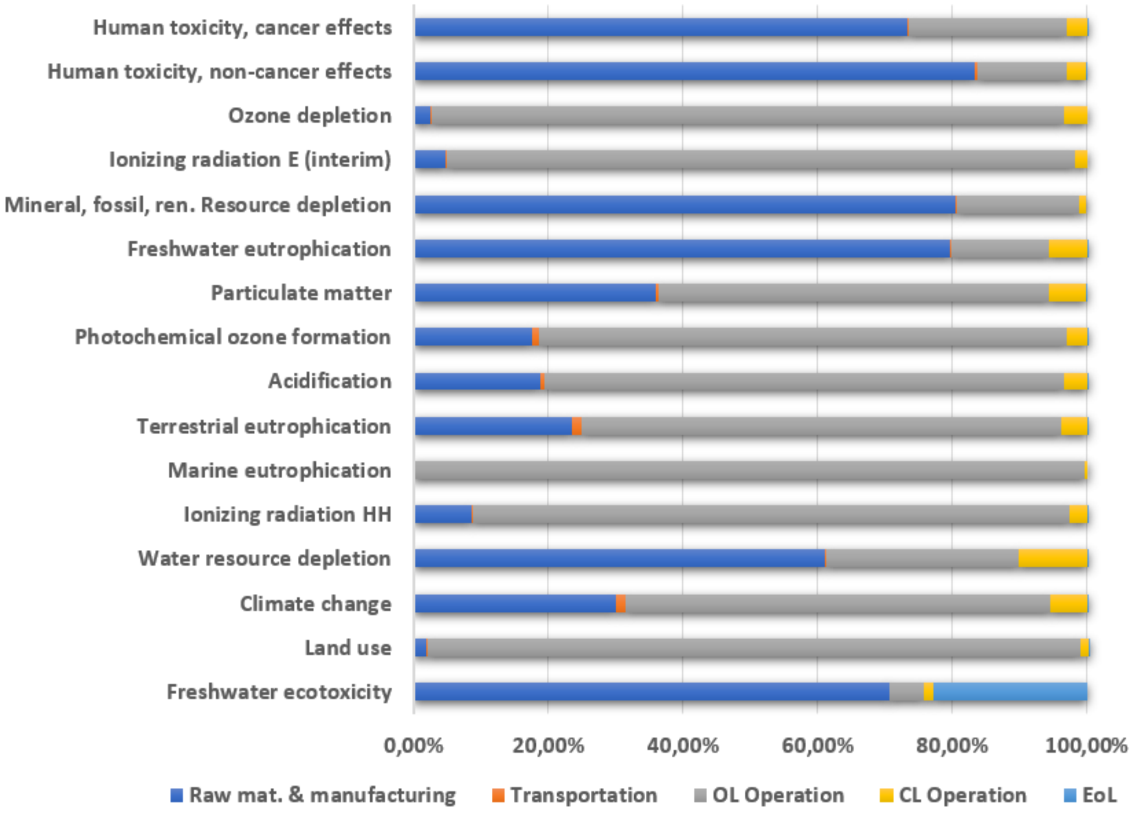

**Figure 12.** LCIA results as contribution percentages per phase.

Out of the 16 impact categories assessed in this study, climate change is one that is represented in all LCIA methodologies (Hauschild et al. 2013, p. 42). The category is assessed via $GWP_{100}$, which is expressed as kilogram of $CO_2$ equivalent per functional unit. $GWP_{100}$ presents the accumulated radiative forcing of greenhouse gases relative to the same value of $CO_2$ emissions over a 100-year period (Hauschild et al. 2013, p. 42).

In the LCIA results of this study, the climate change impact category results were 0,00014 kg $CO_2$ eq/FU. The majority (63,19%) of these potential impacts were accumulated by open loop operation. The potential impacts from this phase were produced in totality by the market process for heavy fuel oil production, which also contains transportation averages. Running the scrubber system increases the fuel consumption of the vessel through increased energy consumption, as described in chapter 4.2.3. Therefore, it is included in the model although the system itself does not have a combustion process. The open loop operation generated 0,088 grams of $CO_2$ eq/FU throughout the life cycle of the system.

The other life cycle phase that had significant contribution to the climate change impact category was raw material extraction & manufacturing of components. The contribution of this phase was 30,08%, which is equivalent to 0,042 grams of $CO_2$ eq/FU. A total of 70,7% of the potential climate change impacts generated during this life cycle phase were accumulated by market processes for electronic component production. Other significant contributors in this phase were average metal product and steel product manufacturing processes and market processes containing transportation for different grades of steel, attributing for 26% of the potential impacts.

Figure 13 shows the top contributors to the impact categories in the raw material extraction & manufacturing life cycle phase. The bleed-off treatment unit, alkali feed module, CEMS, and pH monitoring unit were assumed to be replaced once during the lifecycle of the system and therefore their processes in the model were duplicated. These components include most of the electronic components in the scope and are also the biggest contributors in most of the impact categories. As in the climate change impact category, also in almost all other impact categories, the most significant contributions to the impact categories were accumulated by the market processes for electronic component production.

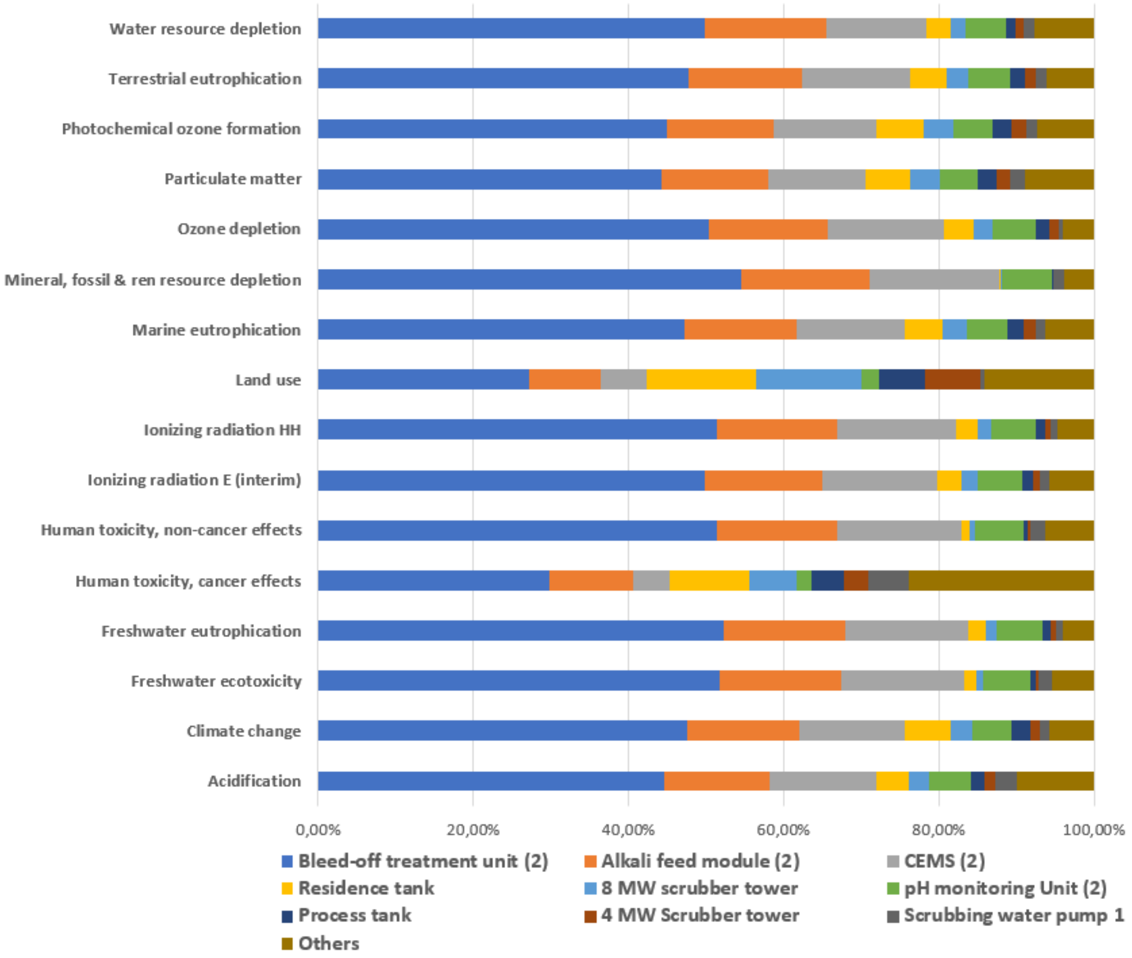

**Figure 13.** Top impact contributors in the raw mat. extraction & component manufacturing phase.

Considering the purpose and operating principle of the scrubber system, marine eutrophication is an essential impact category to be considered. The impact category measures potential impacts with a unit of kg nitrogen equivalent. Nitrogen is considered a growth-limiting nutrient that contributes to planktonic growth and eventually to oxygen depletion and hypoxia-related damage especially in coastal waters (Cosme et al. 2017, p. 676).

Open loop operation contributed for 99,64% of the total impacts in marine eutrophication category. This is expected due to the ratio of open loop and closed loop usage, and their different operating principles. In open loop operation, the amounts of scrubbing water and discharge water are the same, which results in increased concentration of contaminants discharged into the sea. The discharge water was modelled to contain PAH compounds and nitrates. PAH compounds contribute to marine ecotoxicity and cause for example immunotoxicity, embryonic abnormalities, and cardiotoxicity in marine wildlife (Honda & Suzuki, 2020, p. 2). In terms of marine eutrophication, the more significant contaminants are nitrates, which contributed for over 99% of the open loop impacts. Nitrate is nitrogen in an oxidized form ($NO_3^-$) and accounts for most of the fixed nitrogen in the oceans (Zakem et al. 2018, p. 2). The total potential impacts in marine eutrophication impact category for open loop operation were 0,049 grams of N eq/FU. The scenario analysis in chapter 5.2 analyses marine eutrophication in scenarios with increased closed loop usage.

## 5.2 Scenario analysis

The scenario analysis contains two additional use scenarios for the V-SOx scrubber system. In the first additional scenario, the system was assumed to operate in closed loop manoeuvring mode for 10% of the running hours and in closed loop port mode for 5% of the running hours. In the second additional scenario, the closed loop manoeuvring mode accounted for 30% of the running hours and closed loop port mode for 5%. Rest of the running hours were assumed to be operated on open loop seagoing mode in both scenarios. The scenario analysis was conducted to gain results on closed loop operation and its potential for environmental impacts. The results in the scenario analysis were calculated per functional unit.

The contribution of each life cycle phase to the impact assessment results of the first additional scenario are presented in a percentage contribution form in figure 14. Although closed loop use is relatively low compared to open loop use in this scenario, it significantly contributes to the potential environmental impacts. Most of the potential impacts in the impact category results are dominated by closed loop use, except for a few categories, for example, marine eutrophication and land use.

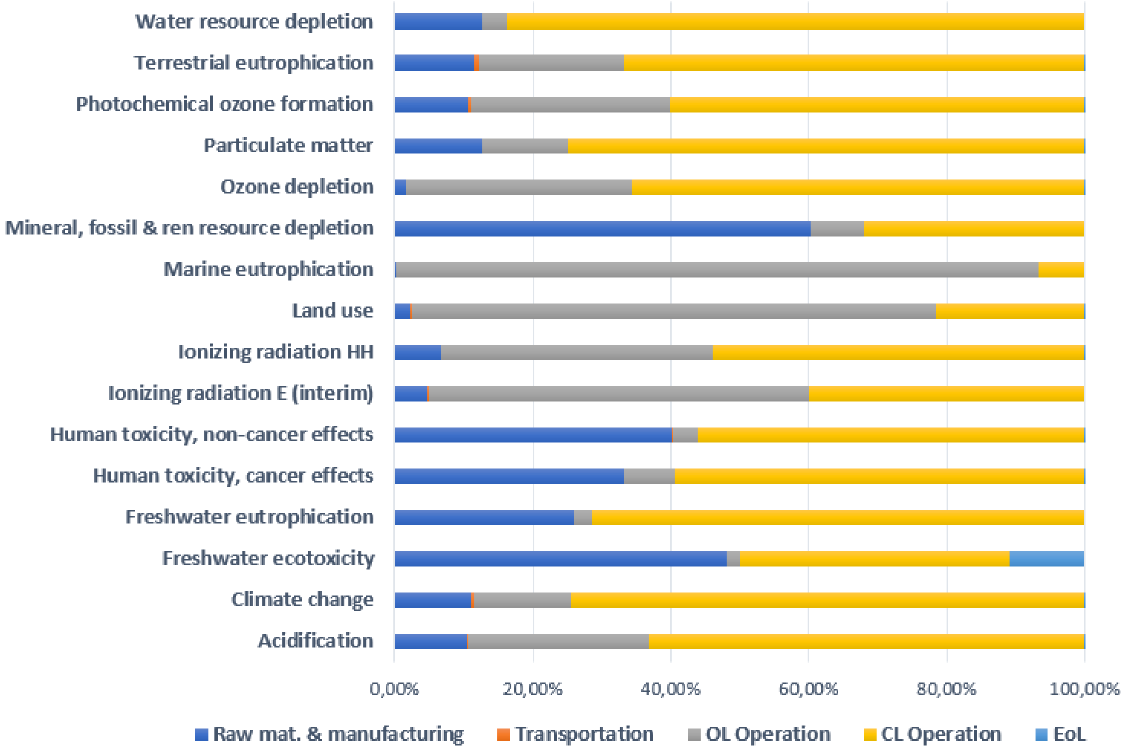

**Figure 14.** Additional scenario 1 LCIA results as contribution percentages per phase.

The most significant factor behind the potential environmental impacts of closed loop operation is the production of sodium hydroxide. In each impact category dominated by closed loop operation, sodium hydroxide production accounts for over 90% of the potential environmental impacts of the life cycle phase. Sodium hydroxide is produced by utilizing different variations of chlor-alkali electrolysis, in which an electrical charge is passed through a cathode and an anode inside a containment device containing brine solution (Lakshmanan & Murugesan, 2014). The solution contains sodium chloride, which is converted into chlorine and sodium hydroxide in the electrolysis process (Lakshmanan & Murugesan, 2014).

The chlor-alkali process is one of the biggest consumers of electricity in the industrial field and contributes significantly to harmful pollution both directly and indirectly (Hou et al. 2018, p. 2). Therefore, the obtained results appear to support the prevailing consensus in the scientific literature about the environmental impacts produced by the chlor-alkali industry. Additional scenario 2, in which the scrubber is assumed to be operated in manoeuvring closed loop mode for 30% of the running hours and in port closed loop mode for 5% of the running hours emphasizes this phenomenon even further. The contribution of each life cycle phase to the impact assessment results of the second additional scenario are presented in a percentage contribution form in figure 15.

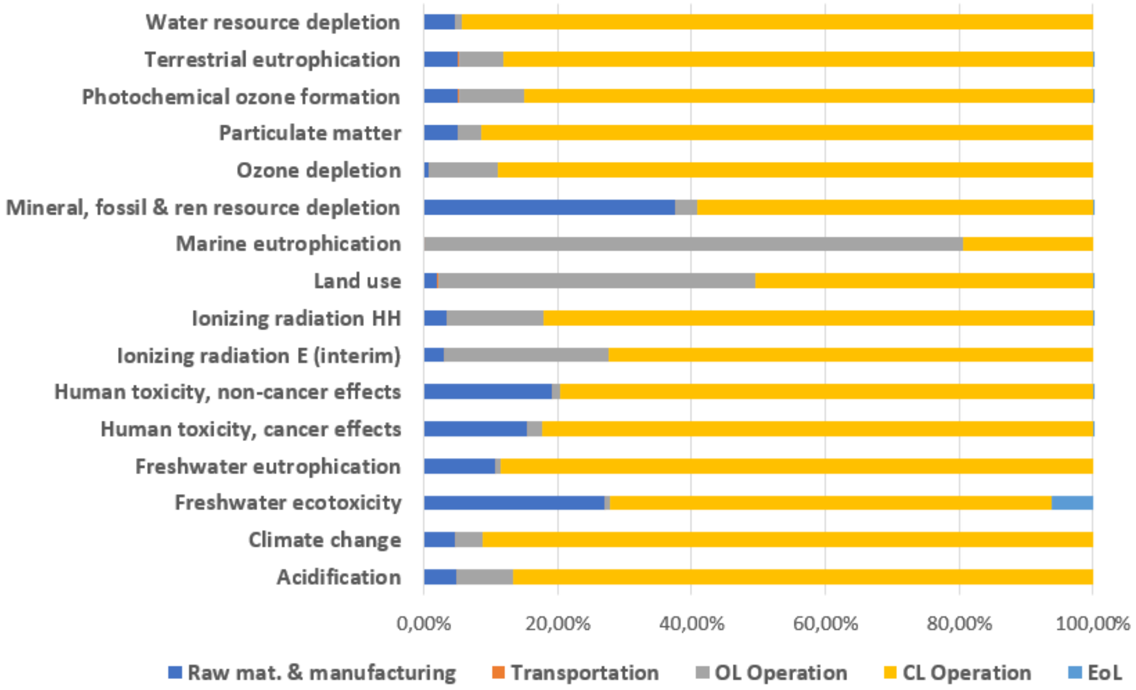

**Figure 15.** Additional scenario 2 LCIA results as contribution percentages per phase.

In additional scenario 2, 14 out of 16 impact categories are dominated by closed loop operation. As in additional scenario 1, also in the second additional scenario the production of sodium hydroxide is the most dominant process in terms of potential environmental impacts. One impact category that does not seem to change significantly in either scenario is marine eutrophication, which is dominated by open loop operation.

In additional scenario 1, open loop operation contributes to 93,04% of marine eutrophication potential impacts. In additional scenario 2, open loop operation contributes to

80,48% of the same impacts. The remaining percentages of the contribution in both scenarios were accumulated mostly by closed loop operation. Marine eutrophication results for the additional scenarios and the baseline scenario, which was covered in chapter 5.1, are presented in figure 16.

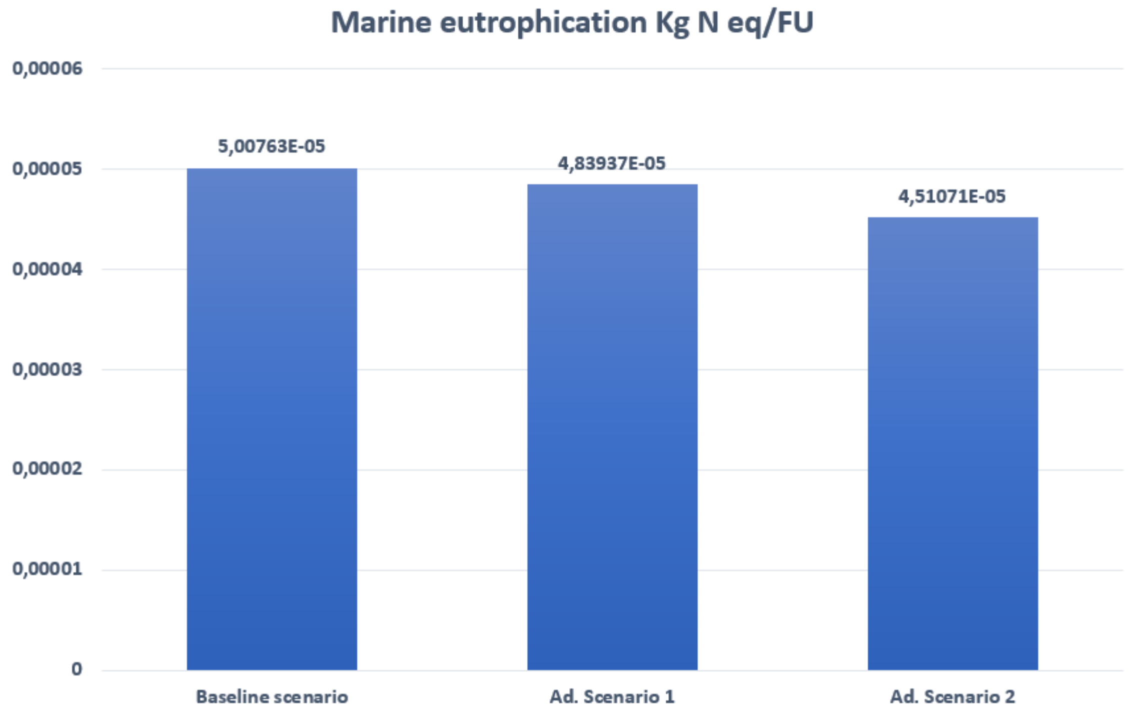

**Figure 16.** Marine eutrophication impact category results for each scenario.

When comparing the marine eutrophication results from the additional scenarios to the baseline scenario, the percentage decrease is 3,4% in the first additional scenario and 10% in the second. Although the discharge water volumes in open loop operation are higher, the discharge water pollutant limitations for closed loop operation are not as strict and therefore the pollutant concentrations are often higher (Osipova et al. 2021, p. 1). The discharge related limitations were considered when modelling the closed loop operation and therefore the nitrate concentration of the discharged effluent was modelled to be significantly higher than in open loop operation.

When observing the climate change impact category, the results differ significantly in different scenarios. Comparing the additional scenarios to the baseline scenario, the potential impacts are 366% higher in the first additional scenario and 889% higher in the second additional scenario. The overwhelming majority of the increased climate change impacts come from the production of sodium hydroxide. Most of the impacts from this process are related to electricity production. The climate change impact category results for each scenario are shown in figure 17.

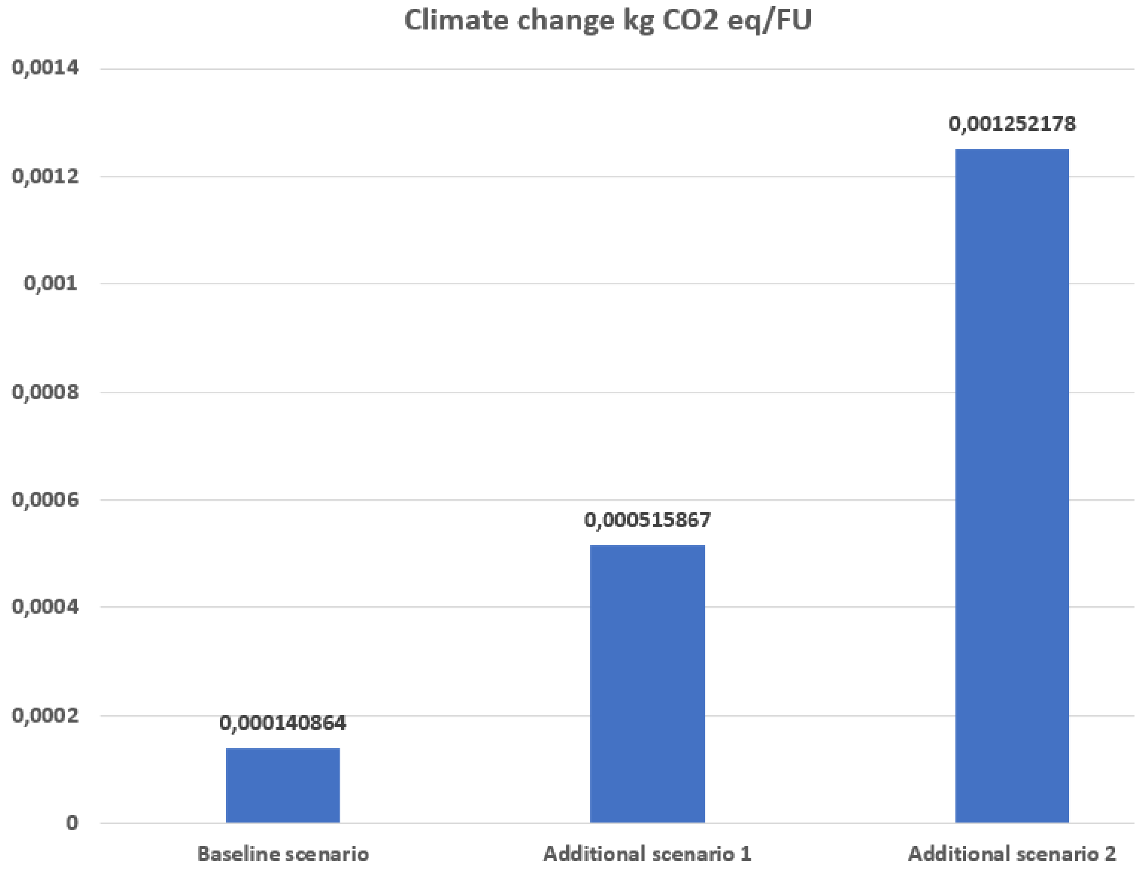

**Figure 17.** Climate change impact category results for each scenario.

As described in chapter 4.2.3, closed loop operation of the system and specifically the bleed-off treatment unit requires the use of flocculation and coagulation chemicals. The market processes for both chemicals did not significantly affect the results in any scenario and their share was less than 5% of the impacts in every impact category.

Sludge generation and its treatment was also considered when modelling the closed loop operation. The process included transportation of the sludge and hazardous waste incineration. The process did not significantly affect the results and accounted for less than 1% of the potential impacts in each category.

## 5.3 KPI development

One objective of the research was to initiate the process of developing KPIs to monitor Wärtsilä's environmental performance during the scrubber delivery projects and possibly also in the later parts of the system's life cycle. Wärtsilä actively promotes environmental actions in collaboration with its stakeholders and is committed to being carbon neutral in its own operations by 2030 (Wärtsilä, n.d. -l). Initiating the development of environmental KPIs aims to support the fulfilment of these objectives.

As described in chapters 5.1 and 5.2, most of the potential environmental impacts during the scrubber system's life cycle occur in the operational phase. Wärtsilä does not have control over the operational phase, apart from possible maintenance and recommendations related to system operation. Therefore, the development of performance indicators is perhaps not suitable for this phase of the system's life cycle. Actions can however be taken to try to reduce the impacts from the operational phase. As was established in the scenario analysis in chapter 5.2, closed loop operation has significant indirect potential for various environmental impacts through the production of sodium hydroxide. However, sodium hydroxide is not the only alkali solution that can be used in a closed loop scrubber system.

Wärtsilä has developed an alkali upgrade program for customers who want to convert their closed loop scrubber systems to be able to operate on magnesium hydroxide instead of sodium hydroxide (Wärtsilä, n.d. -m). The closed loop conversion requires some hardware and software updates, but it has many safety benefits and could potentially be a more sustainable solution compared to operating the system with sodium hydroxide. Sodium hydroxide is a hazardous material and can cause serious issues on human health if inhaled or in contact with the skin (Ahmadi & Seyedin, 2019, p. 10812). Magnesium hydroxide is a much safer alkali to handle, and it is generally also cheaper than sodium hydroxide (Zhu et al. 2016, p. 129). It has also been proven to have efficient SOx removing capabilities and can therefore be utilized in achieving compliance with the IMO regulations (Zhu et al. 2016, p. 124).

The availability of sodium hydroxide is generally better, but in case the environmental footprint of the magnesium hydroxide industry is found to be smaller, Wärtsilä could assess the opportunity of promoting the alkali upgrade program as a more sustainable option. The program could then be used to build an environmental metric to measure averted indirect environmental impacts of the closed loop scrubber systems operation.

The second most significant life cycle phase in terms of environmental impacts was the raw material extraction and manufacturing phase. The components in the scrubber systems are mostly obtained from suppliers and therefore the measurement of the environmental footprint produced by manufacturing is difficult. However, Wärtsilä could take a proactive step to initiate a program in which suppliers are asked about their environmental performance during manufacturing and supply chain operations. This could be embedded in a wider supplier monitoring or mentoring strategy, which are becoming more common among companies and supply chains (Meqdadi et al. 2020).  As sustainability and environmental issues are being discussed and probably regulated more in the future, Wärtsilä can also be expected to have to provide information about its environmental performance to its customers.

Wärtsilä has set environmental requirements for suppliers in forms of certain environmental and quality certificates, which provide useful information and set the standard for supplier quality. These requirements could be complemented with further detailed questions about environmental performance, for example the $CO_2$ emissions that the manufacturing of the component produced. As enough data on the environmental performance of different suppliers would be gathered, it could be used to build a KPI on indirect $CO_2$ emissions related to supplier choice. Environmental performance could also be used as a more weighted criteria when choosing suppliers in the future, as the transparency related to environmental performance between companies increases.

Compared to other phases of the scrubber system's life cycle, transportation from suppliers to shipyard did not have significant contribution on the potential environmental impacts. However, as it is a phase that is controlled by Wärtsilä, it should be observed in case the environmental performance of the actions in the phase can be improved. The components in the scope were transported to the shipyard in three air deliveries, four ship deliveries, and 18 road deliveries. Figure 18 demonstrates the contribution percentages of each transportation method on selected impact categories.

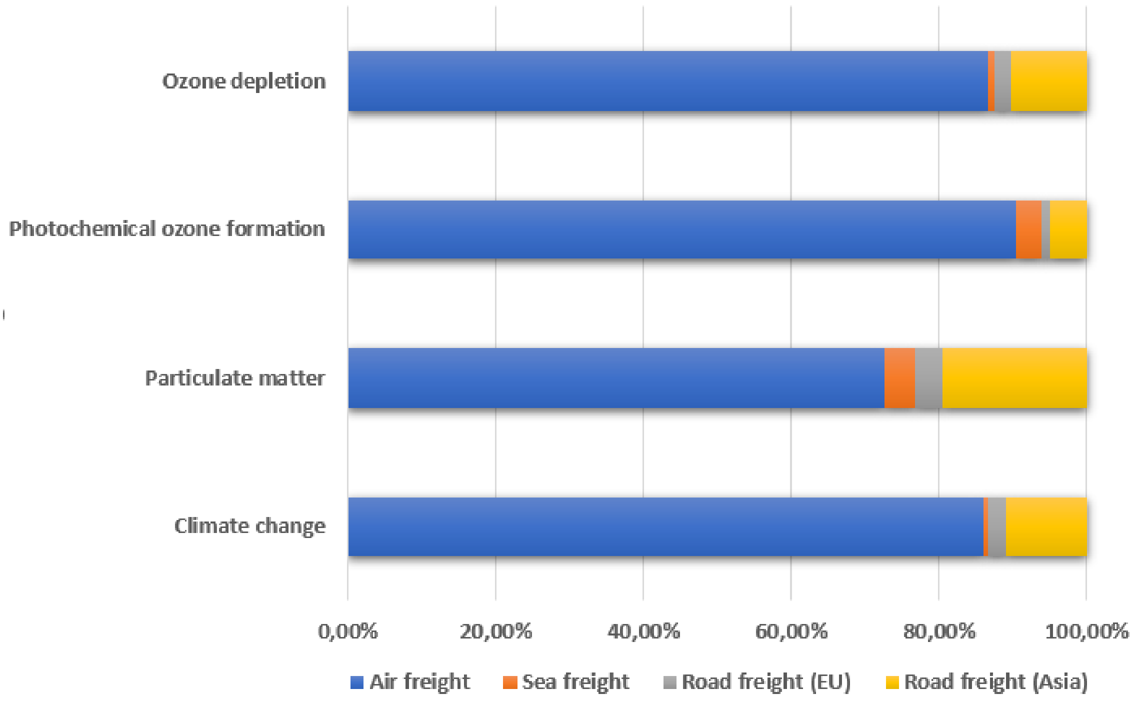

**Figure 18.** Contribution percentages of different transportation methods to selected impact categories.

As shown in figure 18, air freight dominates the contribution to the selected impact categories. Air freight was also the biggest contributor in most of the other impact categories. A total of 6,43% of the combined mass of all the components in the scope were delivered via air freight, but it contributed, for example, to over 80% of the potential climate change impacts of the life cycle phase. The flight distances were long as the components were flown from different parts of Europe to South Korea, but the overwhelming potential for environmental impacts highlights the need for mitigating air freight.

In addition to being a burden on the environment, air freight is also expensive. Wärtsilä has implemented actions and policies to reduce flying whether it is related to the delivery of components or work-related travel. However, air freight cannot be completely removed as it is often the only choice to deliver components on time. Air freight is mostly used in non-conformity related situations, in which a component has been damaged or forgotten from the delivery scope. These situations often require fast re-delivery, and air freight is often the only viable option.

Wärtsilä already monitors the use of air freight in delivery and non-conformity related situations. However, a KPI measuring the GHG emissions due to these flights could be built and used to improve delivery processes and to assess supplier quality. Also, the geographical location of the suppliers is something to consider in relation to the concentration of quality non-conformities and the geographical concentration of the scrubber business. The KPI could also be extended to field service operations, in which flying to the site is typical. The indicator could be measuring GHG emissions of these operations or, conversely, averted environmental impacts in case multiple maintenance visits can be made on different vessels. Like in the delivery phase, field service operations could perhaps be improved in terms of environmental performance by reviewing the GHG emissions in relation to the geographical locations from which the service engineers were dispatched.

The end-of-life phase of the scrubber system was modelled as mostly waste incineration and landfill processes in this study. In this regard, the built model simulated the worst-case scenario, in which recycling was not considered apart from the waste iron recycling process. However, as described in chapter 4.2.4, the ship scrapping industry is highly competent in terms of recycling and therefore Wärtsilä could use this information on KPI development in the research and development of the scrubber systems.

One way of measuring environmental performance related to the EoL phase would be a design-for-recyclability indicator. The indicator could be built to measure the share of recyclable material in the total mass of the system. Indicators could also be built to measure the share of hazardous materials and non-recyclable materials to get a comprehensive overview of potential EoL impacts. The information provided by these indicators could also be used to create recommendations for EoL activities and to promote recycling and other sustainable disposal of Wärtsilä’s scrubber systems.

### 5.3.1 Managerial implications

Wärtsilä Exhaust Treatment has been certified against ISO 14001, ISO 9001 and ISO 45001 standards that assess environmental, quality, and health and safety performance. The company is audited at regular intervals to ensure the continuity of compliant and efficient performance in all the categories. The prevailing view on the audits, especially on the environmental side, is that the standards are moving to a stricter direction and the audits are each time focusing on broader aspects of environmental performance. Therefore, a proactive approach on improving environmental performance is likely to be beneficial even if the current regulatory framework does not yet impose it.

Based on the results of this study, Wärtsilä has initiated conversations on how the identified potential for KPI development can be embedded in the current and future sustainability efforts and programs. Also, discussions have been initiated on whether the results can be used to improve the environmental performance of sourcing processes, field service operations, and research and development. A large part of the identified potential environmental impacts of the scrubber systems life cycle were produced indirectly or in phases that are not under Wärtsilä’s control. However, Wärtsilä can potentially improve the environmental performance of these phases by providing information and recommendations based on the results of this study and further research on the matter.

The results of the study can be used as supportive material when evaluating the guiding principles in Wärtsilä’s processes. Wärtsilä is actively working to decarbonize its operations and studies like this are a way of raising environmental awareness in the company and identifying potential actions for achieving this goal faster. The areas of improvement that are identified in the audits related to environmental certification can also be potentially improved utilizing the results of this study.

# 6 Conclusions

The results of the life cycle assessment showed that in all three scenarios, most of the potential environmental impacts occur during the operational phase. The scrubber system was modelled to be in operation for 20 years, during which a lot of fuel, alkali and other water treatment chemicals are consumed, and wash water and effluent is discharged. The duration of the phase and the magnitude of inputs and outputs in the model give justification to the obtained results.

The scenario analysis provided insightful findings about closed loop operation and its potential environmental impacts. Although contributing less to marine eutrophication impact category, closed loop operation was found to produce a significant number of indirect impacts on many other impact categories. This phenomenon was caused mainly by the processes related to the production of sodium hydroxide. However, it should be noted that the discharged wash water and effluent during the operational phase were modelled using only PAHs and nitrates as inputs, which may distort the differences of the environmental impacts caused by the different operating modes.

Although the operational phase was found to be the biggest contributor to potential impacts, other phases were also observed, as Wärtsilä may have more opportunities to mitigate impacts during them. The raw material extraction & manufacturing of components phase significantly contributed to the total potential impacts in the baseline scenario in relation to the other phases. Therefore, the possibilities of developing KPIs for the activities in this phase were actively explored in chapter 5.3.

The transportation to shipyard phase did not have a relatively significant contribution to the total potential impacts in any of the scenarios. However, the phase was also considered in the initiation of KPI development, as it is a process that is directly under Wärtsilä's control. The EoL phase of the life cycle was modelled using mostly waste incineration and landfill processes, which deviates from the more sustainable and likely scenario of recycling most of the scrapped materials. The EoL phase did not have a significant effect on the environmental impacts relative to the operational and raw material extraction & manufacturing phases. However, opportunities to develop KPIs related to the phase were identified.

## 6.1 Recommendations for reducing environmental impacts

The LCA conducted in this study provided insight into the source of environmental impacts occurring during the life cycle of a scrubber system. Regardless of the use scenario, the operational phase was the biggest contributor to most of the measured impact categories. Based on the results obtained in the scenario analysis, the marine eutrophication impacts decrease as the share of closed loop operation increases. However, the increase in the closed loop operation was also found to indirectly increase the magnitude of impacts, for example in the climate change impact category through the production of NaOH. This trade-off should be researched further with different operation mode usage ratios and other parameters to improve comprehensive understanding of environmental impacts between the modes.

To mitigate the environmental impacts in the operational phase, operators who regularly run the system in closed loop mode should pay attention to the environmental performance of their NaOH suppliers. Considering the energy intensity of the production process, favouring manufacturers that utilize renewable energy in their operations could be a significant improvement to the indirect environmental performance of the scrubber system’s life cycle. The environmental performance of the open loop operation can be mitigated by favouring fuels with a smaller sulphur and other pollutant content. In case the number of no-discharge zones and other wash water discharge restrictions increase, open loop scrubbers might become a less used SOx mitigation method. This could increase the popularity of closed loop scrubbing and hence put pressure on understanding its environmental impacts thoroughly.

To mitigate the environmental impacts in the raw material extraction & manufacturing of components phase, the focus should be on the production of steel and electronic components. As in the recommendations for operational phase, favouring manufacturers that produce these components utilizing renewable energy is also recommended. Also, future research should include more primary data on this phase to increase the reliability of the LCIA results.

After the system is commissioned, Wärtsilä has little control over the operational and disposal phases of the life cycle. However, an increasing number of companies might be subject to a mandatory disclosure of indirect emissions produced in their value chains in the future. These so-called ‘scope 3’ emissions are the most significant source of emissions in the majority of companies (Stridsland et al. 2023, p. 3). Therefore, in addition to the recommendations mentioned above, scrubber systems should be designed for maximum recyclability to ensure an environmentally friendly EoL phase to end the life cycle. The three different emission scopes are demonstrated in figure 19.

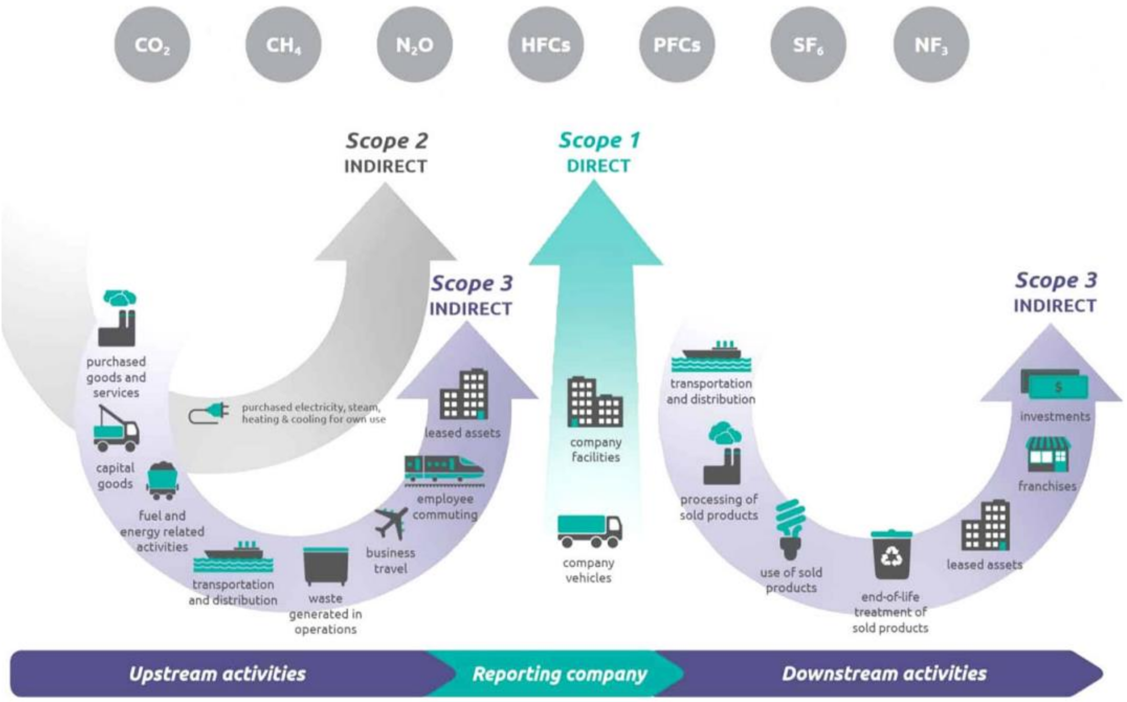

**Figure 19.** GHG Protocol scopes and emissions across the value chain (WRI/WBCSD, 2011, p. 5).

Wärtsilä is actively working to decarbonize its operations by 2030. To support Wärtsilä’s efforts to improve environmental performance, several areas where environmental KPIs could be developed were identified. As Wärtsilä orders most of the components from suppliers, most of the proposed indicators could have potential in creating an overview of mainly indirect $CO_2$ emissions related to supplier choices, logistics, and research and development. However, this type of information could be valuable regarding potential future environmental audits and regulations.

The results obtained in this study create opportunities to continue researching Wärtsilä's EGC system business. Future research could focus on complementing the scope and inputs of this study or conducting a new comparative LCA study for a different type of scrubber system, using this study as a benchmark. Also, further research on closed loop operation using magnesium hydroxide in the water treatment process could provide beneficial results to potentially improve the system's environmental performance.

## 6.2 Limitations

The LCI built in this study contained assumptions for each phase of the life cycle. The inventory data uncertainties are described in chapter 4.2.5. The mass-based cut-off was determined as 86,7% due to lack of accurate data on the total weight of the system. This study did not include maintenance of the system, besides a few components that were assumed to be replaced during the life cycle. This is a limitation, considering that the system requires regular maintenance, and the service engineers are often flown to the site.

The operational phase of the studied system was built using running hours provided by the customer and Wärtsiläs technical documentation of the system. However, the phase contains assumptions that might deviate significantly from the actual operation of the system. Also, the lack of data on discharged wash water and effluent contaminant concentration is a significant limitation, that should be addressed when interpreting the results.

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# Appendices

## **Appendix 1.** LCIA impact categories and their measurement units

| **Impact category** | **Unit** | **Definition** |
|---|---|---|
| Land use | kg C deficit | Kilogram of soil organic carbon deficit equivalent |
| Freshwater ecotoxicity | CTUe | Comparative toxic unit (environment) |
| Climate change | kg CO2 eq | Kilogram of carbon dioxide equivalent |
| Water resource depletion | $m^3$ water eq | Cubic metre of water equivalent |
| Ionizing radiation HH | kBq U235 eq | Kilo Becquerel (number of atom nuclei that decay per second) of U235 equivalent |
| Marine eutrophication | kg N eq | kg of nitrogen equivalent |
| Terrestrial eutrophication | molc N eq | moles of nitrogen equivalent |
| Acidification | molc H+ eq | moles of hydrogen equivalent |
| Photochemical ozone formation | kg NMVOC eq | Kilogram of non-methane volatile organic compounds equivalent |
| Particulate matter | kg PM2.5 eq | Kilogram of fine particulate matter equivalent |
| Freshwater eutrophication | kg P eq | Kilogram of phosphorus equivalent |
| Mineral, fossil & ren resource depletion | kg Sb eq | Kilogram of antimony equivalent |
| Ionizing radiation E (interim) | CTUe | Comparative toxic unit (environment) |
| Ozone depletion | kg CFC-11 eq | Kilogram of chlorofluorocarbon 11 equivalent |
| Human toxicity, non-cancer effects | CTUh | Comparative toxic unit (Human health) |
| Human toxicity, cancer effects | CTUh | Comparative toxic unit (Human health) |