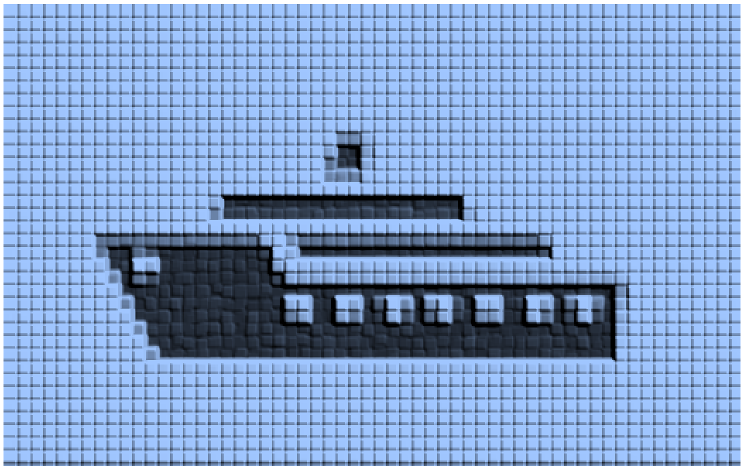
Simplified Life Cycle Assessment of Onshore Power Supply for Cruise Ships



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Master Thesis in Climate Change Management

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Sogndal
June,2021

I confirm that the work is self-prepared and that references/source references to all sources used in the work are provided, cf. Regulation relating to academic studies and examinations at the Western Norway University of Applied Sciences (HVL), § 10.

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TITLE

Master thesis in Climate Change Management

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This thesis is a part of the master's program in Climate Change Management (Planlegging for klimaendringer) at the Department of Environmental Sciences, Faculty of Engineering and Science at the Western Norway University of Applied Sciences. The author(s) is responsible for the methods used, the results that are presented and the conclusions in the thesis.

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Preface

My special gratitude goes to my supervisors Morten Simonsen and Hans Jakob Walnum, my family and friends for guiding me through this time of writing. This thesis stands as the first attempt at quantifying the emissions from the implementation of OPS, making it unique and innovative. I humbly hope that this thesis will inspire others in continuing my work, building on it, or even assess the whole life cycle of OPS.

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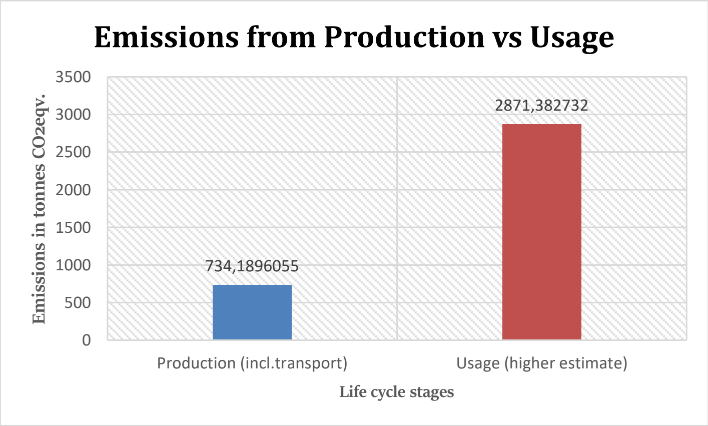
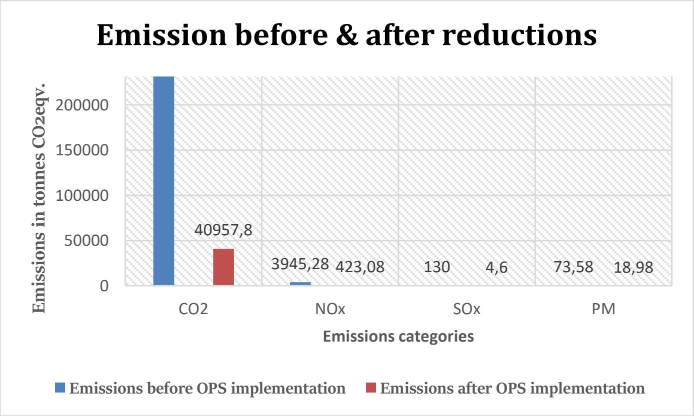
Abstract

This thesis focuses on the implementation and usage of onshore power supply (OPS) for cruise ships at berth and the reduction of emissions and air pollution caused by the latter. The thesis is considered innovative as it stands as the first study of its kind that makes use of the holistic- environmental assessment tool that is an LCA to assess the emissions caused/reduced by the implementation and consequential use of the shore power facilities. The LCA is based on a real-life implementation in Bergen and as such follows the exact composition of the latter in terms of components. Furthermore, materials and technical data has also been derived from Bergen harbour. Ultimately, the findings of the LCA showed that the emissions from the implementation of OPS are relatively low in comparison to the potential reductions achieved. However, the findings also revealed the strong dependency of reductions on demand and the electricity mixture available. For a successful reduction in emissions, shore power needs to be strongly utilized by the cruise industry, which is not the case to-date. The capabilities do exist, and more cruise ships than ever are either outfitted or retrofitted with the necessary equipment. However, only a fraction of the global cruise ship fleet is capable of receiving shore power, and still fewer do so actively-Additionally, it is recommended that the electricity mixture used is fully or partly renewable to avoid the relocating of emissions and thereby pseudo-reductions. However, the implementation and usage of OPS might still be recommended even if the electricity mixture is non-renewable as air pollution will still be eradicated. This recommendation can be made as the essence of shore power, i.e. its purpose, is the reduction of air pollution in ports and port cities rather than climate mitigation.

The figures of 1 & 2 showcase the emissions from the implementation and usage of the facility and the emissions in absence of OPS and with OPS installed, respectively.

Keyword: On-shore power supply, cold ironing, shore power, alternative marine power, life cycle assessment, innovative, new, demand, supply, electricity mixture, air pollution, purpose, reductions.


Emissions from Production vs Usage
Emissions in tonnes CO2eqv.
3500
3000
2500
2000
1500
1000
500
0
734,1896055
2871,382732
Production (incl.transport)
Usage (higher estimate)
Life cycle stages


Emission before & after reductions
Emissions in tonnes CO2eqv.
200000
150000
100000
50000
0
40957,8
3945,28
423,08
130
4,6
73,58
18,98
CO2
NOx
SOx
PM
Emissions categories
Emissions before OPS implementation
Emissions after OPS implementation

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Samandrag på norsk

Denne masteroppgaven setter søkelyset på implementasjon og bruken av landstrøm for cruise skip ved havn samt reduksjonspotensialet i forhold til utslipp og luftforurensing. Studien er nyskapende ettersom den er den første av sitt slag som bruker en livssyklusanalyse (LCA) for å vurdere utslipp som reduseres eller genereres ved implementasjonen og bruk av landstrøm-fasilitetene. Livssyklusanalysen er basert på en faktisk implementasjon i Bergen og følger oppbygningen av dette anlegget i form av komponentene som kreves for denne implementasjon. Deler av sammensetningen til komponentene samt teknisk data som effekt av trafoer og frekvensomformere etc. er hentet fra Bergen havn.

Resultatene fra LCAen viser at utslippene fra implementeringen av landstrøm-anlegg er relativ lave i forhold til de mulige reduksjonene som kan oppnås. I tillegg viser resultatene at reduksjonspotensialet er sterkt avhengig av etterspørsel etter landstrøm samt elektrisitetsmiks. En vellykket reduksjon av utslipp fra bruk av landstrøm forutsetter bruk av anlegget, noe som ikke er tilfellet per i dag. Mulighetene for effektivt bruk eksisterer, og flere cruise skip enn noen gang før er utstyrt eller er i ferd med å bli utstyrt med nødvendig koplingsutstyr. Likevel er det bare en brøkdel av den globale cruiseskipsflåten som er i stand til å motta landstrøm og en enda mindre brøkdel som faktisk gjør det.

I tillegg til hyppig bruk av landstrøm anbefales det at elektrisitets-miksen som brukes helt eller delvis er basert på fornybare energikilder for å unngå relokalisering av utslippene og dermed pseudo-reduksjoner. Til tross for en ikke fornybar elektrisitets-miks kan likevel implementering og bruk av OPS anbefales siden lokal luftforurensing vil bli sterkt redusert ved utstrakt bruk av anlegget. Denne anbefalingen kan gis ettersom den vesentlige målsetting med landstrøm er reduksjon av lokal luftforurensing i havner og havnebyer snarere enn reduksjon av utslipp av klimagasser.

Zusammenfassung

Diese Master-These konzentriert sich auf die Implementierung und somit Nutzung der Landstrom-versorgung für Kreuzfahrtschiffe am Liegeplatz, und die daraus reduzierte Anzahl an Emissionen und Luftverschmutzung. Die These gilt als innovativ, da sie die erste Studie ihrer Art ist, die das holistische Umweltbewertungsinstrument einer Ökobilanz verwendet, um die durch die Implementierung und Nutzung der Landstromanlage entstehenden/reduzierten Emissionen zu bewerten. Die Ökobilanz basiert auf Informationen einer realen Implementierung in Bergen, und folgt als solche einer genauen Zusammensetzung, beschrieben in jener Information. Darüber hinaus wurden auch Materialien und technische Daten in Bezug auf die Komponenten abgeleitet.

Letztlich zeigten die Ergebnisse der Ökobilanz, dass die Emissionen aus der Umsetzung der Landstromanlage im Vergleich zu den erzielten Reduktionen deutlich geringer ausfielen als angenommen. Die Ergebnisse enthüllen aber auch die starke Abhängigkeit der Reduktionen von Nachfrage und dem verfügbaren Strommix. Für eine erfolgreiche Reduzierung von Emissionen müssen Landstromanlagen stark in Anspruch genommen werden, was bisher global gesehen nicht der Fall war. Die Möglichkeiten der effektiven Stromversorgung sind vorhanden, und mehr Kreuzfahrtschiffe denn je werden mit den notwendigen Gerätschaften ausgestattet oder nachgerüstet. Dennoch ist nur ein Bruchteil der globalen Kreuzfahrtschiffsflotte in der Lage, Landstrom zu beziehen und noch weniger tun dies. Darüber hinaus wird empfohlen, dass der verwendete Strommix ganz oder teilweise erneuerbaren Energiequellen entspringt, um eine Verlagerung von Emissionen und damit pseudo-Reduktionen zu vermeiden. Die Implementierung und Nutzung von Landstrom kann jedoch auch dann empfohlen werden, wenn der Strommix aus nicht-erneuerbaren Energien besteht, da die Luftverschmutzung weiterhin eine Reduktion erfährt. Diese Empfehlung kann als Kernstück der Landstromversorgung gesehen werden, da der Zweck von Landstrom die Verringerung der Luftverschmutzung in Häfen und Hafenstädten ist und nicht der des Kilmaschutzes.

Table of contents

List of Figures

List of tables

1. Introduction

1.1 Background on emissions from international shipping

The economic sector of international shipping constitutes one of the main pillars of global trade and stands as a paradigm of globalization. Despite economic stagnation its growth is constant, and the sector manages 80 % of global commerce in terms of volume and 70 % in terms of value (United Nations Conference on Trade and Development, 2018). International shipping Is therefore undeniably important for economic growth, as well as a steppingstone for economic development. Nevertheless, its economic benefits are tainted by its various environmental impacts. At current international shipping accounts for 714 mtCO_2 emissions per annum, representing approximately 2-3 % of total global CO_2 emissions, placing it above Germany in terms of emissions (IEA, 2020; Global Carbon Atlas, 2018). If no appropriate steps are taken to mitigate emissions from international shipping, a 50 % to 250 % increase is expected by 2050 (Wan, el Makhloufi, Chen, & Tang, 2018)

Furthermore, the sector not only covers CO_2 emissions, but also an array of other emissions such as nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter, also called $PM_{2.5}$ and PM_{10} (2.5 and 10 micrometer). Both NO_x and SO_x are having a profound climatic effect when released in large quantities. Furthermore, both are dangerous gases in terms of human health. The third air polluter, particulate matter is especially harmful for humans. The term particulate matter refers to particles found in the air typically emitted by fuel sources such as diesel engines or power plants, such as dust, dirt, soot, and liquid droplets (World Health Organization, 2019). If inhaled they can have a negative effect on one's respiratory system, heart and lungs (World Health Organization, 2019). According to Simonsen, Gössling, & Walnum (2019) NOx and PM emissions from shipping, which are the most relevant in terms of human health, accounted for 16% and 2 % of global emissions respectively in 2015.

1.1.1 Cruise tourism

A small fraction of the international shipping sector are cruise ships, constituting a meagre 1 % of the world fleet (Paiano, Crovella, & Lagioia, 2020). Cruise ships provide cruises, a form of leisure activity that can be defined as going on a journey on a large ship for pleasure, during which you visit several places (Cambridge University Press, 2021). Nowadays cruise ships are characterized as hotels / resorts rather than transport mode. Furthermore, they are often described as a controlled, safe, and pleasurable environment, offering a wide range of recreational facilities and activities, underlining the fact cruise ships are floating hotels (Jaakson, 2004, p. 46).Furthermore, its capabilities earned it the reputation as pinnacle of tourist transportation, representing all four faces of the tourism industry, namely transportation, accommodation, attractions, and tours, while only constituting 2 % of the tourism industry (Brida, Bukstein, & Tealde, 2013 ; Carić & Mackelworth, 2014).

In the last 15 years, the cruise industry experienced extensive growth and became one of the most attractive tourism sectors, generating a global economic revenue of more than $130 billion in 2018 (Paiano, Crovella, & Lagioia, 2020). Furthermore, its clientele has risen substantially with 26,5 million passengers in 2017 compared to 20.9 million passengers in 2012 (Klein, 2011; Simonsen, Gössling, & Walnum, 2019). While mostly contributing positively to economic development, cruise tourism remains one of the most energy-intensive tourism segments on a per tourist per trip basis, emitting significant GHG emissions and air pollutants (Simonsen, Gössling, & Walnum, 2019).

However, in the context of international shipping, the cruise industry only accounts for a small share in overall emissions, with a mere 35 Mt of Co2 in 2012 (5 % of the 2.2 % contributed by international shipping to global emissions) (Simonsen, Gössling, & Walnum, 2019). Nonetheless, their contribution has been increasingly discussed in other sustainability contexts, such as that of local and regional air pollution. It is important to note that cruise ships are the cause of various environmental impacts and greatly contribute to the impairment of human health in ports and port cities by the deterioration of local air quality and noise pollution. Furthermore, cruise ships often visit sensitive geographical sites and nature reserves on their route, thus not only affecting the health of humans, but also negatively affecting buildings and wildlife.

1.1.2 Problematic emissions from cruise ships

Emissions from cruise ships include Carbon dioxide (CO_2), sulphur oxides (SO_x), carbon monoxide (CO), unburned hydrocarbons, nitrous oxides (NO_x) and particulate matter ($PM_{2.5}$, PM_{10}). When berthed, cruise ships rely on auxiliary aggregates to meet their energy needs. This demand for energy originates from running hotel mode, i.e. the provision of electricity for the purpose of lighting, food production, heating, and other facilities which are highly requested by the vessel's populace. The auxiliary aggregates normally run on cheap and low-quality fuels, e.g. heavy fuel oil or marine gas oil, which are often high in various exhaust pollutants. Cruise ships therefore emit high amounts of GHG emissions and air pollutants near port. Particularly the air pollutants of PM and NOx have been increasingly scrutinized, due to their influence on human health, having been linked to bronchitis, lung cancer and heightened cardiopulmonary mortality (Simonsen, Gössling, & Walnum, 2019). Furthermore, they are the causing for around 60 000 deaths per annum along European, East Asian, and South Asian coastal areas (Kumar, Kumpulainen, & Kauhaniemi, 2019) and further 14500 – 37500 premature deaths worldwide (Simonsen, Gössling, & Walnum, 2019). According to the European Sea Ports Organisation (ESPO), air quality has become a key component in the acceptance of cruise ships and port activities and is therefore seen as a top priority since 2013 (Darbra, Wooldridge, & Puig, 2020). In conjunction with an ever-stricter regulatory framework, the cruise industry therefore must find suitable solutions for reducing its carbon footprint and environmental impact to allow for unhindered future growth.

1.1.3 How to reduce emissions?

Possible solutions range from operational and market-based approaches to technical solutions. The latter aims at using technical means to improve a ships energy efficiency, ergo reducing its environmental impact. There is an array of technical solutions available, ranging from design choices for ships and waste heat recovery systems to alternative power sources such as fuel cells, solar and wind power and lastly onshore power supply (OPS). Ideally, innovative technologies should provide power to ships, and cut emissions in the process (Wan, el Makhloufi, Chen, & Tang, 2018).

The practice of onshore power supply (Am. Cold Ironing) is a prime example of such a technology, and addresses the problem of local air quality deterioration, as well as that of noise pollution. It should be noted that OPS is known under the following names: Alternative Power (AMP), "Cold ironing" as previously mentioned, On-Shore Power Supply and shore-to-ship power (SSP). Those names are all synonyms for the same technology and will be considered interchangeable for the purpose of this paper. Cold ironing is the oldest term, first appearing when ships were using coal-fired engines. When berthed, there was no need to further feed the fire and the iron engines literally cooled down, hence the term cold ironing. Nowadays cold ironing is defined as the provision of electricity from the national grid or other energy sources and the consequently shutdown of the auxiliary aggregates onboard. According to Schnabel & Beiersdorf (2018) a successful implementation could theoretically reduce emissions by approximately 80 % (70 – 100% (NOX), 50 – 70% (PM), 30 – 60% (SOX), 40 % (CO2)) depending on the electricity mix (renewable vs. non-renewable). Additionally, the implementation shore power could reduce noise pollution by up-to 10 db (Schnabel & Beiersdorf, 2018). Furthermore, onshore power supply could potentially reduce overall emissions, given the fact that cruise vessels spend large amounts of runtime in harbour areas. A likeness presented by Colarossi & Principi (2020) affirms that if all European ports were to make use of OPS, a potential 800,000-ton reduction in carbon emissions could be achieved, including reductions from container ships, ferries etc.

1.2 What is life cycle assessment?

The International Standardization Organization (ISO) defines LCA in its standard 14044 as "a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (International Standardization Organization, 2006). Thus, a life cycle assessment is able to touch upon a product's whole life cycle, from possible resource extraction, distribution, to product manufacturing, via usage, to its disposal or recycling, i.e. from *cradle-to-crave or cradle-to-cradle*. An LCA is one of the most popular tools for quantitative environmental comparisons. Moreover, it is heavily used by the government or industry to assess the environmental impact of various processes or systems. This popularity is grounded in the now business imperative that is global awareness, i.e. the sourcing of resources, manufacturing procedures, assembly stages, usage and disposal (Curran, 2013). This expanded view, together with the wish of sustainable conduct have prompted managers and decision makers to look at all stages of their products life cycle, creating the holistic environmental assessment tool that is an LCA (Curran, 2013).

The usage of an LCA as an environmental assessment tool can result in many benefits, especially in conjunction with company procedures and product development. The results of an LCA are expected to improve upon product development, marketing or strategic planning et cetera (Golsteijn, 2020). The information from the LCA assessment will also be readily available for almost everyone, meaning consumers and companies alike can gather environmental information about the product a question (Golsteijn, 2020).

1.2.1 Environmental product declarations

The LCA that has been conducted in conjunction with this dissertation actively uses environmental product declarations as the base of its calculations. An explanation of those might therefore be in order.

An Environmental Product Declaration (EPD) is an independently verified and registered document, which delivers transparent information about the life cycle of a products environmental impact (The International EPD System, 2021). The foundation of an EPD is an LCA, and as such it takes into consideration the full value chain, from material extraction to manufacturing, to the usage of the product, and lastly its end of life. An EPD is created in conjunction with the ISO standard 14025, which establishes the principles and specifies the procedures for developing said EPD (International Standardization Organization, 2006a). The creation of an EPD for the construction sector must also follow other standards, such as the standard EN 15804, which sets requirements for its various modules (Gaasbeek, 2019). The standard got revised in 2019, ultimately making the inclusion of the life cycle modules of A1-A3, C1-C4 and D mandatory (Gaasbeek, 2019). Under very specific conditions this could be evaded, and one might be allowed to just include A1-A3 (Gaasbeek, 2019).

Said modules represent the systems boundaries of an LCA, as they cover the different stages of the said LCA. The modules of A1-A3 for instance cover the production stage, with raw materials acquisition, transport, and manufacturing, i.e., *cradle-to-gate*. Cradle to gate is one of four LCA scopes, indicating the extent to which life cycles are covered. There are four scopes in full, all of them differ in terms of modules covered. A full presentation of these scopes will be given in the next chapter.

1.2.2 The Scope of an LCA

There are four Life cycle assessment scopes, namely Cradle-to-Gate, Cradle-to-Gate with options, Cradle to Grave, cradle to cradle and lastly gate to gate. These different approaches all include different modules and cover different stages of the LCA. The following scopes cover the following stages/modules.

Cradle to Gate
The cradle to gate scope covers the production stage of a product or material from extraction (cradle) to factory gate (gate) The modules of A1 – A3 cover raw material acquisition/supply, transport of raw materials and the manufacturing of products. Cradle to gate assessments are often the basis of certain EPDs, so called business-to-business EPDs.

Cradle to gate with options (the scope applied for this dissertation)
This category covers the product stage, as previously mentioned, and an arbitrary second stage, either from the user stage or the end-of-life stage. The user stage covers the modules of B1-B7, i.e. the use, maintenance, repair, replacement, refurbishment, operational energy use and operational water use. The end-of-life stage covers the modules C1-C4, i.e. De-construction, demolition, transport, waste processing and final disposal. Furthermore, it can include benefits and loads that are beyond the system boundary, such as reuse, recycling or recovery potential in the form of module D. This brings us to the third assessment scope, Cradle to Cradle.

Cradle to Cradle
Cradle-to-cradle as the name suggests is a closed cycle, much as the circular economy approach commends. It is a specific kind of cradle to grave assessment, with the difference being that end-of-life disposal is exchanged with a recycling/reuse process (Mizi Fan & Feng Fu, 2017/2017, pp. 529–544; Cao, 2017). The framework of the cradle-to-cradle approach seeks to create essentially waste free production techniques. All inputs and outputs are basically seen as nutrients, ad nutrients can be recycled or reused with little to no loss in quality (Presidio Graduate School, 2018).

Cradle to Grave
The cradle to grave category covers all life cycle stages as a minimum, and benefits and loads beyond the system boundary may be included.

Gate to Gate
The gate-to-gate approach is a partial LCA method, focusing on only one value-process in the production chain. A good example is brought forth by Muhamad, Sahid, Surif, Ai, & May (2012) which looked at palm oil production and restricted their LCA to the process regarding the palm oil seedlings and their seed up, nursing and transport to further processing. The flowchart in figure 4 is taken from that specific case study and visualizes a gate-to-gate approach.

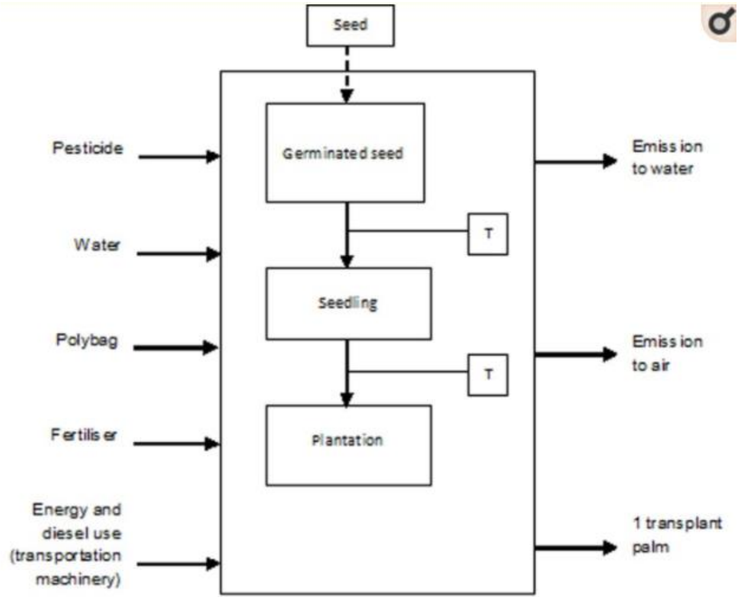


Figure 1: The flowchart visualizes a gate-to-gate partial LCA of palm oil seedlings and their seed up, nursing and transport to the plantation. It includes all inputs and outputs of the process. Figure adapted from Muhamad, Sahid, Surif, Ai, & May (2012)

1.2 Aim and Research Question

The aim of this study is to explore OPS as a technical solution for cruise ship emissions when at berth. The focus mainly lies on Bergen as it has already implemented OPS successfully, but the study also envelops other European ports and their implementation.

This dissertation seeks to answer the following question, which will ultimately guide this research:

> *"How much emissions can be saved per year by switching to onshore power supply?"*

The following sub-questions were designed to adequately answer the formulated research question and give this dissertation the needed structure.

- *What are the technological and non-technological challenges and barriers connected to the implementation of onshore power supply?*
- *What are the indirect emissions of onshore power supply (components, materials etc)?*

1.3 Scope and Limitations

This dissertation focuses specifically on onshore power supply as a technical solution for the problem of air pollution in urbanized ports, thus it intends to deliver a review and analysis of said technology and its implementation.

The underlying aim of this dissertation is the exploration of OPS as a technology for emission reduction in urbanized ports and the provision of its emission reduction potential. In order to assess said potential the studies focal point is it to gather information about real life implementations, technological and non-technological barriers for the implementation of OPS for cruise ships, in addition to the indirect emissions associated with the construction of OPS at port-side. The indirect emissions of said facility are explored through the realization of a simplified Life Cycle Assessment (LCA).

Regarding the geographical scope, this study is carried out mainly in the Norwegian context, where the OPS facilities in Bergen are taken as a reference system for the LCA and build-up. Existing foreign experiences within Europe are also embraced to further detail the barriers and opportunities that the transition to onshore power supply can encounter and provide.

The research is constrained by the availability of literature, and industry collaboration. The knowledge gap in indirect emissions is compensated by an LCA, which's success depends on industry collaboration, since available research is very limited or nonexistent on the topic of OPS and its life cycle.

2. Methodological theory

This chapter describes the methodology that was applied for the Life Cycle Assessment and literature review.

2.1 Literature review

The literature review helps synthesizing existing literature in most applied fields. As science is a cumulative endeavour literature reviewing plays an important role in generating stronger evidence-based research. It is considered one of the, if not the most important tool in exploring specific topics in-depth, such as onshore power supply or cruise tourism. If the literature review is conducted well enough, it potentially becomes a much-cited piece of summarized knowledge, serving as the first clear outline of further research in that specific scientific field.

This specific dissertation first utilized a scoping review to provide an indication as to how much literature was available. A scoping review aims at mapping existing literature in a field of interest, in terms such as volume, nature or characteristics of the primary research (Pham et al., 2014). The scoping review method is often used when the topic has not yet been extensively reviewed or is of complex nature (Pham et al., 2014). Ergo a scoping review can help in identifying the range, and extent of the research activity in the area of interest. Additionally, it can provide muse on whether a potential systematic review might be in order.

The scope review was followed up by a descriptive review to identify to what extent those various studies revealed any patterns or trends with respect to the research questions/s of this dissertation (Paré & Kitsiou, 2016, pp. 157–163). In contrast to narrative reviews, descriptive reviews follow systematic and transparent procedures, including searching, screening and so on (Paré & Kitsiou, 2016, pp. 157–163).

Through analysing a portfolio of technical reports, academic journals and per reviewed papers available on academic databases I initially gathered background information that would serve me as a base for future research. A more encompassing systematic literature review followed, pursuing the goal of adequately covering the following topics:

- Current available technology and its current state.
- Indirect emissions associated with the implementation of OPS.
- The environmental and health benefits associated with the implementation of OPS solutions.
- The problem of air pollution from cruise ships and its effect on human health in urbanized ports.
- Challenges and barriers linked to the implementation of OPS.
- A technical description of an example system which is currently in place.

2.2 Data collection for the literature review

Data refers to a body of information, which can be extracted from various sources. The literature review presented in this dissertation is the result of data collection. What initially leads to a literature review can be viewed as the collection of data, i.e. collecting a body of information pertinent to a topic of interest Onwuegbuzie & Frels 2016, pp. 49–51) . The data that was collected for this dissertation was sourced from a variety of sources. An array of academic papers was found on google scholar or web of science. However most data was gathered from searching for individual keywords using the google search engine. The most used keywords and key-sentences were:

Onshore Power Supply, Cold ironing, Port emissions, Air pollution in ports and port cities, shore power configuration, transformer, Frequency converter, ABB, Bergen landstrøm, Landstrom in Hamburg, Reduction's potential of shore power.

2.3 The LCA method

The standard 14044, which was first mentioned in the introduction, is part of a series of standards published by the International Standardization Organization. The content of the series are the standards of 14044 and 14040. Both ISO 14044 and ISO 14040 describe the general framework, principles and requirements for life cycle assessment, the framework can be viewed in figure 9. According to the International Standardization Organization (2006) the framework can be divided into four different stages: Goal and Scope definition, Life cycle inventory analysis (LCI), the life cycle impact assessment (LCIA) and the life cycle interpretation phase.

The first stage of every LCA is the goal and scope definition. In this stage the system boundaries are set, and the assumptions are listed. According to Harding the goal and scope defines what it is that is to be investigated. The goal of the study should be described explicitly together with the functional unit. The functional unit is the product or process that is investigated, e.g., the production of 1 ton of masonry

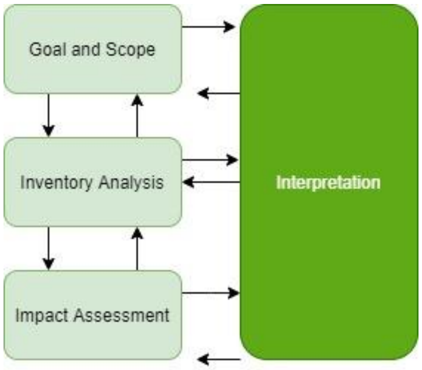


Figure 2: The LCA framework as described by the International Standardization Organization

products driving 5 km in a small transporter. The functional unit is depended on how detailed the study is required to be. An entire life cycle, with multiple processes may result in multiple products, ergo an unclear definition of the functional unit.

The second stage, the life cycle inventory analysis, involves the actual collection of data consisting of input/output data. Thereafter the inputs/outputs of the system are modelled and quantified. In the third stage, the life cycle impact assessment, the results from the analysis are converted into environmental impacts. A well-known example of this is the carbon footprint calculation, where the emissions calculated in the analysis are converted into global warming potentials in the impact assessment. The final stage of an LCA is the interpretation phase, which is based on the three former stages, and summarizes and discusses the conclusions and possible recommendation in accordance with the specified goal and scope.

2.4 Type of LCA

This sub-chapter covers the type of LCA that was conducted.

2.4.1 Attributional or Consequential life cycle assessment?

According to Maria Jose Bastante-Ceca (2020), an LCA should be considered as a family of methods, rather than one methodological approach. Both Attributional LCA (ALCA) and Consequential LCA (CLCA) belong to this family of methods, and both are guiding subsequent methodological decisions, such as the choice of input data, physical flows, allocation or modelling.

There are several definitions for both LCA methods, but I prefer the definitions of Finnveden et al. (2009) over the others, as it represents one of the most cited papers on LCA.

- ◊ Attributional LCA: “Attributional LCA is defined by its focus on describing the environmentally relevant physical flows to and from a life cycle and its subsystems.”
- ◊ Consequently LCA: “Consequential LCA is defined by its aim to describe how environmentally relevant flows will change in response to possible decisions.”

According to the Schuller & Baitz (2020) an ALCA can be described as accounting, book-keeping or descriptive. An attributional LCA aims at using fact-based, measurable data, that has a known uncertainty to it, and includes all processes that are identified as relevant towards the system being studied. Additionally, an ALCA is conducted based on average or generic data, as goods and services stem from a wide mix of producers or technologies (Schuller & Baitz, 2020). A summary of the characteristics of an ALCA is provided by table 2

Table 1: The table above is loosely based on the table by Schuller & Baitz (2020) and incorporates a slightly changed description and combination of topics. The table presents an overview of the characteristics of an attributional LCA.

Topic	Attributional modelling
Definition (Finnveden et al., 2019)	An Attributional LCA is defined by its focus on describing the environmentally relevant physical flows to and from a life cycle and its subsystems
Goal	The analysis of an average functional unit (e.g. annually)
Explanation	An ALCA is describing the potential environmental impacts that can be attributed to a specific product system in a retrospective fashion.
Guiding question	For example, what are the potential environmental impacts of the generic production of 1 kg steel (under oxygen steelmaking)?
Users	Every LCA practitioner from every sector (e.g. petroleum, paper production, or farming) or policy makers seeking to quantify and improve products.
Application	• LCA for a product or carbon footprint of the latter. • Hot-spot or weak point analysis of a product. • Comparison of goods and services. • Development of type 1 ecolabels and type 3 Environmental product declaration. Type 1 and 3 indicate different gradations of environmental assessment.
Typical results	The typical results of ALCA are expressed as for example average CO_2-eqv. per functional unit.
Abundance	An attributional LCA is without a doubt the most prominently used type of LCA. >95 % of all LCAs performed are ALCA.

This thesis's LCA is conducted as an attributional LCA (ALCA), due to most of the data used is predefined as such by the databases used, such as ProBas and EPD-Norge.

2.4.2 Simplified LCA

The grade of sophistication for this LCA is low in comparison to standalone LCAs. This LCA does not represent a detailed LCA, but rather a simplified one. There are three levels of LCA, namely detailed, simplified and conceptual. These three are not separate LCAs, but rather represent a continuum. As such, an LCA can increase in detail and usefulness. A detailed LCA is the most complete LCA, conversely a conceptual LCA is the simplest. This dissertation uses a strongly simplified LCA, due to the lack in life cycle inventory and impact categories.

2.4.3 Data collection and Data sources

The acquirement of primary data was deemed a necessity for the completion of the LCA. Hence various online databases which provide such data were searched thoroughly. Such online appearances include the German ProBas for process oriented basic data for environmental management systems or EPD-Norge for Norwegian Environmental Product Declaration. The databases are described in more detail below.

ProBas

Prozessorientierte Basisdaten fuer Umweltmanagementsysteme, abbreviated as ProBas, was created out of the need for basic data for environmental management decision making and the increasing importance of environmental issues in companies, schools and municipality environmental advising. The database of ProBas is a product of collaboration between the Federal Environmental Agency of Germany and the international institute for Sustainability Analysis and Strategy (IINAS) based in Darmstadt (Germany). The web presence of ProBas offers a library of life cycle inventory. Several public data sources have been integrated into ProBas to allow for a wide spectrum of accessible life cycle data sets. Through extensive search functions and advanced filtering, one can access more than 8000 records of the latter. In addition, one can categorize products into different process categories, such as Energy, Materials & Products, Transport or Disposal, to allow for more efficient searching.

The materials needed for the LCA were found using keywords or terms related to the materials needed. The full-text search option of ProBas allows for several methods. One can search for the material needed, such as atom, or atom* to include words that include atom as part of the word, e.g. the german word “atomkraft”, engl. Nuclear energy. Furthermore, one can exclude words from the search results by writing atom*-atomkraft, ergo excluding the word “atomkraft” from the results. Additionally, one can search after different production methods, where it applies. Steel for instance has several production methods, i.e. oxygen steelmaking, electric arc furnace etc. By searching “MetallStahl” for the metal steel and including “-Oxygen-DE-20XX” one can find the specific data set for steel, made with oxygen steelmaking, in Germany (DE) for a specific year.

Most of the materials used for the completion of the LCA were sourced from here. ProBas was chosen due to its convenience in terms of language, simplicity and wide range of basic data.

EPD-Norge

EPD Norge has been created by the Norwegian EPD foundation and is both a database of environmental product declarations and a program operator for type 3 environmental declarations. The program combines the verification, registering and publishing of environmental product declarations and its storing. EPD-Norge actively counsels' companies to communicate environmental achievements of their products by using verified and comprehensible environmental product declarations.

The database was searched by using terms such as steel, cobber or concrete etc. Data was selected based on subjective decision making and field of use. Since most of the materials needed for the LCA were already earmarked by ProBas, only sub-fabricated products, such as form steel or concrete reinforcement mesh for the sub-station building were derived from EPD Norge. They were carefully chosen based on field of use and whether they were conceived for buildings or not. Additionally data regarding the emissions from electricity mixture were sourced from here.

Eco-Invent

Eco-Invent is a database for life cycle inventory data, such as EPD-Norge and ProBas. However, Eco-invent is the world's leading LCI database and provides process data for thousands of products. The database scintillates in terms of transparency and consistency making it the most popular choice for LCA practitioners. For instance, most of the EPDs from EPD-Norge utilize Eco-Invent as a source for various product processes. Although Eco-Invent has been accessible for the conduction of this dissertation, its services were not utilized. However, Eco-Invent has been used indirectly through the usage of a study by Walnum (2020) and the usage of emission factor for two steel types from the latter.

Bergen harbour

Data was also directly collected from Bergen harbour. The exchange of several messages through e-mail correspondence with the companies of BKK and Plug, secured invaluable information about the OPS facilities at Bergen harbour and its composition. The data that was received included some of the quantity of components, initial weight, and the quantity of materials used. A complete and complemented overview of the received information can be found in table 2. The list has been complemented with composite materials as far as practicable.

AIS Database

The AIS database used in this thesis was provided by Vestlandsforskning and includes datasets from all major cruise destinations in Norway, e.g. port stays. It gathers the information directly from the cruise ships themselves. The information can include, amongst other, laytime, energy consumption, fuel consumption and emissions for CO_2,SO_x etc. The AIS database is available through the appendix.

Table 2 This table presents the received information from the energy company BKK and its daughter company Plug.

Components	Weight	Measures	Composite Materials
21 x standard steel containers	ca. 3 ton each	6k x 2.5k x 2.9k mm	Steel
Substation building	20500 kg steel 500 kg reinforcing steel 155 m^3 concrete		Concrete & steel (steel reinforcement and steel)
Electrical components			
24 x 4 (x4) MVA transformators	168 tonn		copper, steel, insulation (transformer oil = mineral oil and pressboard and/or cellulose)
12 x 4 (x4) MVA frequency convertors	54 tonn		copper, steel, aluminium, plastic, other minor materials
3 x ABB 24 kV busbar and switchboard	12 tonn		copper, steel
3 x auxiliary transformators 200 KVA	-		copper , steel, insulation
3 x cabinets (grounding apparatus, 3 x switchboards, 4 x contacts (ProConnect, neutral)	-		steel
3 x cooling solutions (thermoelectric cooling? Fan-based? Vortex?)	3,3 tonn		steel/aluminium
Cables			
400 m2 treleder jordkabel		2 km	Copper, Aluminium, polyethylene

35 mm2 cobber neutral		1 km	Copper, Aluminium, polyethylene
24 VDC cable		1 km	Copper, Aluminium, polyethylene
110 VDC cable		1 km	Copper, Aluminium, polyethylene
Other components			
Cable reel for cable management (a tower that supports a cable reel, davit and frame)			Steel
2 x Transport units	4.5 tonn each		-
3 x cable trailer	5 tonn		Steel
Various cables	22.5 tonn		Copper, Aluminium, polyethylene

The received data initially allowed the LCA to proceed and gain representativeness as it followed the exact composition of a real-world implementation as close as manageable.

2.5 System boundaries

There are several requirements when it comes to system boundaries. The system boundaries act as limits and must be specified, otherwise the assessment can become too complex, as it includes to many processes/products. System boundaries must be specified in several dimensions, as for instance in time and space or between the technological system and nature (Tillman, Ekvall, Baumann, & Rydberg, 1994).

The geographical boundary plays an important role in the LCA, in that various parts of the product which is being assessed could be produced anywhere in the world (Tillman, Ekvall, Baumann, & Rydberg, 1994). In addition, electricity generation, transport systems or waste management can all differ from region to region (Tillman, Ekvall, Baumann, & Rydberg, 1994). Additionally, pollution can affect the environment differently, depending on the area (Tillman, Ekvall, Baumann, & Rydberg, 1994). A practitioner of LCA must therefore try to restrict said geography.

Boundaries should not only be set in space, but also in time. On the same line as the geographical boundaries, the boundaries set in time, i.e. the time horizon needs to be specified. Essentially, an LCA is concerned about present impacts and future outcomes. The impact that already occurred should be of lesser interest. However, prior levels of pollution are important for the assessment of present-day pollution and future trends (Tillman, Ekvall, Baumann, & Rydberg, 1994). The time horizon is specified by the product in question. Typically, the time horizon consists of the lifetime of a product, pollutants lifespan etc, i.e. the timespan during which the technology or product can be surveyed/assessed.

Another important system boundary is the boundary between the technological system itself and nature. Usually, the life cycle begins in the extraction of raw materials or the acquisition of an energy carrier. For non-renewables, the life cycle starts with the extraction of natural resources, such as oil or gas, or the prospecting of it (Tillman, Ekvall, Baumann, & Rydberg, 1994). For resources such as farmland, forest or husbandry products, all activities should be included that lead to the initial harvest of those products, such as ploughing, fertilizing etc (Tillman, Ekvall, Baumann, & Rydberg, 1994). Every LCA of a product usually follows the same path, from the extraction of the material to the manufacturing of the desired product, to its subsequent disposal at the end of its life cycle. In the end-of-life cycle, the product is released in form of heat or waste, in a solid, liquid or gaseous form and received by either soil (landfill), water (sewage), or air (emissions), ergo the environment, i.e. nature as can be viewed in figure 12. Here the line between the technological system and nature is drawn.

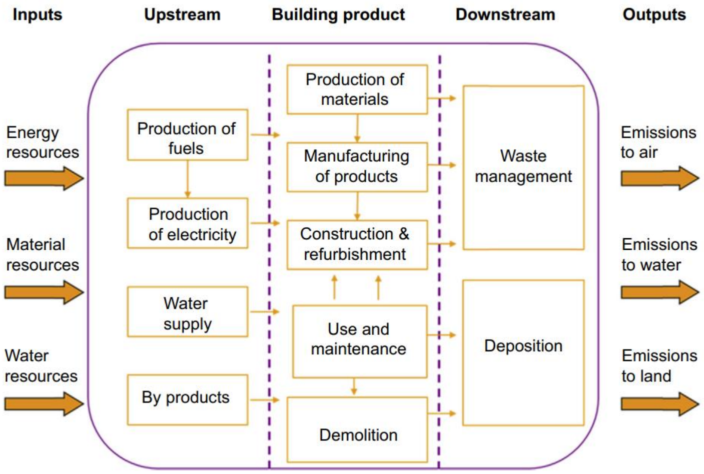


Figure 3 Apprehended figure from Cao (2017) showing the life cycle of a product with upstream and downstream processes and inputs/outputs to and from the system.

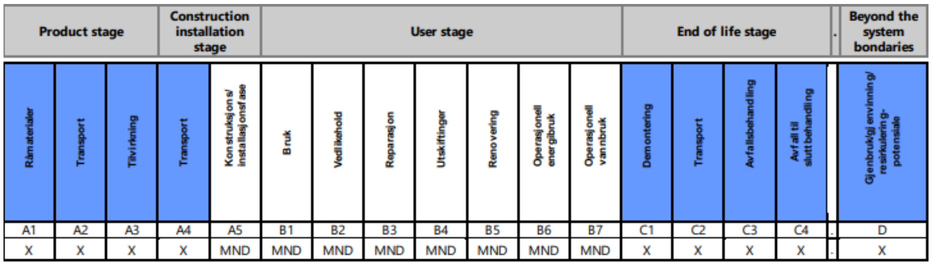
2.5.1 System boundaries for the life cycle assessment

Only the processes that are relevant for my LCA are included within the boundaries of the system. A process such as steelmaking can result in various products, as such the system boundaries prevents that from happening and thus minimizes the risk of allocation problems. The system boundaries specified for this LCA er mainly linked to the time horizon, the geographical boundaries and the boundary between the technological system and nature.

The geographical boundary was set in alignment with the availability of materials. The production of the various materials, e.g. steel, aluminium, plastic or cobber are geographically divided between Germany,Norway and China. This division arises from the absents of key materials in the Norwegian market and the assumption that some materials would be traded from outside Norway because of that. For example, Germany is a primary supplier of steel and cobber products, whilst Norway is a known supplier of aluminium. Thus, most of the steel and cobber was sourced from Germany, and just a fraction of the materials/products were sourced from Norway. In the case of steel sub-products, such as steel reinforcement and structural steel, Norway was selected, due to the availability of environmental product declarations, and the lack of variety in ProBas. Furthermore, Engineering steel and Stainless steel were sourced from Walnum (2020). These materials were specifically chosen for one of the components of this LCA, namely steel containers. The geographical boundary therefore also includes China as a place of origin, which both materials originally stem from.

The time horizon was adjusted to the lifetime of a typical OPS facility. The lifetime of the OPS facility was set to 20 years on average and the time horizon was adjusted accordingly (Fasting,2018). Furthermore, the time horizon was also in line with many of the major components of the facility, such as the frequency converter and the transformer.

The boundaries in respect to the natural system are predefined by the sources used, i.e. ProBas and EPD Norge. The sub-products sourced from EPD-Norge for example follow the standard EN 15804, which defines how companies should prepare their Environmental Product Declarations (EPDs). In accordance with the standard, products/materials need to cover the modules A1-A3, C1-C4 and D. However, this dissertation only focuses on the modules of A1-A4 and B1 due to the theme of this dissertation being the implementation of OPS and its resulting usage, but not its end-of-life. The life cycle of the OPS facility starts in the product stage of the materials used, with the extraction of the raw materials, the transport of former, the resulting manufacturing of the products/materials and the transport of said products/material from the site of production to the site of installation. The life cycle is cut off at the assembly stage with the construction/installation of the OPS facility and reentered in the user stage at B1. The assembly is not assessed, neither is the end life stage of the materials. The modules used in conjunction with ProBas are not known specifically, though the life cycle assessed is



Product stage			Construction installation stage		User stage							End of life stage				.	Beyond the system bondaries
Råmaterialer	Transport	Tilvirkning	Transport	Konstruksjons/ installasjonsfase	Bruk	Vedlikehold	Reparasjon	Utskiftinger	Renovering	Operasjonell energibruk	Operasjonell vannbruk	Demontering	Transport	Avfallsbehandling	Avfall til sluttbehandling		Gjenbruk/gjenvinning/ resirkulering-potensiale
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	.	D
X	X	X	X	MND	MND	MND	MND	MND	MND	MND	MND	X	X	X	X	.	X

Table 3: A typical representation of the different stages of a products life cycle, beginning with the production and installation to end of life and beyond. Apprehended from Norsk Stål (2020a)

that of production (A1-A3). Hence the module of A4 (transport) needed to be added manually and the results can be viewed in chapter 3.5 in the results section.

2.5.2 Functional Unit

The functional unit, abbreviated as FU, is a quantified description of the function of a product, which serves as a reference basis for all calculations regarding impact assessment (Arzoumanidis, D'Eusanio, Raggi, & Petti, 2019). The functional unit can be based on different features of the product studied, such as performance, quality, cost or aesthetics (Arzoumanidis, D'Eusanio, Raggi, & Petti, 2019). The functional unit for the LCA conducted in this dissertation is defined by the kWh delivered from shore power in Bergen during the lifetime of the facility, from 2017 until 2036 (20 years). Thus, the performance of the OPS facility can be compared to other facilities with similar configuration.

2.5.3 Energy chains

An energy chain is the preceding energy usage of a product, expressed in terms of transport, precursor products and energy usage. The database of ProBas already predefines energy chains for all their materials, and so does EPD-Norge or ECO-Invent. An energy chain can be visualized as in figure 4.

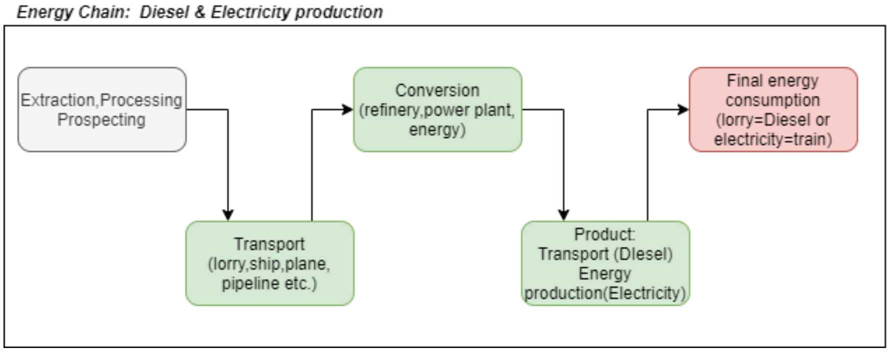


Figure 4: The energy chain for diesel and electricity, simplified.

ProBas also includes the full energy chain of a material, though not visualized as a diagram but rather a list with interactive links to follow the energy/supply chain, which can be viewed in figure 5.

Funktionelle Einheit ist »**1 TJ Diesel generisch**«.

Inputs - Aufwendungen für den Prozess

Input	Aus Vorprozess	Menge	Einheit
Elektrizität	El-KW-Park-generisch	0,0268	TJ
Öl-roh	Öl-roh-mix-generisch	1,06	TJ
Prozesswärme	Öl-schwer-Kessel-gross-generisch	0,0779	TJ

Inputs - Aufwendungen für Produktionsmittel

Produkt	Aus Vorprozess	Menge	Einheit
Stahl	MetallStahl-mix-DE-2000	4284793	kg
Zement	Steine-ErdenZement-DE-2000	5355992	kg

Outputs

Output	Menge	Einheit
Diesel generisch	1	TJ

Figure 5: The typical In/Outputs table from ProBas with Inputs and Outputs for 1 TJ generic diesel. The table includes the electricity input, raw oil etc. Apprehended from Öko-Institut (2020d)

2.6 Allocation methodology

Aguirre-Villegas, Milani, Kraatz, & Reinemann (2012) describe allocations in LCA methodology as follows; "allocation is the process of attributing the relative environmental burdens and benefits of a system to each primary product and co product of the system". Some systems, e.g. food systems have multiple inputs and outputs, ergo allocation or system expansion is needed. The choice of strategy will have a large impact on the results of an LCA and it is highly recommended to use system expansion whenever possible. Only if system expansion is not possible, allocation can be used instead. According to Luo, van der Voet, Huppes, & Udo de Haes (2009) one then must use methods that reflect the relationship between the products, such as mass and energy content, or cost.

2.6.1 An example of allocation methodology

To further visualize this relationship let us assume one owns a soybean field. This soybean field produces both soybean meals and soybean oil. We allocate the two products by cost, with the soybean meal costing 60 kr and the Soybean oil 40 kr. The emissions are already known, and we divide those emissions by cost, meaning 60 % of the emissions stem from the soybean meal and 40 % from the Soybean oil. The allocation by weight can be performed the same way. Whole process allocations can shift this ratio of environmental burden from one product to the other. This can eventually result in higher variability than introduced by poor data quality or by the usage of different system boundaries (Aguirre-Villegas, Milani, Kraatz, & Reinemann, 2012). The ISO standard 14044 therefore recommends dividing unit processes into sub-processes or use system expansion to include co-products (Luo, van der Voet, Huppes, & Udo de Haes, 2009). Villegas et al. (2012) however states that the subdivision of processes cannot eliminate the need for allocation, but rather lessen the need for it.

The solving of eventual allocation problems is not necessary for this LCA. The databases that were used have predefined allocation methods. ProBas uses no allocation method for most of the products used in the LCA, due to them being primary products without any sub-products or processes. However, copper being of secondary origin produces three joint-products, allocation is therefore necessary and done for two of three co-products. EPD Norge uses allocation by mass as its method of choice for all products used in the LCA.

2.7 Key assumptions

In the dictionary of statistics and methodology, W.Paul Vogt defines an assumptions as follows: a) A Statement that is presumed to be true, often temporarily or for a specific purpose, such as building a theory ; b) the conditions under which statistical techniques yield valid results (W. Paul Vogt, 2005/2011).

The LCA that is applied in this dissertation is based on various assumptions regarding materials, components etc. The following key assumptions have been included to assure the realization of the LCA.

2.7.1 Components and materials

- Materials used in the components of the Bergen facility have the same output in terms of emissions as the generic materials found on ProBas, Eco-Invent or EpD-Norge as well as the same energy usage when produced.
- As information is limited regarding the composition of components, reference components were found that resemble said components as close as possible based on available information, such as apparent power (MVA). These reference components also determine material composition.
- Not every composite material can be included in the LCA, due to restrictions in the availability of information regarding those materials. Additionally, some materials only represent a very small share and were therefore exempt from the study. It was therefore assumed that those materials would have little to no influence on the emission outcome of the LCA.

- Only major components are included in the LCA, such as Frequency converters, transformers, cables, buildings and storage if applicable. Minor components such as switchboards, surge barriers etc. are not included as they are believed to have little impact on the overall emissions.

2.7.2 Reduction potential

- The lifetime of the facility is set to 20 years in accordance to Fasting (2018). From 2017 to 2036.
- To assess said reduction potential, this dissertation assumes that every ship is apprehended and aided throughout its whole stay. Later, possible future scenarios are assumed in the form of a higher and lower estimate for OPS utilization to gain a more representative sample for emission reduction.
- The cruise year of 2017 is used as reference year and replicated over the span of 20 years. It is assumed that the reference year is representative for a typical cruise year. Additionally, a cruise year unaffected by covid-19 was considered more representable.
- Various conversion factors have been used in the course of the LCA, which are assumed as correct and representative, e.g. the emission factor diesel.
- The MSC Virtuosa and AIDASol have been assumed to represent typical cruise ships for their respective weight class and build year.

2.8 Validity and Reliability

The assessment of validity and reliability involves the judging of both the research design and research method, and whether they produced an accurate picture of the indirect emissions associated with the implementation of OPS. Both the external and internal validity is important. The internal validity expresses wherever one's study is trustworthy, and wherever we can be confident that a cause-and-effect relationship is credible and trustworthy.

The internal validity can generally be compromised by flaws within the study itself or its design of the research method/data collection.

The external validity refers to whether a studies results can be replicated and applied to other situations. In the case of this study, external validity refers to the transferability of the results to other ports and port cities.

There is an array of factors that can influence internal and external validity negatively. Factors that can influence internal validity include:

- Variability of cruise traffic over the time horizon of the study
- The accuracy of the data that was collected.

- The range of components assessed, consequently the exclusion of minor components.

Factors that can influence external validity include:

- The differences in OPS facilities and implementation between different countries, with different system boundaries, scale and climate.
- The level of sophistication of the Life Cycle Assessment.

Reliability is a measure of consistency or repeatability of the research. It resembles the quality of the research and the data that was collected. The reliability can be affected by various factors, including:

- The availability of data sources.
- The quality and trustworthiness of the latter.
- The up-to-dateness of the data received.

2.8.1 Reliability of the LCA

The basis for this LCA, i.e. the information regarding the facilities at Bergen harbour, was directly derived from BKK and Plug. Last mentioned Plug is a daughter company of BKK and operates the facilities in Bergen. The data was obtained through email correspondence with BKK/Plug and stands as trustworthy.

The data that was used in the LCA regarding materials is derived from trustworthy sources such as ProBas, EPD-Norge or Eco-Invent. Both ProBas and EPD-Norge are official databases for life cycle data sets. The latter also verifies, registers and publishes type III environmental product declarations from various known Norwegian companies, such as *Norsk Stål*. The database of ProBas also stands as reliable, having been created as a product of collaboration between the federal environmental agency of Germany and IINAS, an independent transdisciplinary research organization, involved in various projects such as REDEX,BIOMASS or ENTIRE. The multiple conversion factors and factors for energy content, emissions etc have all been sourced from either LCI databases or peer reviewed academic papers and websites.

The various reference components used in the assessment have also been derived from reliable sources and have been realised according to various standards. Additionally, all of reference components are sourced from either EPD-Norge or directly from the manufacturer ABB.

2.8.2 External validity

The LCA that was conducted stands as very simplified, contrarily to stand-alone LCA studies. As such it does not have the same extent or sophistication as a detailed LCA. Its level of sophistication resembles rather that of a conceptual/simplified LCA. A conceptual LCA tries to answer basic questions and is often described as LCA thinking. The LCA conducted for this dissertation crucially delimits itself from conceptual LCAs through the addition of impact assessment and an LCA inventory consisting of various processes. Additionally, these processes are predefined by the data source and as such are constant. Because of that, the LCA will be convertible to some extent, depending on the geographical location of the facility in question. Furthermore, all the calculations are mathematically simple and rely on predefined information. Solely the electricity mixture that has been applied in some of the calculations will change from country to country.

The composition of the facility might also be subjected to change, as not every port tries to cover the same energy demand as Bergen. Consequently, the quantity of components could decrease or increase, depending on the port in question. Furthermore, the composition of the latter might change as well, ergo the quantity in materials needed.

The external validity of the LCA might therefore be compromised if replicated in another geographical environment other than Europe.

2.8.3 Internal validity

The internal validity of the LCA is considerably weakened through the omission of many of the minor components of an OPS facility. Only the most important components have been included, due to time limitations and little to no availability of environmental product declarations or LCI data sets for other components other than major components. The lack of data might be a product human error or the lack of demand for such data sets.

2.8.4 Construction Validity

The construction validity of an LCA relates to the system borders and their implementation. The system boundaries are set in time and space and are upheld in the LCA analysis. The functional unit that must be defined together with the system boundaries was defined as the amount of kWh delivered from shore power in Bergen during during the lifetime of the facility, with the cruise year 2017 as reference year. Geographical boundaries are upheld by the data source and have been verified. The system boundaries regarding the natural system are the same for all materials and follow the modules A1-A4. The LCA focuses on the modules of A1-A4 (production and Installation) for the materials, and B1 (Usage) for the installed facility in operation. The electricity mixture applied to the LCA is predefined for all materials derived from ProBas, EPD-Norge and Eco-Invent. The electricity mix for the usage phase was taken from Eco-Invent and accounts for the production of transmission lines, in addition to direct emissions and electricity losses. Various electricity mixtures have been used in the sensitivity analysis to examine potential.

3. The life cycle assessment of shore power implementation

In this chapter, the technical solution of OPS will be introduced ones more. Furthermore, the results from the LCA are presented.

3.1 What is onshore power supply?

Onshore power supply, also called shore-to-ship power (SSP), Alternative power (AMP) or cold ironing, is a technical solution for the reduction of air pollution in an area around a dock that experiences a deterioration of air quality due to ship traffic. The International Maritime Organisation (IMO) considers OPS as a *"measure to improve air quality in ports and port cities, to reduce emissions of air pollutants and noise and, to a lesser extent, to reduce carbon dioxide through ships at berth replacing onboard generated power from diesel auxiliary engines with electricity supplied by the shore"* (IMO,2012). In conclusion, its basic principle is the provision of shore power to cover the energy needs of various marine vessels calling at port (Zis, 2019). The air quality in urbanized ports suffers due to marine vessels using auxiliary aggregates onboard for the provision of energy for various activities. That is particularly true regarding cruise ships, which still need to provide an array of services and processes, such as that of heating, light, loading and unloading, and an array of leisure activities typically provided in an hotel/resort context.

A cruise ships energy consumption reflects upon its diversified energy needs, resulting in a substantially higher energy consumption than most other ship types. According to Fasting (2018) cruise ships possess a capacity demand three times higher than that of ferries when at port. A related case study in the port of Helsinki estimated that ferries had a capacity demand of 1,8 MW, whereby cruise ships possess an average capacity demand of 5.5 MW (Fasting, 2018). Hence OPS infrastructure must meet certain energy requirements to efficiently provide energy for cruise ships.

If these energy requirements are met by the OPS infrastructure, the ships auxiliary aggregates can be turned off. Ship operations can then proceed uninterrupted, while emissions are reduced, if not eliminated, due to the supplementation of electricity from a centralised source onshore. According to Sciberras (2015) this gives a locally emission free solution, though the overall emissions will be a function of the electricity mix employed onshore. In the Norwegian context these overall emissions are almost non-existent, due to the electricity mixture being 96 % renewable, mostly deriving from hydropower (Nordic Energy Research,2018).

OPS infrastructure can come in different shapes and sizes depending on the needed energy output and ship type. According to EAFO eighty-two OPS facilities exist today, ranging from high voltage infrastructure for cruise vessels to low voltage infrastructure for inland vessels (European Alternative Fuels Observatory, 2020). This thesis intends to focus on OPS systems construed for cruise vessels and there like. According to de Jonge, Hugi, and Cooper (2005) a typical OPS system for cruise vessels should include the following components and configuration:

1. A connection to the national grid is needed, carrying 20-100 kV electricity from a local sub-station where it is transformed to 6-20 kV.

2. Cables are then required to deliver the 6-20 kV power from the sub-station to the port terminal.

3. The electricity may then require power conversion. The electricity supply in Europe generally has a frequency of 50 Hz. A ship designed for 60 Hz may be able to use 50 Hz, but only to a degree, such as for domestic lighting and heating. Other equipment and activities however require 50 Hz for operation, such as pumps,winches and cranes. Based on this limitation, a ship using 60 Hz electricity will require 50 Hz electricity to be converted to 60 Hz by an electricity converter, also called frequency converter or frequency changer.

4. Electricity is then distributed to the terminal. Cables need to be installed underground, possibly within existing conduits. Alternative canalisation may be required. Electricity is metered.

5. In order to avoid accidents and safety hazards cable management should proceed through a cable reel system. A cable reel tower could be built on the berth supporting a cable reel, davit, and frame. The davit and frame would be used to raise and lower the cables to the vessel. The system would be electro-mechanical powered and controlled. One could even consider using an automated system, though that remains conceptual.

6. As previously mentioned, vessels need to be fitted with special connectors/sockets to connect with the shore power cable.

7. There is also a need to transform the incoming high voltage electricity (6 – 20 kV) into 400 V in order to make it usable for the onboard system. This is done by a transformer situated onboard the ship or onshore.

8. After the electricity has been stepped down from the initial high voltage to a lower voltage it now is made usable and distributed throughout the ship, resulting in the shutdown of the auxiliary engines.

For a more visual representation of a generic OPS infrastructure, please consult figure 1. The figure successfully simplifies the normally complicated configuration of a high voltage OPS facility.

3.1 Technical overview and functionality of shore power infrastructure

An OPS system is a multi-layered compound of several technical installations. The system can be centralized or decentralized, depending on the space that is available. The segmentation, as well as the number of components that the system includes is a product of energy demand and grows depending on ship size, which again asserts energy demand. Figure 3 shows the configuration of a reference system in Bergen on shore and its counterpart onboard the ship. The facility in Bergen is one of the world's biggest shore power facilities, fit for providing energy to three full-sized cruise ships simultaneously.

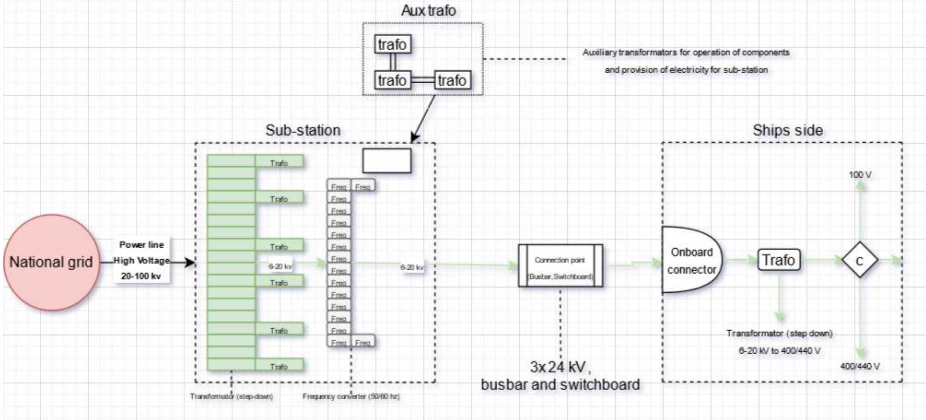


Figure 6 This flow chart loosely represents the system in place in Bergen, the sub-station houses Transformers (Green) and Frequency converters (grey/white), the system also possesses an auxiliary transformer station for powering the sub-station, seen above the sub-station.

3.1.1 Main Substation Building

The main substation building hosts the heart of the system, as it includes most of the systems passive electrical components and main components. A sub-station houses an array of smaller coupling equipment such as breakers, surge arresters and disconnectors. In addition, bigger components such as transformers and frequency converters are located here. In the case of Bergen 24 transformers and 12 frequency converters are housed inside the sub-station building. This makes the sub-station a centre piece of a shore power system.

3.1.2 Frequency converter

As aforementioned, the sub-station houses an array of components and equipment. That also includes so-called frequency converters or frequency changers. These frequency converters can come in different sizes depending on the power that is required for the task. The frequency converters in

Bergen for instance are construed for 4 x 4 MVA, ergo for cruise ships. The onboard grid often operates in the frequency of 60 Hz. According to Fasting (2018) most European shore grids, including the ones in Norway,Finland, Estonia and Germany operate with a frequency of 50 Hz, hence conversion is needed in most cases. The latter is supplied by before-mentioned frequency converter/changer.

Figure 7 A common frequency converter from the manufacturer ABB. This specific model (ACS6080/ACS6000 family) has been used as a reference model for the LCA in terms of material distribution. Apprehended from ABB (2018)

3.1.3 Transformer

The transformer is one of the main components and is needed when voltages between the onboard system and onshore grid differ in magnitude. The transformer adapts the high voltage supply to the voltage used by the electrical system onboard. The transformer is often used in two instances: in the first initial scale down from the national grid to the onshore power supply infrastructure and again in another scale down either onshore or onboard the ship. According to Ericsson and Fazlagic` (2008) the transformer for the second scale down should be designed for 50 Hz and not 60 Hz, avoiding possible damage to the transformer in the case of a decrease in frequency. The facility in Bergen houses 24 transformers, with power ratings up-to 16 MVA/16 MW, however power ratings of transformers can go as high as 1 000 MVA/MW.

Figure 8 A Transformer configurated for up-to 10 MVA from the electrical equipment manufacturer ABB. This specific transformer has also been used in the subsequent LCA, serving as reference component for material distribution.Apprehended from ABB (2011)

3.1.4 Cable management system

The cable management system (CMS) Is a vital part in ensuring safe handling of cables during connection and disconnection procedures. It is installed onshore, as predefined by the ISO standard 80005-1:2019, and normally operated manually (Fasting, 2018; International Standardization Organization (ISO), 2019). In the case of container ships the CMS is installed onboard due to space constraints on the berth (Fasting, 2018). Both onboard and onshore CMS`s share distinct features, such as a cable drum, electrical connectors (up to 12 kV), flexible cables, an electrical control panel and so on (Fasting, 2018).

3.2 Documentation of materials and components

Prior to the life cycle assessment, I obtained valuable information about the composition of the OPS facility in Bergen, Skolten. This information was obtained through the correspondence with BKK/Plug and can be viewed in chapter 2.2.4 Bergen Harbour. The information that was received includes a list of components, their quantity and weight per unit and/or total weight, in addition to values for apparent power in megavolt amperes (MVA) for some of the electro-mechanical components. However, the list does not include any materials used for the construction of those components, apart from the materials used for the construction of the sub-station building. This information has been complemented manually and the process can be viewed in chapter 2. The following table contains all relevant components for this LCA, and the composite materials that have been assessed.

Table 4: The tables shows the quantity of each component, available reference component and assessed composite materials.

Quantity	Component	Assessed materials
24	Transformer (Reference component: **EPD 55 Large Distribution Transformer 10MVA)**	Steel Copper
12	Frequency converter (Reference component: **ACS6080**	Steel Copper Aluminium Polyethylene
21	Steel Container	Stainless steel Engineering steel
1	Sub-station building	Steel (Structural Steel & Reinforcement Steel) Concrete
5 km	Cables (Reference component: **Elektroskandia, TSLF 24kV 3x1x240 AFR/35**	Copper Aluminium Polyethylene

The following figures include the composition of each component in percentages. Additionally, a table is accompanying every figure with information regarding the total weight of the materials used.

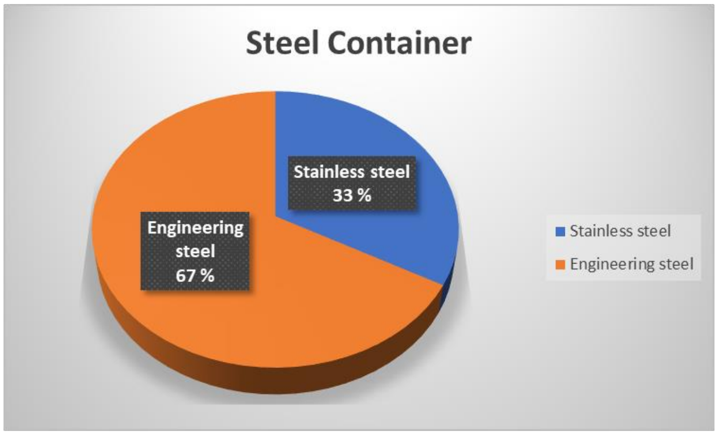


Figure 9: A visualization of the material distribution for steel containers

Table 5: Stainless Steel and Engineering Steel respective quantities.

Materials	Amount (total)	Unit
Stainless Steel	960	kg
Engineering Steel	1950	kg

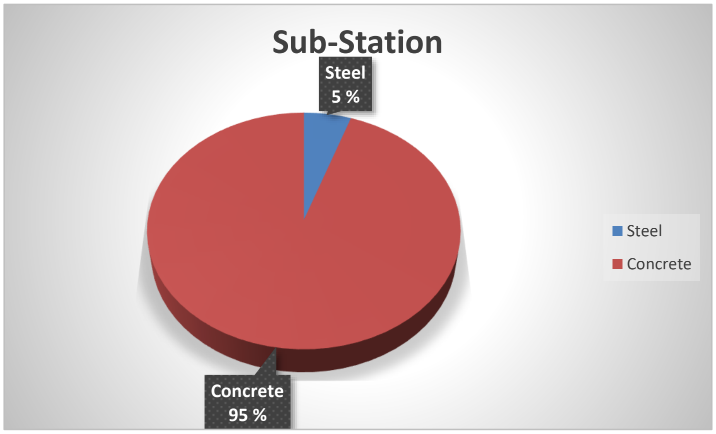


Figure 10: A visualization of the material distribution for the Sub-Station building. The table and figure differ in that the two steel types are combined.

Materials	Amount (per product)	Unit
Steel (concrete reinforcement)	500	kg
Concrete	155	kg
Steel in total (excl. Concrete reinforcement)	20 500	kg

Table 6: Steel,Concrete and Steel reinforcement respective quantities.

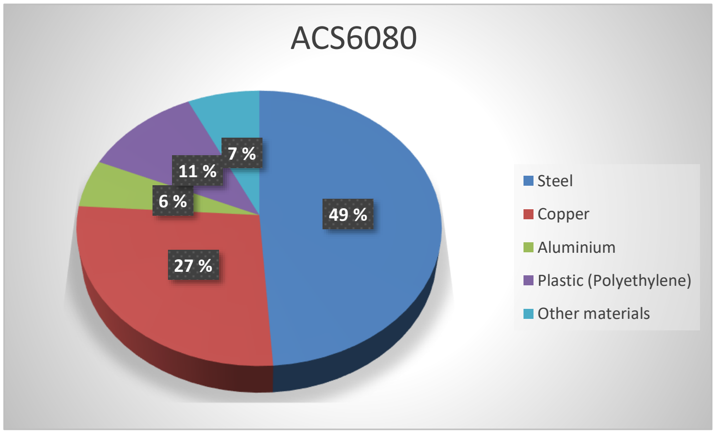


Figure 11: A visualization of material distribution for the frequency converter. ACS6000/ACS6080 indicates the product family.

Table 7: Respective quantities of the materials used in the frequency converter.

Materials	Amount (per product)	Unit
Steel	2 205	kg
Copper	1 215	kg
Aluminium	270	kg
Plastic	495	kg
Other	350	kg

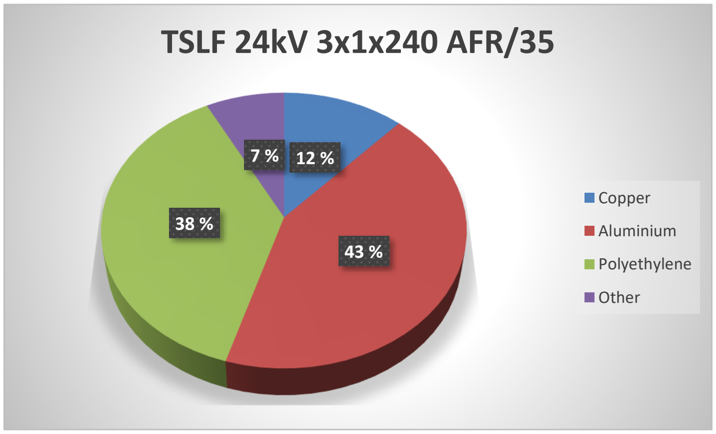


Figure 12: A visualization of the materials distribution for the cables. TSLF 24kV 3x1x240 AFR/35 indicates the voltage limit, size and main material aluminium.

Table 8: Materials and their respective quantities used in the cables.

Materials	Amount (per meter)	Unit
Copper	0,59	kg
Aluminium	2,14	kg
Polyethylene	1,88	kg
Other	0,38	Kg

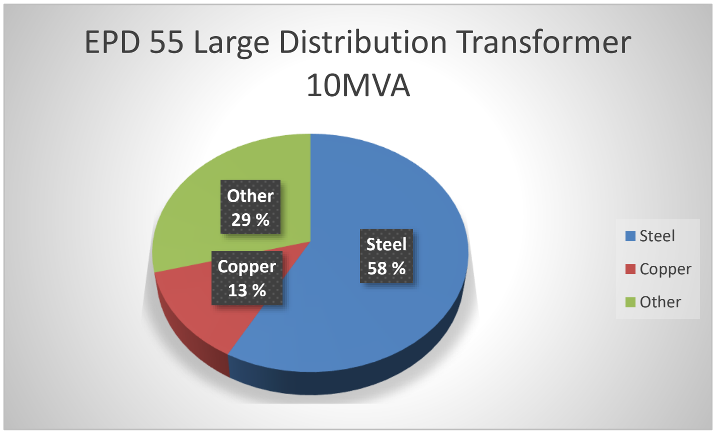


Figure 13 A visualization of the material distribution for the transformer. EPD 55 is the product name of the reference model, and 10 MVA its rated apparent power.

Table 9: Respective quantities in materials for the transformer.

Materials	Amount (per product)	Unit
Steel	4 060	kg
Copper	910	kg
Other	2 030	kg

3.2.1 Reference components

This sub-section explains the reasoning behind the reference components chosen. Due to lack of information regarding the components, except for their composition and quantity, reference components had to be found in order to assess configuration and material distribution.

EPD 55 Large Distribution Transformer 10MVA, from ABB
The EPD 55 is designed for 9600 kVA or 9.6 MVA/10 MVA. It operates within a 50 Hz frequency and 6,3 kV voltage. It was chosen due to the lack of other suitable transformers in that power range. The availability of EPDs and environmental information also played a distinct role in the choosing of a reference component. The EPD 55 was the reference model situated nearest to the apparent power of the actual component in Bergen Harbour, and as such was the logical choice.

Its material distribution was therefore copied for the materials assessed in this LCA, namely copper and steel.

TSLF 24kV 3x1x240 AFR/35, Aluminium core cables from Elektroskandia
The TSLF cables are construed for medium voltage applications and consist of a single aluminium core covered in polyethylene and ripcords. It is applicable for up-to 24 kV, which is more than enough for various installations such as connections to the grid, wind farms etc. An onshore power facility uses medium voltage (6-20 kV) for most of its micro grid. The cables from Elektroskandia were therefore seen as more than sufficient. Only its material distribution regarding copper, aluminium and polyethylene was used in conjunction with this LCA.

ABB frequency converter 6080/6000 product family
The frequency converter derived from ABB stems from the 6080/6000 product family. The ACS6080 was ultimately chosen due to its higher performance in industrial operations compared to its predecessor ACS6000. Its range in power also played a major role in its choosing. The ACS6080 has a power range from 5 to 36 MW, making it more than sufficient for the use in OPS applications. The material distribution of Aluminium, Polyethylene, Copper and Steel was derived from ACS6080

3.3 Documentation of the emissions from stage 1: Production

This sub-chapter provides the reader with the emissions from material production and its energy consumption.

3.3.1 Steel

The alloy of iron, steel, is used in almost every aspect of the OPS facility. Most of the components include composites of steel, or other steel types such as stainless steel. The total amount of steel that flows into the assessed part of the OPS system amounts to 206.010 kg or 206 tonnes of steel. The steel is subdivided into generic steel, structural steel, reinforcement steel, stainless steel and engineering steel, with generic steel representing the biggest share. Due to so many different steel types, production methods and the difference in place of origin, emissions from steel production can vary. The following table presents the different types of steel and their respective emissions per kg steel produced and the emissions from energy consumption. Please note that the table on emissions from energy consumption includes another EPD not included in the table for emissions from production. The EPD of Cold-rolled coils & plates have been included as there is a lack of information regarding energy consumption of stainless steel and its respective emissions. The EPD has been chosen based on its emissions from production, as they are very similar to those of stainless steel.

Table 10 The table summarizes all steel types used in the assessment and their respective emission factors for production and energy consumption per 1 kg steel.

Steel type	Emissions per kg steel (production)	Unit	Source
Generic Steel (GER)	1,76	kg CO_2eq.	(Öko-Institut, 2020)
Structural Steel (NOR)	1,2068	kg CO_2eq.	(Norsk Stål, 2020a)
Reinforcement Steel (NOR)	0,4542	kg CO_2eq.	(Norsk Stål, 2021)
Stainless Steel (CN)	2,62	kg CO_2eq.	(Walnum, 2020)
Engineering Steel (CN)	1,4	kg CO_2eq.	(Walnum, 2020)
Steel type	**Emissions per kg steel (energy consumption)**	Unit	**Source**
Cold-rolled coils & plates in stainless steel (NOR)	0,50	kg CO_2eq.	(Norsk Stål, 2020b)
Generic Steel (GER)	0,0054	kg CO_2eq.	(Öko-Institut, 2020)
Structural Steel (NOR)	0,2605	kg CO_2eq.	(Norsk Stål, 2020a)
Reinforcement Steel (NOR)	0,1878	kg CO_2eq.	(Norsk Stål, 2021)

The majority of materials are stemming from official databases, namely ProBas (Öko-Institut, 2020) and EPD Norge (Norsk Stål, 2020; Norsk Stål, 2021; Norsk Stål, 2020b), whilst Stainless Steel and Engineering Steel are a result of a study conducted by Walnum (2020) and obtained from Eco-Invent and a Chinese study on steel production from two Chinese steel mills.

Generic steel

Generic steel is the most used type of steel in the LCA. There had to be a steel type that could be used for all components as many of the components do not specify the materials used in their composition. Generic steel was sourced from ProBas and is found under the name of “MetallStahl-Oxygen-DE-2020”. Its denotation includes the method used to produce it, its origin and the year of production. We can therefore deduce that the generic steel used in this LCA Is an output of basic oxygen steelmaking and was produced in Germany in 2020.

As aforementioned generic steel represents a considerable portion of the LCA. The lack of composite data prompted the usage of a generic representation of steel, fit to be used whenever need be. Generic steel and its emissions factor were used in the calculations of the overall emission of both the transformer and frequency converter. Generic steel constituted 58 % and 49 % of the transformer and frequency converter respectively, resulting in a combined 218064 kg CO_2eq or 218 tonnes of CO_2eq.

The total emissions were first calculated as the total emissions for each of the components. Reference components for both the frequency converter and transformer were found in order to get a better idea as to how much steel was used in each component. The found steel share was then applied to the weight of the component resulting in 2205 kg steel for the frequency converter and 4060 kg for the transformer. Eventually the emission factor was multiplied with the found share in order to find the emissions caused by its production.

Furthermore, to assess the full range of emissions connected to the production process of steel, energy consumption was included as it could represent further emissions. The energy consumption of the material was accessible through ProBas, as well as the emission from the production of 1 TJ of energy for the German electricity mix. The energy consumption of the material was thereafter multiplied with the emissions from the production of 1 TJ, resulting in the emissions generated by the energy consumption of the production of 1 kg of generic steel. A full overview of the emissions related to generic steel can be viewed in table 12.

Table 11 The table summarizes the total emissions from generic steel used in the transformers and frequency converters, from the perspective of production and energy consumption of the materials produced .It also includes the electricity mixture applied for the calculation of emissions from energy consumption.

Material: **Steel**	**Component**	**Quantity (total)**	**Unit**	**Emissions (material production)**	**Unit**	**Emissions (energy consumption)**	**Unit**	**Energy-mix**
Generic Steel (DE)	24x Transformer	97 440	kg	171 494,4	kg CO_2eq	533,57	kg CO_2eq	German
	12x Frequency converter	26 460	kg	46 569,6	kg CO_2eq	144,89	kg CO_2eq	German

Structural and reinforcement steel

Both structural steel and reinforcement steel were sourced from EPD Norge and were applied for the sub-station building. Little to none of the materials used in the construction of the Sub-station building are known except for the quantites in concrete and steel used. Since generic steel does not represent structural steel, nor reinforcement steel, new data had to be found. ProBas was of little help in this regard as they only deliver information about primary materials which were not fabricated further into sub-products. The materials were therefore consequently found on EPD-Norge and chosen based on the field of usage. The structural steel used in the LCA is based upon a Norwegian environmental product declaration from *Norsk Stål* (Norwegian Steel), namely *Bjelker og Formstål*, translating directly into beams and form steel. The manufacturer Norwegian Steel also delivered the EPD for reinforcement steel, namely *Armeringsnett til bruk I betong*, translating to reinforcement for usage in concrete. The EPD of Beams and form steel was found to be adequate for the usage in the sub-station building since its primary usage was in bridge or building construction. The EPD for reinforcement steel, *Armeringsnett til bruk I betong*, was also found to be adequate as it is used in concrete. The EPDs, being LCAs in their cores, offered valuable information on the emissions per kg produced and the energy consumption per kg produced. The same calculations as used prior could therefore be replicated for both products, and the results can be viewed in table 5.

Table 12 This table summarizes the total emissions for the structural and reinforcement steel applied for the sub-station building. It includes the total emissions from the production of the materials and their energy consumption. Furthermore, the electricity mixture applied for the calculation of the emissions from energy consumption are also included.

Material: **Steel**	**Component**	**Quantity (total)**	**Unit**	**Emissions (material production)**	**Unit**	**Emissions (energy consumption)**	**Unit**	**Energy-mix**
Structural steel (NOR)	Sub-Station building	20 500	kg	24 739,4	kg CO_2eq	5 340,47	kg CO_2eq	Norwegian
Reinforcement steel (NOR)	Sub-Station building	500	kg	227,1	kg CO_2eq	93,94	kg CO_2eq	Norwegian

Stainless steel and Engineering steel

Stainless steel and engineering steel were sourced from Walnum (2020), which again had sourced his estimates from Eco-Invent and a Chinese LCA of the production of steel from two Chinese steel mills. Stainless steel and Engineering steel were used in the emission estimation for the steel containers used in the configuration of the OPS facility. The study conducted by Walnum (2020) looks at steel containers configurated as housing units, named NCL 20. These housing units are comprised of 34 % engineering steel and 16 % stainless steel. In comparison to a conventional steel container, this particular steel container includes electronic amenities, wood flooring and windows. A conventional steel container however includes none of those components. The steel content therefore needed upward adjustments. By assuming the same ratio between stainless steel and engineering steel as in NCL 20 , the steel content was adjusted to 65 % engineering steel and 32 % stainless steel. The remaining 3 % percent are other minor materials, such as plywood for flooring.

According to Walnum (2020) stainless steel emits 2,62 kg CO_2eq per kg steel produced, assuming the steel has been produced by oxygen steelmaking and stems from China. The emission factor for engineering steel was taken from eco-invent and correlates to 1,4 kg CO_2eq per kg steel produced. A full overview of the emissions connected to both steel types can be viewed in table 14. The table is supplemented with the emissions from energy consumption, although information on that was not available for the two steel types. Energy consumption was therefore based on other steel products/materials similar in emissions and characteristics. Engineering steel was based on generic steel from ProBas and stainless steel was based on an EPD from *Norsk Stål*, namely *Kaldvalsede plater og coils I rustfritt stål*, or engl. cold-rolled coils and plates in stainless steel.

Table 13 This table summarizes the total emissions from the stainless and engineering steel applied for the steel containers. It includes the total emissions from the production of the materials and their energy consumption. Furthermore, the electricity mixture applied for the calculation of the emissions from energy consumption are also included.

Material: Steel	Component	Quantity (total)	Unit	Emissions (material production)	Unit	Emissions (energy consumption)	Unit	Energy-mix
Stainless Steel	21 x Steel Containers	20 160	kg	52 819,2	kg CO_2eq	10 114,11	kg CO_2eq	Norwegian
Engineering Steel	21 x Steel Containers	40 950	kg	57 330	kg CO_2eq	224,23	kg CO_2eq	German

3.3.2 Aluminium

Aluminium is mainly used in electricity components such as the frequency converter and cables. The latter has much of its composition consisting of aluminium. The cables used in this LCA are delivered by Elektroskandia and consist of an aluminium core with an outer sheath of polyethylene. The emission factors regarding the aluminium used for both the frequency converters and cables assessed in the LCA was sourced from ProBas and can be viewed in table 15.

Table 14 The table summarizes all aluminium types used in the assessment and their respective emission factors for production and energy consumption per 1 kg Aluminium. It also includes a country code signalling its origin.

Aluminium type	Emissions per kg aluminium (production)	Unit	Source
Generic Aluminium (NOR)	11	kg CO_2eq	(Öko-Institut, 2020a)

Aluminium type	Emissions per kg Aluminium (energy consumption)	Unit	Source
Generic Aluminium (NOR)	0,8707812	kg CO_2eq	(Öko-Institut, 2020a)

Aluminium makes up 6 % of the frequency converter and conversely 42,82 % of the cables. The frequency converter is based on the composition of the ACS6080 and therefore follows its configuration in terms of material distribution. The cables follow the same material distribution specified by Elektroskandia in TSLF 24kV 3x1x240 AFR/35. A full overview of the emissions regarding the aluminium used can be viewed in table 16.

Table 15 This table summarizes the total emissions from the Generic Aluminium applied for the cables and frequency converter. It includes the total emissions from the production of the materials and their energy consumption. Furthermore, the electricity mixture used in the calculations of emissions from energy consumption is included.

Material: Aluminium	Component	Quantity (total)	Unit	Emissions (material production)	Unit	Emissions (energy consumption)	Unit	Energy-mix
Generic Aluminium	Frequency converter	3 240	kg	35 640	kg CO_2eq	2 821,33	kg CO_2eq	Norwegian
	Cables	10 700	kg	117 700	kg CO_2eq	9 317,35	kg CO_2eq	Norwegian

3.3.3 Concrete

The concrete used in this assessment is sourced from EPD-Norge and construed for the appliance in wall elements, pillars and other construction elements. The concrete is delivered as ready mixed concrete, or *Ferdigbetong* and is only used in conjunction with the sub-station building. Around 155 m^3, or approx. 373 000 kg of concrete are required for the construction of the sub-station building, making it one of the most emitting materials in this section of the LCA. A full overview regarding emissions in conjunction to the concrete used can be viewed in table 17.

Table 16 This table summarizes the total emissions from the production and energy consumption of the concrete used for the Sub-Station building. Furthermore, it includes the respective electricity mixture for the country of production.

Material: Concrete	Component	Quantity (total)	Unit	Emissions (material production)	Unit	Emissions (energy consumption)	Unit	Energy-mix

Concrete	Sub-Station building	155/373 000	m^3/kg	33 780	kg CO_2eq	4 966,76	kg CO_2eq	Norwegian

Table 17 This table presents the emissions factor for per m^3 concrete and also a country code signalling its origin.

Concrete type	Emissions per m^3 concrete(production)	Unit	Source
Ready mixed concrete (NOR) *Ferdigbetong*	217,935	kg CO_2eq	(Sola Betong, 2020)

3.3.4 Copper

The copper used in the LCA is sourced from ProBas and consists of secondary copper. Secondary copper is won out of primary products, e.g. copper, bronze, or brass scrap, but also clinker and slur containing copper residue. Every electrical component included in the LCA contains copper, with the transformer containing the most. Approximately 39 tonnes of copper have been used in the construction of the components. A full overview of the emissions linked to the production of copper can be viewed in table.

Table 18 This table summarizes the total emissions from the production and energy consumption of the secondary copper used for the Sub-Station building. Furthermore, it includes the respective electricity mixture for the country of production, which has been used in calculating the emissions from energy consumption.

Material: Copper	Component	Quantity (total)	Unit	Emissions (material production)	Unit	Emissions (energy consumption)	Unit	Energy-mix
Secondary Copper (DE)	Transformer	21 840	kg	38 875	kg CO_2eq	9 089,11	kg CO_2eq	German
	Cables	2 950	kg	5 251	kg CO_2eq	1 227,696	kg CO_2eq	German
	Frequency converter	14 580	kg	25 952	kg CO_2eq	6 067,73	kg CO_2eq	German

Table 19 This table presents the emissions factor for per kg secondary copper and also a country code signalling its origin.

Copper type	Emissions per kg concrete(production)	Unit	Source
MetallKupfer-DE-sekundär-2020	1,78	kg CO_2eq	(Öko-Institut, 2020b)

3.4 Documentation of the emissions from stage 2: Transport

Emissions from transport are assessed in all environmental product declarations used in the LCA. However, materials sourced from ProBas and Walnum (2020) do not include emissions from transport for the desired production and installation site. ProBas does not include transportation as it only considers the production of the product. Emissions from transport were therefore assessed manually by using predefined factors for fuel consumption, conversion factors and process data from ProBas for diesel. The calculating of shipping emissions from Shanghai to Hamburg was made possible with the emission factors obtained from Andersen et al. (2010).

Kommentert [CF1]: Må se på en gang til, tallene er fra 2010

Generic steel example

As generic steel was obtained from ProBas, no transport emissions were included for the distance between the place of production and the place of installation. Hence a place of production needed to be selected in addition to the mode of transport. The choice of production site and producer fell on Duisburg and ThyssenKrupp. The steel would be transported by road using a lorry with a load capacity of 40 tonnes. The distance from the site of production to the site of installation was calculated to 1752 km, spanning over four countries, namely Germany, Denmark, Sweden and Norway. The capacity utilization of the lorry was set to 60 %, which is the prevalent default value for trucks with a load capacity of 40 tonnes.

Generic steel constitutes 123 900 kg of material that needs to be transported to Bergen, as such four lorries are needed. Three of them will be fully loaded with steel (40 tonnes), whilst one will transport the remainder of the materials (3,9 tonnes). With the distance and load defined one can calculate the tonne-km, abbreviated as tkm. The Tonne-km is a unit of measure for freight transport and is defined as transport of one tonne of goods, by the given transport mode over a distance of one kilometre. The tonne-km is calculated by multiplying distance by freight weight.

Equation 1:

$$1\ 886\ km\ \times 40\ tonnes = 75\ 440\ tonne - km\ (or\ tkm)$$

The obtained 75440 tonne-km can then be used to make other calculations. In order to obtain the emissions factor of a typical 50-60 tonne diesel truck one first must find the energy used to produce one litre generic diesel and the CO_2 content of the latter. Generic diesel was sourced from ProBas and the kwh per litre for diesel from Well to Wheel was calculated to 13,8316 kWh/litre. Said energy consumption per litre diesel was obtained from dividing the energy consumption of 1 TJ of diesel by the litre content of 1 TJ of diesel.

Equation 1: Showing the process of calculating the energy consumption in MJ per litre diesel.

$$\frac{1\ 290\ 000\ MJ}{25\ 906{,}735\ litres} = 49{,}79\ MJ/litre$$

The obtained 49,79 MJ per litre diesel can then be converted to kWh per litre diesel by applying the conversion factor of 3,6 for the conversion of MJ to kWh.

Equation 2: The energy consumption per in kWh per litre diesel.

$$\frac{49{,}79\ MJ}{3{,}6} = 13{,}83\ kWh/litre$$

The calculated 13,83 kWh/litre is the energy consumption of one litre diesel from Well to Wheel. The CO_2-eq content per litre diesel can be found by dividing the CO_2-eq of 1 TJ diesel by the litres of diesel contained in one TJ diesel.

Equation 3: The emissions per litre diesel produced.

$$\frac{21\ 345\ kg\ CO_2 - eq}{25\ 906{,}\ 735\ litres/TJ} = 0{,}823\ kg\ CO_2 - eq/litre$$

The found emissions per litre diesel can then multiplied by kWh/litre to find the emission per kWh.

Equation 4: The emissions per kWh used.

$$0{,}823\ kg\ CO_2 - eq \times \frac{1}{13{,}83\frac{kWh}{litre}} = 0{,}059\ kg\ CO_2 - eq/kWh$$

By using the average consumption values of a lorry with a weight limit of 24-40 tonnes per tonne-km given by Clecat (2014) and multiplying it with kWh/litre diesel one receives kWh/tonne-km, well-to-wheel.

Equation 5: The kWh per tonne-km driven.

$$0{,}023\ litre/tkm \times 13{,}83\ kWh/litre = 0{,}3181\ kWh/tkm$$

The kWh/tonne-km is then multiplied with the preceding kgCO₂eq/kWh in order to obtain the emission per tkm, Well-to-tank.

Equation 6: The emission per tonne-km driven.

$$0{,}059\ kg\ CO_2/kWh\ \times 0{,}3181\ kWh/tkm = 0{,}0189\ kgCO_2eq/tkm$$

What remains is the emissions per tkm for tank to wheel. First, one must find the emissions per kWh. By multiplying the energy consumption of one litre diesel for tank to wheel with the emissions contained in 1 litre diesel we obtain emissions per kWh for tank to wheel. The energy consumption of one litre diesel, tank to wheel, is easily found by dividing the energy content of 1 litre diesel by the conversion factor 3,6 for MJ to kWh conversion.

Equation 7: kWh content per litre diesel.

$$\frac{38MJ}{3{,}6} = 10{,}722\frac{kWh}{litre}$$

Now that the energy consumption for tank to wheel Is calculated, we can obtain the beforementioned emissions per kWh for tank to wheel.

Equation 8: The emissions per kWh from diesel.

$$\frac{2{,}64\ kgCO_2eq/litre}{10{,}72\ kWh/litre} = \ 0{,}2462\ kgCO_2eq/kWh$$

The calculated kgCO₂eq/kWh, tank to wheel, is then multiplied with the already calculated kWh/tkm in order to obtain kg CO₂eq/tkm,tank to wheel.

Equation 9: The emissions per tkm from diesel, tank-to-wheel.

$$0{,}2462176\ kgCO_2eq \times 0{,}3181\ kWh/tkm = 0{,}0783\ kgCO_2eq/tkm$$

Now that one possesses both emissions for tank to wheel and well to tank, the emissions for Well to wheel can be calculated by adding the two together.

Equation 10: The emissions from Well-to-tank and Well-to-wheel added together.

$$0{,}0189\ kgCO_2eq/tkm + 0{,}0783\ kgCO_2eq/tkm = 0{,}0972\ kgCO_2eq/tkm$$

The emissions factor can then be multiplied with the tkm of a specific material, resulting in the overall emissions of the transport of that material.

Equation 3: The emissions per litre diesel produced

$$75\,440\ tkm\ (Generic\ Steel) \times 0{,}0972 \frac{kgCO_2eq}{tkm} = 7338{,}719\ kgCO_2eq$$

The calculating of emissions was also necessary for the materials of copper, polyethylene and aluminium, as they all were sourced from ProBas. The parameters remained mostly the same, except for the distance from production site to installation site, the place of production, load weight and consequently tonne-km. Copper for instance was based in Hamburg, and is produced by Aurubis AG, whilst polyethylene is based in Aachen and produced by W. Köpp GmbH & Co. KG. The aluminium was of Norwegian origin and therefore based in Øvre Årdal and produced by Hydro Aluminium. The steel that was used for the steel containers was initially sourced from Walnum (2020) and therefore needed calculations regarding the transport emissions as it was stemming from China.

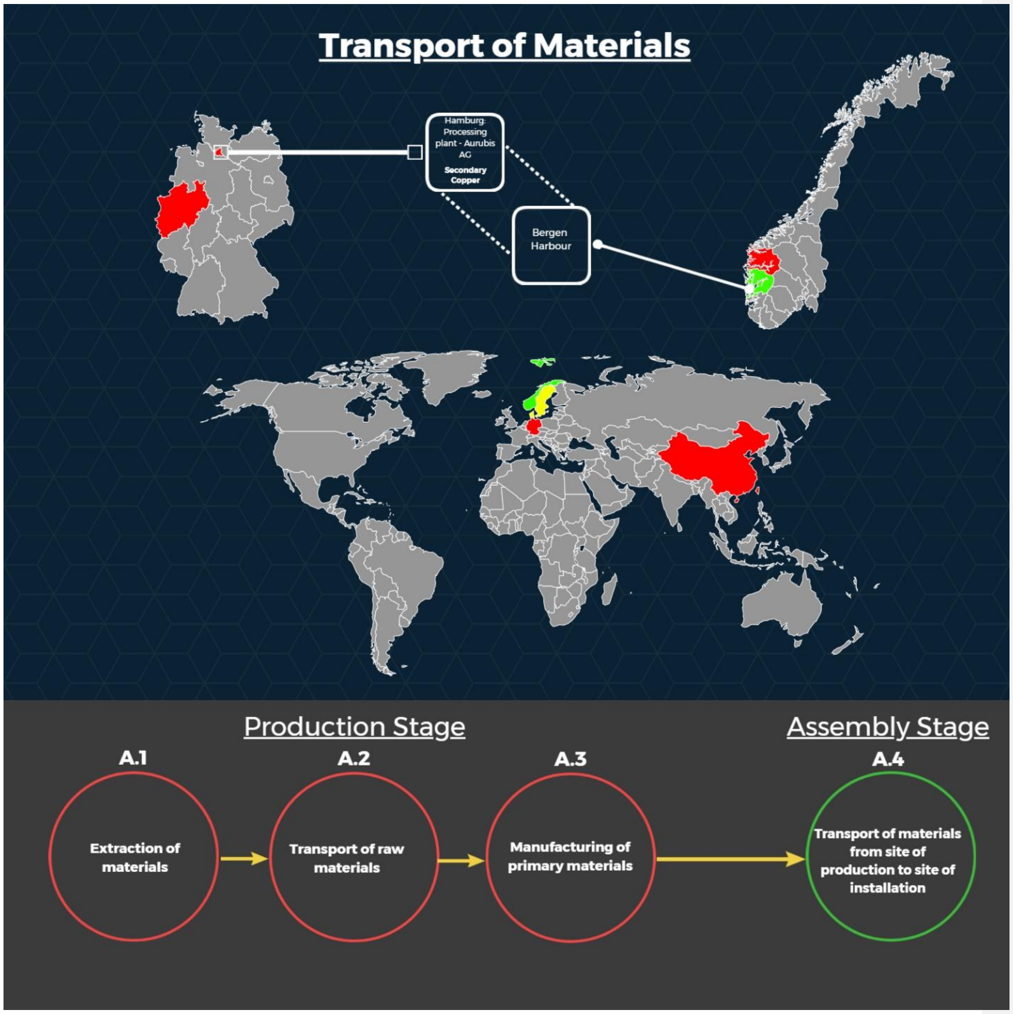


Figure 14: This graphic visualizes the transport of materials. The colour red marks the site of production or origin of the material, yellow marks transit countries and countries/counties marked in green represent the site of installation or material destination. Below, a flowchart presents the different modules in the production stage (red) and assembly stage (green), that are connected to the figure above.

3.5 Documentation of the emissions from stage 3: Usage

This sub-chapter documents the emissions from stage 3, Usage. It presents the electricity usage of the facility and the appertaining emissions that emerge from it. Furthermore, it looks at the total emission from the cruise year of 2017 and a single ship scenario. The single ship scenario uses the AIDASol as the reference ship as it Is known for having the needed capabilities for shore power.

3.5.1 Assumptions and necessary groundwork

The calculation of the emissions connected to the facilities usage can only be calculated with certain presumptions in place regarding utilization, energy and port specifics. The LCA assumes the average laytime and power generation of the cruise ships at berth to resemble the average laytime and power generation calculated from the dataset obtained from the AIS database used in this thesis, which can be accessed in the appendix. Additionally, the emissions per kWh consumption for the Norwegian electricity mixture were sourced from EPD-Norge as it includes the production/construction of transmission lines, in addition to direct emissions and losses.

Furthermore, estimates on how many ships are able to connect to OPS infrastructure were needed, which required an analysis of the global cruise fleet. Subsequently two estimates were created, namely a lower and higher estimate. In total 18 out of 33 cruise lines were analysed. The cruise lines analysed included only major players of the cruise industry such as Royal Caribbean International, Carnival Cruise Lines and MSC Cruises. Smaller cruise lines were left out due to time limitations.

3.5.2 Energy usage of the facility

The energy usage of the facility is given by the amount of cruise ships at berth and their respective energy usage. In total 78 unique cruise ships berthed at Bergen Harbour in 2017 with 291 calls. Their power demand was covered by inhouse power generation and amounted to 19,17 GWh or 69,012 TJ. The emissions are calculated from the energy usage of the facility, which is a product of energy demand from cruise ships. The electricity mixture in Norway is a result of several energy carriers and according to Eco-Invent causes approx. 8806 kg CO_2eq./TJ or 0,0317 kg CO_2eqv./kWh. The emissions caused by the facility are calculated by multiplying the emissions caused by the electricity mixture with the total power generation of the cruise ships at berth. Those emissions aggregate to 607,689 tonnes CO_2eqv. for the cruise year 2017.

The total power usage and associated emissions over the span of 20 years, i.e., the lifetime/time horizon of the facility/LCA, has been found by replicating the composition of cruise ships from 2017 and its respective energy usage over the span of 20 year. Hence, the total power output amounts to 383,4 GWh or 20 times the power generation of 2017 (19,17 GWh). With the emissions per kWh for the Norwegian electricity mix in mind, the facility causes 12153780 kg CO_2eqv or 12153 tonnes CO_2eqv. The emissions caused are based on two assumptions. Firstly, that every ship is apprehended, and secondly that every ship is outfitted with the necessary equipment to receive shore power. However, these assumptions do not mirror reality, and rather represent an ideal scenario. For that reason, a more representative sample had to be created. In order to assess the usage of the facility one needs estimates on how many ships can receive shore power. A total of 18 cruise lines representing 193 cruise ships were analysed, representing approximately 70 % of the global cruise fleet, which amounts to roughly 271 ships in total. Approximately 74 of these ships are outfitted with the necessary equipment to receive shore power and 25 of these utilize shore power actively. The 25 ships that are utilizing shore power actively will serve as the lower estimate, whilst the total number of "plug-in" ready cruise ships, amounting to 75 ships, will serve as the higher estimate. The average laytime for a cruise ship at berth in Bergen Harbour amounts to 12 hours minus an hour for connection and disconnection procedures, thus the laytime amounts to 11 hours on average. The total power production onboard calculates to 0,060386598 GWh on average or 0,005 GWh per hour laytime, if adjusted for connection and disconnection procedures. Hence the total power output of the facility for the supplementation of 25 cruise ships needs to cover 1,50 GWh over the course of one year (2017). Thus, over the span of 20 years the facility must cover an energy demand of 30,19 GWh, which is approximately 1 207 731,95 kWh per ship. Thus, with the emissions from the electricity mixture in mind, every ship produces 38 285,10 kg CO_2eq. in terms of emissions during the lifetime of the facility. Hence the total emissions for 25 cruise ships over a period of 20 years amount to approx. 957 127,57 kg CO_2eq. or 957,12 tonnes CO_2eqv.

Assuming all 74 "plug-in" ready cruise ships utilize shore power, energy demand increases to 90,57 GWh for the lifetime of the facility. This can be likened to the average annual energy consumption of 5663 norwegian households with a total of 16 000 kWh per household (Statistisk sentralbyrå, 2018). Ultimately, emissions rise in conjunction with energy demand and reach 2871,38 tonnes CO_2eqv. Both the lower and higher estimate are possible future scenarios as more cruise lines and port cities invest in green technology.

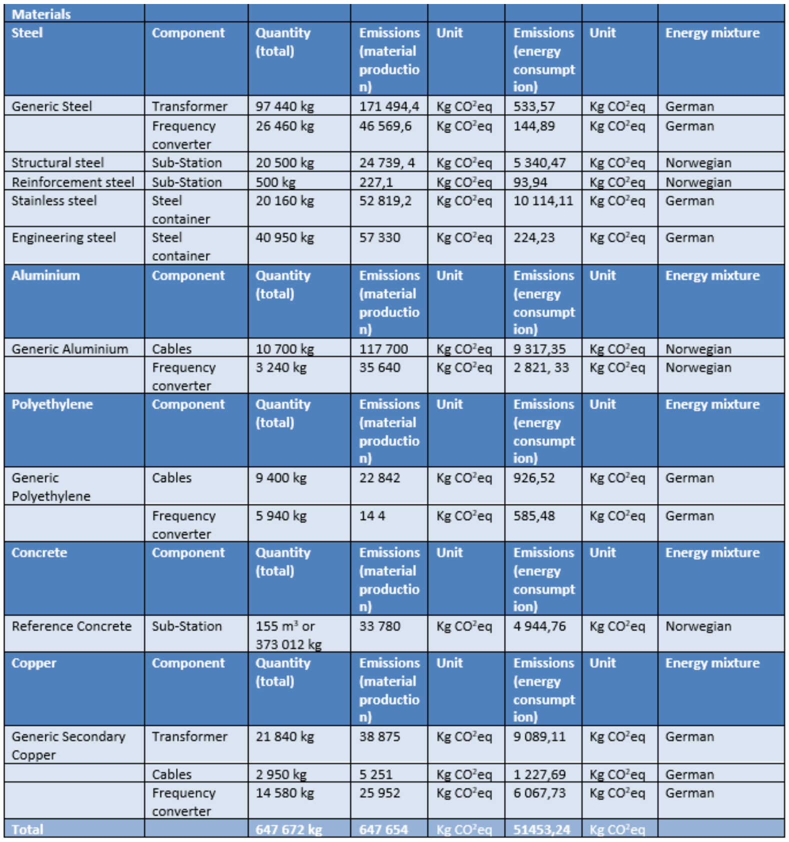
Kommentert [CF2]:

With initiatives such as Green Ports promoting sustainability and national/international policies limiting the use of certain fuels, green technologies such as OPS or LNG are indirectly furthered and consequently implemented by various Cruise lines and Port authorities worldwide. Supply and demand are key to efficient usage of an OPS facility. Firstly, ships need to come with the necessary equipment preinstalled or retrofitted, and secondly ports/port cities need to construct the necessary facilities. The one cannot exist without the other. As previously mentioned, 74 ships have been found to be capable of receiving shore power. However, only 25 out of 74 do so actively as they call at ports offering OPS. That is a mere 13 % of the ships assessed from the 18 cruise lines 193 ships, and less than 10 % of the global cruise fleet amounting to 271 cruise ships.

3.6 Full indirect emissions from stage 1,2 & 3: Production, Transport and Usage

The full indirect emissions from the production of materials,transport of the latter and the indirect emissions associated with the usage of the facility are summarized in table 20, 21 and 22 respectively. Table 20 includes every material hither assessed and their respective emissions. Additionally, the emissions from production and energy consumption of the materials are summed up. Table 21 presents the transport emissions from the materials sourced from ProBas and Walnum (2020). Finally, the tables of 22 & 23 summarize the indirect emissions from the usage of the facility in Bergen Harbour.

Table 20: The full indirect emissions from the production and power consumption of materials used in the construction of the reference facility in Bergen. Not every material has been assessed in this LCA. This list represents the materials that were seen as most important in the process of implementation.



Materials							
Steel	**Component**	**Quantity (total)**	**Emissions (material production)**	**Unit**	**Emissions (energy consumption)**	**Unit**	**Energy mixture**
Generic Steel	Transformer	97 440 kg	171 494,4	Kg CO^{2}eq	533,57	Kg CO^{2}eq	German
	Frequency converter	26 460 kg	46 569,6	Kg CO^{2}eq	144,89	Kg CO^{2}eq	German
Structural steel	Sub-Station	20 500 kg	24 739, 4	Kg CO^{2}eq	5 340,47	Kg CO^{2}eq	Norwegian
Reinforcement steel	Sub-Station	500 kg	227,1	Kg CO^{2}eq	93,94	Kg CO^{2}eq	Norwegian
Stainless steel	Steel container	20 160 kg	52 819,2	Kg CO^{2}eq	10 114,11	Kg CO^{2}eq	German
Engineering steel	Steel container	40 950 kg	57 330	Kg CO^{2}eq	224,23	Kg CO^{2}eq	German
Aluminium	**Component**	**Quantity (total)**	**Emissions (material production)**	**Unit**	**Emissions (energy consumption)**	**Unit**	**Energy mixture**
Generic Aluminium	Cables	10 700 kg	117 700	Kg CO^{2}eq	9 317,35	Kg CO^{2}eq	Norwegian
	Frequency converter	3 240 kg	35 640	Kg CO^{2}eq	2 821, 33	Kg CO^{2}eq	Norwegian
Polyethylene	**Component**	**Quantity (total)**	**Emissions (material production)**	**Unit**	**Emissions (energy consumption)**	**Unit**	**Energy mixture**
Generic Polyethylene	Cables	9 400 kg	22 842	Kg CO^{2}eq	926,52	Kg CO^{2}eq	German
	Frequency converter	5 940 kg	14 4	Kg CO^{2}eq	585,48	Kg CO^{2}eq	German
Concrete	**Component**	**Quantity (total)**	**Emissions (material production)**	**Unit**	**Emissions (energy consumption)**	**Unit**	**Energy mixture**
Reference Concrete	Sub-Station	155 m^3 or 373 012 kg	33 780	Kg CO^{2}eq	4 944,76	Kg CO^{2}eq	Norwegian
Copper	**Component**	**Quantity (total)**	**Emissions (material production)**	**Unit**	**Emissions (energy consumption)**	**Unit**	**Energy mixture**
Generic Secondary Copper	Transformer	21 840 kg	38 875	Kg CO^{2}eq	9 089,11	Kg CO^{2}eq	German
	Cables	2 950 kg	5 251	Kg CO^{2}eq	1 227,69	Kg CO^{2}eq	German
	Frequency converter	14 580 kg	25 952	Kg CO^{2}eq	6 067,73	Kg CO^{2}eq	German
Total		**647 672 kg**	**647 654**	**Kg CO^{2}eq**	**51453,24**	**Kg CO^{2}eq**	

Table 21: The direct emissions from transport of the materials. The table includes the transport of steel, cobber and polyethylene from the German production sites. It further includes the materials of Aluminium and Stainless & Reinforcement steel from the Norwegian and Chinese production site. All materials are ground shipped, except the materials of Chinese origin which are shipped by a combination of maritime shipping and ground shipping.

Transport emissions			
Generic steel (GER)			
Tours	**Distance**	**Weight**	**Emissions in tonnes CO_2eq.**
#1	1 886 km	40 tonnes	7,33
#2	1 886 km	40 tonnes	7,33
#3	1 886 km	40 tonnes	7,33
#4	1 886 km	3,9 tonnes	0,71
Copper (GER)			
Tours	**Distance**	**Weight**	**Emissions in tonnes CO_2eq.**
#1	1 540 km	39,37 tonnes	5,89
Polyethylene (GER)			
Tours	**Distance**	**Weight**	**Emissions in tonnes CO_2eq.**
#1	1 998 km	15,34 tonnes	2,98
Aluminium (NOR)			
Tours	**Distance**	**Weight**	**Emissions in tonnes CO_2eq.**
#1	250 km	13,94 tonnes	0,33
Stainless & Reinforcement Steel (CH)			
Tours	**Total Distance (ship & truck)**	**Weight**	**Emissions in tonnes CO_2eq.**
#1	24 270 km	21 tonnes	13,12

Table 22: The lower estimate for the usage of OPS at Bergen Harbour. The power generation is simultaneously the energy demand which needs to be covered by the facility. The emissions have been calculated using emission factors from Eco-Invent for the Norwegian electricity mix. Furthermore, average laytime has been calculated from available AIS data from 2017 and is adjusted for connection and disconnection procedures. The average power generation is also taken from the AIS database.

Lower Estimate	Quantities	Unit
Ships apprehended	25	ships
Average laytime per ship	11	hours
Average power generation per ship	0,060	GWh
Power generation per year (kWh)	1 509 664,94	kWh
Total power generation (kWh)	30 193 298,97	kWh
Emissions (1 year)	47 856,37	kg CO2eqv.
Emissions (20 years)	957 127,57	kg CO2eqv.

Table 23: The higher estimate for the usage of OPS at Bergen Harbour. The power generation is simultaneously the energy demand which needs to be covered by the facility. The emissions have been calculated using emission factors from Eco-Invent for the Norwegian electricity mix. Furthermore, average laytime has been calculated from available AIS data from 2017 and is adjusted for connection and disconnection procedures. The average power generation is also taken from the AIS database.

Higher Estimate	Quantities	Unit
Ships apprehended	75	ships
Average laytime per ship	11	hours
Average power generation per ship	0,060386598	GWh
Power generation per year (kWh)	4 528 994,845	kWh
Total power generation (kWh)	90 579 896,91	kWh
Emissions (1 year)	143 569,1366	kg CO2eqv.
Emissions (20 years)	2 871 382,732	kg CO2eqv.

3.7 Sensitivity Analysis

A sensitivity analysis can help in analysing how a target variable, for example total direct emissions from material production, are affected by changes in other variables, so called input variables. Furthermore, it can reveal which input variable has the biggest impact on the target variable. A sensitivity analysis can also be called a “What-if?” scenario. What if we changed Generic Aluminium from Norway to its high-quality counterpart from Norwegian Hydro, a company widely known for its production quality? Would the target variable experience any significant changes?

A sensitivity analysis is assistive in the uncovering of mistakes. It can be of help in determining better choices for input variables, e.g. for aluminium. The input variables that were chosen for this LCA were chosen without much hesitation which could have both good and bad. Therefore, better choices were likely not taken into consideration. This sensitivity analysis therefore tries to exchange some of the materials for copper, aluminium and steel with other variants to see if there are any significant changes to the overall indirect emissions from the production stage. Additionally, the electricity mixture for stage 3: Usage will be exchanged for other mixture from other countries to see if changes can be caused by mixture at hand.

3.7.1 Changes for Stage 1: Production of materials

Steel

Various steel types have been used in the LCA, namely stainless steel, engineering steel, construction steel and so on. Generic steel has been the most used form of steel with 123 900 kg, used in the construction of the transformers and frequency converters. Generic steel was sourced from ProBas under the name of *MetallStahl-Oxygen-DE-2020*. The emissions per kg steel produced are 1,76 kg CO_2eqv. Generic steel could potentially be replaced by two other steel variants, both derived from ProBas. *MetallStahl-mix-DE-2020* as well as *MetallStahl-Elektro-DE-2020* are situated below MetallStahl-Oxygen-DE-2020 in terms of CO_2 emissions per kg steel. *MetallStahl-mix-DE-2020* is a mixture of 20 percent electro steel and 80 percent oxygen steel. The 20 % percent electro steel decreases emissions from 1,76 to 1,5, which can be considered a relatively small reduction. The *MetallStahl-Elektro-DE-2020* however reduces emissions per kg substantially. With just 0,0397 kg CO_2eqv. per kg steel it has the least emissions per kg steel in comparison to the two other steel variants. *MetallStahl-Elektro-DE-2020* is pure steel, however scrap steel has been used in its production. Hence *MetallStahl-Elektro-DE-2020* is made from recycled steel, and thus does not include any emissions, except from its production.

If generic steel is exchanged with electro steel, overall emissions are reduced from a combined 218 tonnes of CO_2eqv. for the transformers and frequency converters, to approx. 4,91 tonnes of CO_2eqv. Conversely emissions from energy consumption are increased, from approx. 0,678 tonnes of CO_2eqv. to approx. 19,53 tonnes of CO_2eqv.

Copper

There were not found any improvements to the materials already in use. The copper variant MetallKupfer-DE-sekundär-2020 is produced from secondary copper sources, such as scrap, or other residue sources such as cinder, sludge or skimming. Hence the emissions per kg fall relatively short, with just 1,78 kg per kg copper including the upstream supply chain.

Aluminium

The production of the aluminium product "Hydro aluminium Holmestrand Circal rolled product 95", 95 indicating the content of 95 % post-consumer scrap, is particularly less emission intensive than its counterpart from ProBas which is of primary origin. With just 1,41 kg CO_2eqv. per kg aluminium, emissions are considerably reduced in relation to primary aluminium obtained from ProBas with 11 kg CO_2eqv. per kg aluminium. This is due to the aluminium originating from ProBas being of primary production, i.e., the aluminium is derived from bauxite and includes an array of upstream processes, such as extraction, transport etc, whilst the aluminium from Hydro is a recycled product from scrap metal. Most of the energy/emission intensive modules, such as resource extraction, transportation and manufacturing have already been realised in the preceding primary product.

3.7.2 Changes in Stage 3: Usage - electricity mixture

The composition of the electricity mixture is crucial for the estimation of reduction potential. A fully renewable energy source will produce far less emissions than a fully or partly fossil based energy source. What difference would the electricity mix make? This sub-chapter will present three different electricity mixtures and their effect on overall emissions from the usage of the facility. The electricity mixtures examined are the Swedish and Danish electricity mixture derived from EPD-Norge and the Finnish and the Latvian electricity mixture also sourced from EPD-Norge. The unchanged total emissions for the usage of the facility are 957 tonnes CO_2eqv. for the lower estimate (25 ships) and 2871 tonnes CO_2eqv. for the higher estimate (75 ships).

The Finnish electricity mixture

The electricity mixture in Finland is made from renewable energy, nuclear energy and fossil and peat energy sources. According to Mincon Nordic Oy (2020) the emissions per kWh amount to approx. 237 gram or 0,237 kg CO_2eqv. /kWh, with the production of transmissions lines, in addition to direct emissions and losses of the grid accounted for. If the shore power facilities in Bergen would draw energy from the Finnish grid instead of the Norwegian grid, total emissions from the lifetime of the facility would increase to 7155 tonnes CO_2eqv. for the lower estimate and 21467 tonnes CO_2eqv. for the higher estimate.

The Danish electricity mixture

The electricity mixture in Denmark is made from coal, renewable energy sources and import of electricity in form of nuclear and hydroelectricity. According to CSK Stålindustri A/S (2021) the emissions per kWh amount to approx. 359 gram or 0,359 kg CO_2eqv./kWh, with the production of transmissions lines, in addition to direct emissions and losses of the grid accounted for. If the shore power facilities in Bergen would draw energy from the Danish grid instead of the Norwegian grid, total emissions from the lifetime of the facility would increase to 10839 tonnes CO_2eqv. for the lower estimate and 32518 tonnes CO_2eqv. for the higher estimate.

The Latvian electricity mixture

The electricity mixture in Latvia is made out of fossil based energy source, wind and hydroelectricity According to CSK Stålindustri A/S (2021) the emissions per kWh amount to approx. 604 gram or 0,604 kg CO_2eqv./kWh, with the production of transmissions lines, in addition to direct emissions and losses of the grid accounted for. If the shore power facilities in Bergen would draw energy from the Latvian grid instead of the Norwegian grid,total emissions from the lifetime of the facility would increase drastically to around 18236 tonnes CO_2eqv. for the lower estimate and 54710 tonnes CO_2eqv. for the higher estimate.

The EU-27 electricity mixture

The average electricity mixture in the EU produces on average 255 grams or 0,255 kg CO_2eqv./kWh (European Environment Agency, 2021). If we applied the electricity mixture of the EU-27 instead of the Norwegian electricity mix to the shore power facility, total emissions from the lifetime of the facility would increase to 7699 tonnes CO_2eqv. for the lower estimate and 23097 tonnes CO_2eqv. for the higher estimate.

3.8 Shore power as climate mitigation technology and technology for air quality improvement

In this sub-chapter the shore power facility hither assessed will be looked at from different perspectives, namely that of climate change mitigation and air quality improvement.

3.8.1 Emissions reduction potential

An overview of indirect and direct emissions is key to quantifying the reduction potential of OPS. The analysis of the production of materials, transportation and usage of the facility, along with the assessment of direct emissions from visiting cruise ships has provided such an overview. The emissions from the production and transportation of materials used in the facility amounted to 734,189 tonnes CO_2eqv. The emissions connected to the usage of the facility are given by the number of cruise ships actively drawing energy from onshore. To assess the emissions connected to the usage of the facility a lower and higher estimate of OPS usage was created. The lower estimate, with 25 cruise ships making use of OPS, amounts to 957,12 tonnes of CO_2eqv. The higher estimate, with 75 ships drawing energy, turns out higher with 2871,38 tonnes of CO_2eqv. The lower estimate stands as more realistic as it represents the cruise ships actively utilizing shore power out of the 193 ships analysed prior to the LCA.

The direct emissions from cruise ships calling at port in Bergen were calculated to 11570 tonnes of CO_2 for the year 2017 for a total of 78 cruise ships and 291 calls. The reduction potential of OPS is manyfold as it includes CO_2, NO_X, SO_X, and PM. However, only CO_2 is of present value as most of the data obtained is expressed in CO_2 or equivalents of the latter. The reduction potential is depended on the energy source. According to Schnabel & Beiersdorf (2018) a reduction of up to 77 % on average is achievable. Schnabel & Beiersdorf (2018) further elaborate that CO_2, PM and SO_x could be reduced by

71 %, whilst NO_x experiences a reduction of up-to 89 %. However, these reductions are seen in comparison to the usage of MDO/MGO and depend heavily on electricity mixture, which in this case is of German origin (Schnabel & Beiersdorf, 2018). The C40 World ports association has also released estimates regarding reduction potential, which ultimately have yielded higher results. According to C40 Cities (2008), the emissions caused by cruise ships at berth can be reduced by up-to 96 % if compared to residual oil with a sulphur content of 2,7 %, or 70 % if compared to 0,1 % sulphur Marine distillate oil. The estimate received from C40 however excludes CO_2 (C40 Cities, 2008).

The Norwegian electricity mixture causes 31,17 grams of CO_2eqv. /kWh, whilst marine diesel oil causes 270 grams of CO_2eqv. /kWh. This is approx. a 90 % reduction from using marine diesel oil. The thesis therefore assumes a approx. 90 % reduction for CO_2 when connected to shore power, based on the difference in energy content, and thus emissions, between marine diesel oil and the Norwegian electricity mixture. The reduction potential for other emissions such as PM, NO_x and SO_x are averaged from the estimates of both Schnabel & Beiersdorf and C40. The final reduction estimates are visualized in figure 16.

Figure 15: The emissions reduction estimates for CO2, SOx, NOx and PM from the usage of OPS in port cities such as Bergen.

With a reduction potential of 90 percent applied to the 78 cruise ships and 291 calls in 2017, emissions could have been reduced by 10413 tonnes CO_2eqv or 3426 Norwegian cars driving the average mileage of 11152 km for the year 2020 (Statistisk Sentralbyrå, 2021).This reduction would however purport a 90 percent usage of the facility, meaning a considerable portion of cruise ships need to own the ability and have the willingness to receive shore power, which is not the case to date. The lower estimate which was previously presented was deemed a better fit as it was regarded as more feasible. However, the emissions from the lower estimates cruise ships are not available. Hence, a reference was needed. The newly build MSC Virtuosa was deemed an excellent choice as it featured state of the art technology and integrated much of the newest environmental technologies, which are presumably going to represent the future standard in cruise tourism in the coming years. The MSC Virtuosa is equipped with the latest green technology, such as shore power equipment, wastewater management etc. However, its weight class is situated near the upper limit with 181541 tonnes, which is higher than all other ships that berthed in Bergen in 2017. The CO_2 emissions reflect its apparent heavy weight with 9,94 tonnes of CO_2 per hour stay, with a total of 109,35 CO_2eqv for 11 hours laytime (adjusted for connection and disconnection procedures). Hence if 25 cruise ships, resembling the MSC Virtuosa, would call at Bergen for a 11 hour stay each in 2017, emissions would total 2733,77 tonnes of CO_2. Assuming the same ship types persists over the course of the lifetime of the facility, i.e. 20 years, emissions reach 54675,52 tonnes of CO_2.

With a reduction potential of 90 percent, these emissions would become strongly reduced, leaving only a small portion of the former CO_2 as leftover. Conversely the emissions from the energy usage of the facility, the indirect emissions associated with the implementation of the latter and the direct emissions from the cruise ships not able to receive shore power are unaffected. The reduction of PM, NO_x and so on will be covered in the following chapter about air quality.

3.8.2 Air quality, what-if scenario

Air quality is of high importance in ports and port cities, representing the top environmental priority for European ports in 2020 and highly probable for the years to come. Cruise ships emit high amounts of PM,SO_x and NO_x, which are highly affecting on human health and can cause lung cancer and cardiovascular diseases amongst other diseases.

Assuming every ship that was berthed in Bergen in 2017 had the necessary connectors, breakers, cubicles etc. to receive shore power. Which emission reductions could be achieved in terms of PM,SO_x and NO_x ? In total 78 cruise ships and 291 calls would need their energy demand covered. The emission reduction achieved in one year and for the lifetime of the facility can be viewed in table 25. However, the fact that every cruise ship will be able to receive shore power is a generous estimate. The following two sub-chapters discuss other more feasible outcomes and scenarios based on two reference cruise ships, namely the AIDASol and MSC Virtuosa.

Table 24: The reductions if every ship in 2017 would use OPS actively.

Cruise year	Emissions reductions for CO^2	Emissions reductions for SO_x	Emissions reductions for NO_x	Emissions reductions for PM	Total Reductions	Unit
2017	11 570	4,615	183,45	2,9432	11761,01	tonnes
Total (x20)	321 400	92,3	3 669,11	58,864	235 220,27	tonnes

3.8.3 Air quality, AIDAsol

Onshore power supply is first and foremost a technical solution for the betterment of air quality in ports and port cities. By applying the reductions visualized in figure 19, air pollution could be substantially reduced, assuming the offer of shore power is frequented. The AIDASol, a common user of OPS in the port of Altona, Hamburg, and thus also a potential user of OPS in Bergen, can be looked at as most fitting for the calculation of emission reductions for PM,NO_x and SO_x (Cruise Europe, 2020). Its smaller size resembles most of the ships berthed in Bergen in 2017. In fact, the AIDASol, a sphinx class cruise ship, visited Bergen ten times during 2017. On average the AIDASol spend 9 hours in Bergen, 8 hours if adjusted for connection and disconnection procedures. The total lay time is thus 80 hours. The emissions amount to 26,15 tonnes of CO_2, 0,3992 tonnes of NO_x and 0,0080 tonnes of PM per 8 hours laytime. SO_x emissions are not ascertained as they amount to under 0.1 tonnes. The reductions are made comprehensible by table 25.

Table 25: The isolated case of the AIDASol and its emissions for its 10 calls in Bergen, 2017. The table presents the emissions caused, and conversely the emissions reduced.

Single Ship Scenario (100% OPS usage) (2017) (AIDASOL)			**Emissions caused**	**2017**	**Lifetime**
-	**Port specific**	**Unit**	Emissions		
Reference ship	AIDASOL		CO (tonne)	26,151	523,022
Reference port	Bergen Skolten		NOx (tonne)	0,399	7,984
Reference life-time of facilities	20	years	SOx (tonne)	0	0
Port specific assumptions	**Bergen - Skolten**	**Unit**	PM (tonne)	0,008	0,162
Port calls per year (2017)	10	calls	**Emissions reduced**	**Per year**	**Total**
Port calls using OPS	10	calls	Emissions		
Avg, Lay time (adjusted)	8	hours	Co2 (tonne)	23,536	470,72
Total laytime per annum	80	hours	NOx (tonne)	0,371	7,425

Annual utitization of OPS	100	%	SOx (tonne)	0	0
			PM (tonne)	0,006	0,129

3.8.4 Air quality, future developments

The lower estimate presented in chapter 3.5.1 could be a possible future scenario for Bergen. With 25 cruise ships taking advantage of OPS, air quality could experience a slight improvement. Future political developments and the resulting paradigm shift could also lead to more environmentally friendly (green) cruise ships visiting Bergen and the fjords around. For that reason, future reductions need to be assessed with future cruise ships. The MSC Virtuosa is serving as a reference ship, as it boasts high technological standards. The MSC Virtuosa is one of the newest additions to the growing cruise ship fleet of MSC Cruises and will enter service in August 2021. The MSC Virtuosa emits 0,462 tonnes of NO_x, 0,091 tonnes of SO_x and 0,034 tonnes of PM for a duration of 11 hours laytime. With the reduction potential from figure 12 in mind, PM, SO_x and NO_x emissions could be reduced by 0,0272, 0,06461 and 0,08463 tonnes, respectively. If 25 ships resembling the MSC Virtuosa would berth at Bergen harbour in 2017 with 11 hours of laytime each, emissions could be reduced by 2,0128, 4,78114 and 6,26262 tonnes of PM, NO_x and SO_x respectively. The reductions are summarized in table 26. The latter also includes the total emissions over the span of the facilities lifetime, i.e., the time horizon of the LCA.

Table 26: The emissions reduction for SOx, NOx and PM for 2017 and the lifetime of the facility, with the MSC Virtuosa as reference cruise ship.

Number of Ships	PM	NO_x	SO_x
25 (MSC Virtuosa) (2017)	0,68 tonnes	2,11575	1,61525
Emissions, facility lifetime (20 year)	13,6 tonnes	52,893 tonnes	32,305 tonnes

3.9 Summary of reductions and the emissions left unaffected.

The following table lists the full reductions from the lower and higher estimate of 25 & 75 ships respectively, i.e. the reduction potential of OPS in the harbour of Bergen and compares them, as far as is possible, to the emissions that remained unaffected. For the sake of simplicity, the estimates were converted into percentages of the total cruise ships that arrived in Bergen in 2017. The lower estimate of 25 ships has therefore been converted to 32 % and the higher estimate of 75 ships has been converted to 96 %. The percentages have then been subtracted from the total emissions obtained from the AIS dataset for 2017. Subsequently the reduction estimates from figure 12 were applied. The direct emissions and its reductions can be viewed in table 27 whilst the sum of indirect emissions can be viewed in table 28. Depended on the estimate used, reductions are either high or low. However, emissions are never nullified. The higher estimate of 75 out of 78 cruise ships naturally achieves the highest reductions. However, emissions are still existent, with 40957,8 tonnes of CO_2 left after reductions. If distributed over the span of 20 years, this number is cut down to approx. 2000 tonnes of CO_2. per year. Other emissions such as PM are almost non-existent with just under 1 tonne per year or approximately 25 times 12 hours laytime of the MSC Virtuosa. Anyhow, the higher estimate would be the desired outcome if one considers implementing OPS. Conversely, the lower estimate only slightly reduces emissions, leaving the lion's share of emissions untouched.

Additionally, the fixed indirect emissions must be considered, constituting 734,18 tonnes of CO_2eqv for the implementation of the facility. The biggest share of these emissions is represented by the production and energy consumption of materials, followed by the transport of the materials. The emissions from materials and transport are fixed emissions and only occur once. The indirect emissions from energy usage however are a product of the number of cruise ships and subsequent calls in Bergen harbour during cruise season. Thus, emissions from energy usage are dynamic and prone to fall and rise with every year.

However, the emissions from the usage of the facility are still small in comparison to the actual reduction by the facility for both the higher and lower estimate, constituting a mere 143 tonnes per year for the higher estimate and 47,85 tonnes of CO_2eqv per year for the lower estimate. In comparison, reductions are approximately 10000 tonnes of CO_2 per year for the higher estimate and 3000 tonnes of CO_2 per year for the lower estimate.

The full indirect emissions can also be viewed in ratio with the energy usage of the lower and higher estimate in. The emissions per kWh for the lower estimate calculate to 0,76 tonnes CO_2eqv/kWh, whilst the emissions per kWh for the higher estimate calculate to 0,255 tonnes CO_2eqv/kWh. A higher utilization of OPS is synonymous with less indirect emissions per kWh and vice versa.

Table 27: The emissions reductions for the lower and higher estimate

Emission reductions **20 Years Total**	**Lower Estimate (25)(32 %)**	**Higher Estimate (75)(96 %)**	**Emissions not reduced**	**Lower Estimate (25)**	**Higher Estimate (75)**
Tonnes CO_2	66 643,2	202 012,2	Tonnes CO_2	176 326,8	40 957,8
Tonnes NO_x	1 174	3 522,2	Tonnes NO_x	2 771,28	423,08
Tonnes SO_x	29,4	125,4	Tonnes SO_x	100,6	4,6
Tonnes PM	18,8	54,6	Tonnes PM	54,78	18,98
Total	67 865,4	20 5714,4	**Total**	179 253,46	41 404,46

Table 28: The indirect emissions per kWh used/produced.

Indirect Emissions per kWh	Quantity	Unit
Lower estimate (25)	0,76	Tonne CO_2eqv.
Higher estimate (75)	0,25	Tonne CO_2eqv.

Table 29: The full indirect emissions with emissions from usage, transport and material production

Indirect emissions total		
Category	Quantity	Unit
Usage		
Lower Estimate (25)	957,1275773	Tonnes CO_2eqv.
Higher Estimate (75)	2871,382732	Tonnes CO_2eqv.
Materials		
Production	647,654	Tonnes CO_2eqv.
Energy Consumption	51,45324891	Tonnes CO_2eqv.
Transport		
Aluminium	0,339016935	Tonnes CO_2eqv.
Steel	25,8633831	Tonnes CO_2eqv.
Copper	5,897999706	Tonnes CO_2eqv.
Polyethylene	2,98153186	Tonnes CO_2eqv.
Sum Total	4562,31508	Tonnes CO_2eqv.

4. Discussion

The purpose of this chapter is the critical examination of my results and analysis/method, and the presentation of its weaknesses and strengths. Furthermore, the results will be compared to the theoretical background presented below.

4.1 Theory: The technical solution of OPS

A proper discussion requires the necessary theoretical foundation. The following sub-chapters will cover the technological and non-technological barriers and challenges connected to the implementation of onshore power supply.

4.1.1 Technological and non-technological barriers and challenges

Onshore power supply is todays answer for emissions reduction in port and port cities, but the technology is still not well established throughout the world and barriers arise from economic and technical issues regarding its implementation. One aim of this study is to explore the current situation, ergo reveal shortcomings and ultimately disclose the gap in knowledge regarding the barriers and challenges connected to the implementation of OPS. This sub-section aims at presenting the reasons for the strong restraints in development.

Standardization

The task of standardization is an ongoing process and as such represents a barrier for future implementation endeavours. As technologies evolve and are implemented, e.g. a new kind of frequency converter, new standards are required to enable efficient implementation and usage. As such it can represent a barrier for future implementations.

The implementation of OPS globally has and must be preceded by international standardization in order to ensure its efficient use. OPS systems are regarded as universal and deliver services to a spectrum of ship types. International standardization increased/increases the compatibility between electrical components onboard and on land enabling fluent global implementation (Tarnapowicz & German-Galkin, 2018).

With the common work of the International Electrotechnical Commission (IEC), the Institute of Electrical and Electronics Engineers (IEEE) and International Standardisation Organisation (ISO) various international standards were implemented, beginning in 2012, that ultimately enabled the building of OPS systems worldwide. The following standards pathed the way for OPS:

IEC/ISO/IEEE 80005-1, High voltage shore side electricity (up to 20 MVA per vessel)
IEC/ISO/IEEE 80005-2, Communication Protocol
IEC/ISO/IEEE 80005-3, Low Voltage shore side (typically less than 1 MVA)
(European Alternative Fuels Observatory, 2020)

The standards will be referred to as -1, -2 and -3 for the purpose of simplification. The standard -1 was the first major standard for OPS systems and elaborated on the high-voltage shore connection system, onboard the ship and on shore, which supplies the ship with electrical power from shore (International Standardization Organisation, 2019). It addresses High voltage shore distribution systems, onshore power supply connection and interface equipment, transformers/reactors, semiconductor/rotating frequency convertors etc (International Standardization Organisation, 2019). Furthermore, its focal point lies on ship types such as RoPax/RoRo or container ships with a power demand over 1 MVA until 20 MVA as contemplated in figure 2. Initially the standard was published in 2012, but got revised in 2019 (International Standardisation Organisation, 2019). The revised version constitutes a technical revision and adds alternative procedures, minimum current values and new optionality's for different components amongst others (International Standardization Organisation, 2019).

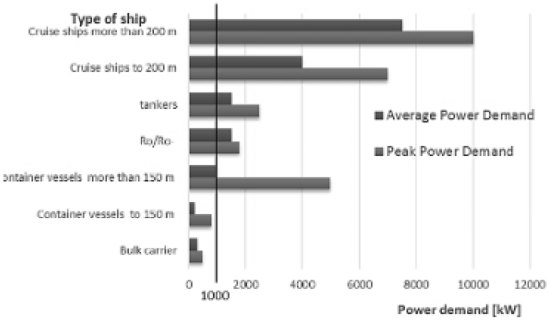


Figure 16 A graphic showing the power demand of various ship types (Tarnapowicz & German-Galkin, 2018)

After the publication of standard -1, the standards of -2 and -3 were added to further standardize the sector. These standards revolved around communication protocols and low voltage shore side electricity, with the latter relating to the high voltage standard. The standard -2 describes the data interfaces of shore and ships together with the step by step procedures for low and high voltage shore connection systems communication for non-emergency functions (International Standardization Organisation, 2016). Standard -3 as mentioned relates to standard -1, with the difference being that vessels not covered by standard -1, such as bulk carriers or container ships in the range of 150 metres are covered by this standard instead. In addition, all ships in the power range of under 1 MVA are encompassed by this standard as can be seen in figure 2 (International Standardization Organisation (ISO), 2014).

The task of standardization is an ongoing process and as such still represents a barrier for future implementation endeavours. As technologies evolve and are implemented, e.g. a new kind of frequency converter, new standards are required to enable efficient implementation and usage. As such it can represent a barrier for future implementations.

Economic issues and business

Onshore power supply is viewed as an excellent technical solution in terms of emissions reduction. Its implementation is environmentally and ecologically beneficial and provides extensive relief for the world's busiest ports and port cities in terms of air quality. Why then is OPS not widespread and extensively used throughout the world? An important factor for the implementation of new technologies is economic feasibility. The problem of air pollution might be high on the agenda for both the EU and WHO, but relatively little has been done to support a fluent transition towards OPS and emissions reduction. The electricity from Auxiliary engines (AEs) is generally cheaper than land-based electricity, due to electricity from AEs being exempt from national energy and electricity tax within the EU. In the case of Germany, electricity from renewable sources underlies special levies, the so-called Erneuerbare-Energien-Gesetz levy (EEG) or Renewable-Energy-Law levy (REL). This levy contributes directly to the financing of renewable energy expansion and amounts to a fixed price of 6,50 ct/kWh (Bundesnetzagentur, 2020). According to the German association of Energy and Water Industries (2021) the overall electricity price is made up out of electricity taxation, network charges and excise dues, equating to 18,25 ct/kWh for 2021, whilst the usage of Marine diesel oil with a 0,1 percent sulphur content only amounts to 10,07 ct/kWh (Jahn & Nellen, 2010). Fuel switching from higher to lower sulphur content fuels is seen as valid emissions reduction strategy, although higher in cost, it is well within the 0.50 % global sulphur limit for 2020 set by the IMO (Seddiek & Elgohary, 2014). In another example from the international port of Shenzhen, both strategies have been evaluated. According to Wang, Mao, & Rutherford (2015) the costs of reducing one tonne of NOx,PM, SOx and CO2 with the help of OPS are close to $56.000, $1.4 million, $290.000 and $2.300 respectively, with a 80% compliance rate. The switching from bunker fuel to Marine Gas Oil (MGO) was found to be economically more feasible, however fuel switching only affected SOx and PM emissions, leaving NOx and Co2 emissions untouched (Wang, Mao, & Rutherford, 2015). The cost of electricity for reducing one tonne of PM and SOx would be substantially lower, with $310.000 and $13.000 respectively (Wang, Mao, & Rutherford, 2015).

That being said, PM emissions are responsible for various health related issues, contributing to more than 60.000 cardiopulmonary and lung cancer deaths per year, ergo the reducing of PM should be prioritized over other forms of air pollution (Simonsen, Gössling, & Walnum, 2019).

If infrastructure is already existing, due to erstwhile developments or sufficiently equipped micro-grids, investment is not needed, leaving only the difference in electricity cost between fuel switching and OPS and the possible cost of retrofitting cruise ships with no ship side infrastructure. If infrastructure is not present, capital investment is required. According to Ballini & Bozzo (2015) the establishment of onshore power supply with electricity provision for three berths simultaneously would require a capital investment of around 37 million euros, when built in Copenhagen, Denmark. This initial investment Is a roundup of several smaller acquisitions such as electrical equipment, cabling etc. According to Wang, Mao, & Rutherford (2015) the frequency conversion equipment and quayside supply of high voltage power accounts for about half of that initial investment. The amount of capital required can vary from port to port and is often depended on power demand, vessel type, port location and the quantity of berths needed. In the EUs biggest port Rotterdam for example the capital investment was calculated to 4 million USD per berth, i.e. 12 million for three berths, whilst the port of Gothenburg only required an initial investment of 225.000 euros for two berths (Papoutsoglou, 2012). There is little doubt that these high installation costs are the main barrier for further implementation of OPS solutions. From the perspective of port authorities, such an investment may lead to better air quality, and thus improved public mood and perception. However, if there are not enough ships calling at port with the required shipside infrastructure, the benefits might be notably reduced. Whereby, alternative green investments may be preferable, such as fuel switching, speed reductions or incentives (Zis, 2019).

In addition, the initial high capital cost could be aggravated by the cost of retrofitting cruise ships that lack the required shipside infrastructure. The modifications onboard could require an additional investment of 300.000 to 2 million USD (Papoutsoglou, 2012). This is in line with estimates from Environ which convey a retrofit cost of approx. 500.000 USD per ship. (Environ International Corporation, 2004).

The different economic barriers and challenges can be summarized accordingly:

- There is a high capital cost related to the implementation of onshore power supply consisting mainly out of the quay side high voltage electricity supply and frequency conversion equipment.

- The high capital cost needed for OPS is aggravated by further investment in terms of retrofitting. This cost can be as high as 2 million USD.

- Electricity from onshore is often taxed and underlies different levies, such as the Renewable-Energy-Law levy. Fuel on the other hand does not underly any taxation or levies, thus it is preferred in terms of price/kWh. Even in the case of more expansive fuels, such as marine gas oil, fuel switching is preferred.

- Overall demand for onshore power supply is low due to other reduction strategies showing to be more cost efficient. There seems to be a consensus of business first, environment after. Though some cruise ships make use of OPS, this is only done loosely and for advertising purposes. The promotion of green cruising and sustainability is trendy and welcomed.

To solve some of these challenges, cities such as Hamburg now discuss alternative solutions. These solutions involve levy reductions by 20 %, obligatory usage of OPS or the usage of power barges. Last mentioned power-barges are actively used in Hamburg, Altona in the form of the power-barge *Hummel*. The power barge Hummel can be regarded as a floating power plant, but also serves as backup power bank to the local electric grid (Ship-technology.com, n.d.). The Hummel, Engl. Bumblebee, burns natural gas to generate electricity. The supplementation of electricity from power barges reduces emissions of CO_2 and NO_x by 80-and 30% respectively (Hybrid Port Energy, n.d.). However, emissions such as PM and SO_x are rather displaced then eradicated. Hence this thesis regards power barges as fuel switching.

Technical issues

Technical issues are mainly sourced from the high power and voltage requirements, along with the diversity in vessels and preferred frequency. The conversion of frequency has forced port officials to heavily invest in conversion equipment. In addition, higher energy demand may precipitate electricity shortage at city or regional level. Specifically, eastern European ports have limited capacities to cope with energy demand of visiting vessels (Kumar, Kumpulainen, & Kauhaniemi, 2019). According to Kumar et al. (2019) the power requirements of OPS can be categorized into small ship power requirement for less than 1 MW, large cruise power requirement for up to 12 MW and for container vessels ranging from 2 to 12 MW in power requirement. The supplementation of energy for the purpose of onshore power supply can be very demanding on the local power grid, especially in the case of cruise vessels, thus energy infrastructure must be improved or created, particularly in smaller cities. An upgrade can often be comprised of a micro-grid, consisting of a transformation substation and other electrical and electro-mechanical components (Krämer & Czermański, 2020). Micro grids have been developed extensively worldwide for different kinds of territories, such as cities, remote villages etc. (Roy, Auger, Olivier, Schaeffer, & Auvity, 2020). The development of micro grids in harbours however has been slow due to the diversity and complexity of energy demand (Roy, Auger, Olivier, Schaeffer, & Auvity, 2020). Energy must be supplemented for buildings, quay cranes and naturally shore power. The diversity in energy recipients dictates different energy management, loads, and different energy requirements of several megawatts. Especially the diversity in marine vessels precipitates issues in energy supply, due to their diversity in required voltage and frequency. Some ships may use 200 volts at 50 Hz, whilst other ships require 440 volts to 11 kilovolts at 60 Hz. Load requirements also differ and range from kW to MW (Arduino, Murillo Carrillo, & Ferrari, 2011).

4.2 Discussion: The life cycle assessment of OPS

How does the implementation of OPS relate to the knowledge that was obtained from the literature review? Can shore power be regarded as “the” solution for air pollution in ports and port cities and is the implementation justified? The reader is presented with some of the answers to these questions as the results from the LCA are critically discussed through the lens of theory. Furthermore, the analysis/method is examined, and the strengths and weaknesses revealed.

4.2.1 Implementation and feasibility

Shore power is widely recognized as an efficient solution for the problem of air pollution in ports and port cities. Its popularity has risen substantially from its humble beginnings in the late 90s with the first high voltage facility in Gothenburg to the state-of-the-art facilities in Bergen. The promise of cleaner air in conjunction to climate mitigation has made global implementation a possibility.

In theory, the potential reductions offered by the implementation of OPS are a near 100 % for various ship emissions. However, the potential reductions are a product of demand and electricity mixture. The demand for shore power is the key for its successful implementation, as it is irrevocably linked to supply. Demand however is relatively meagre to date, with only a handful of ships using the technology actively. The initial data collection leading up to the LCA has shown that from a 193 cruise ships (around 70 percent of the global fleet), only 75 do possess the necessary equipment, and from these 75 only 25 utilize shore power. Hence demand is almost non-existent. Moreover, other challenges and barriers further decrease attractiveness of the technology. An important factor for the implementation of “new” technologies is economic feasibility. Shore power is generally considered a heavy investment, as it boasts a high capital cost, which is further aggravated by the necessary investments on ship side. As previously mentioned in the theory part of this chapter, an OPS facility which can provide energy to three berths simultaneously, will cost a total of 37 million euros if built in Copenhagen, Denmark. The cost of retrofit increases overall investments by 500 000 to 2 million USD per ship.

The combined ship and shore side costs discourage both cruise lines and port authorities from implementing said OPS. Additionally, the cost of electricity further prevents implementation, as fuel switching is considerably cheaper, though that is dependent on location. The results obtained from the LCA draw a clear picture of what can be anticipated in emissions reduction, and it does not look very promising if demand Is low. The estimate that has been looked at as most promising as a future scenario is that of 25 or 30 % of cruise ships in Bergen in 2017 making use of OPS. The reductions achieved from 25 cruise ships are expectably low in comparison to a full reduction, i.e., the full coverage of 291 calls and 78 cruise ships in 2017. Moreover, indirect emissions per kWh produced are considerably higher if less cruise ships utilize the facilities onshore, as the total indirect emissions have to be divided between less ships. The estimate of 25 cruise ships is therefore only considered as a drop in a bucket full of water, its neither economically feasible, nor does it bring any considerable betterment in air quality. Though one can argue that it is a good step into the right direction.

The higher estimate is the preferred future scenario as it achieves the highest reductions, with 75 cruise ships or 98 % of cruise ships in Bergen in 2017 utilizing OPS. However, it is questionable if the estimate can be achieved during the lifetime of the facility, especially if the economics remain unchanged.

One can also argue that the indirect emissions associated with the implementation of OPS are an additional barrier to its implementation. Especially if the technology is regarded as climate mitigation technology rather than a technology for the deterioration of air pollution. Furthermore, the indirect emissions can be used as an argument against OPS, if seen through the lens of CO_2 reductionism. Conversely one could argue that the reduction of air pollution in ports and port cities is of greater importance, than the emissions regarding CO_2. As such the electricity mixture will become unimportant as the purpose of shore power is the reducing of air pollution in ports and port cities and not that of climate mitigation. The emissions will still exist, though they will be relocated to the place energy production. Additionally, the emissions at port only represent a tiny proportion of the actual emissions associated with cruise tourism, further supporting the unimportance of CO_2 reductions.

The emissions that have been generated in conjunction with the implementation of the facility can be regarded as less significant as they represent fixed emissions, i.e. they only occur once during the facilities lifetime. Furthermore, the emissions from the implementation of the facility covered in this LCA are only a fraction of the possible reductions of both the lower and higher estimate, further emphasizing the benefits of shore power in terms of emissions reductions.

4.2.2 The life cycle assessment, weak and strong suites

The purpose of this sub-chapter is the revealing of the strengths and weaknesses of my LCA analysis and method.

Weaknesses

The life cycle assessment that has been conducted for this thesis is a first attempt at calculating the emissions connected to the implementation of OPS and its subsequent usage. To my knowledge such an attempt has never been made, which makes this LCA innovative and new. However, innovation can often postulate failure. As a method, life cycle assessment can incorporate unwanted errors. After all, an LCA depends on assumptions and scenarios in order to assess the world in a simplified way.

Industry Secrecy and reference components

The life cycle assessment is based on the data that was received from Bergen harbour. The received data set included relatively little information, except for the general quantity of some of the main and sub-components and quantities of major composite materials such as steel. One can argue that the provided information is limited due to the secrecy surrounding this industry branch. This “secrecy” has influenced the choosing of reference components substantially. Some of the reference components, such as the transformer and frequency converter were chosen based on apparent power alone, as no other information was available that could identify the used components. Additionally, they were the only components found which matched the given description from Bergen harbour. Moreover, the environmental product declaration found for the transformer *EPD 55 Large Distribution Transformer 10MVA* was first published in October 2002, thus material distribution might differ substantially from the transformers of today and the ones installed in Bergen. The lack in information from the real-life implementation, decreases the reliability of the results obtained as they do not mirror reality.

Materials chosen and not chosen

The full spectrum of composite materials of the components have not been fully assessed. Only major materials such as steel, copper, aluminium etc. were assessed, assuming minor materials would have little to no impact on the emissions outcome. The materials chosen, were initially chosen subjectively and from only three sources, namely ProBas,EPD-Norge and Eco-Invent. Most of the materials from ProBas were of generic origin, produced by the prevailing generic production method. Materials sourced from EPD-Norge were also chosen subjectively, with emphasis on field of use. As a result, materials which could have been a better fit were ignored, as they were not actively searched for. The possible exchanges that could have been made have been detailed in chapter 3.8.

Cradle-to-gate with options

The life cycle assessment has been conducted from cradle-to-gate with options, covering the product stage (A1-A3), Installation (A4) and Usage (B1) of the facility. All other stages and modules were omitted due to time limitations and lack of information. Most of the materials used in the production stage don't include usage, or end-of-life modules. Much of the Usage stage of the facility could not be assessed due to lack of information regarding reparations, maintenance and other modules, except for Usage (B1) Hence, the omission/inclusion of the remaining modules could have had potentially altered the emission outcome as emission heavy processes, such as construction, demolition etc, were not included.

Strong suites

Transparent assessment

The LCA was conducted with outmost care regarding the choosing of sources for its life cycle inventory. Hence materials were sourced from trustworthy suppliers such as ProBas,Eco-Invent and EPD-Norge. Every factor used in the calculation of the results has been obtained from peer reviewed paper, academic journals or official websites. The execution of the LCA is highly transparent as most steps are easily replicable. The usage of industry programs/databases such as SimaPro was evaded as it represents a possible limitation for future research.

Furthermore, an LCA for shore power implementation has never been conducted before, making this specific LCA innovative and new. It indirectly lays the headstone for future research, making it possible for other researchers to build upon this thesis.

5. Conclusion

The technical solution of OPS and its market segment are mature enough to become widespread in use. The environmental benefits, especially regarding human health, are several. However, OPS struggles to take off, as it faces various barriers and challenges. The main findings and conclusions reached will be summarised here underneath. The research question which guided this thesis was:

“How much emissions can be saved per year by switching to onshore power supply?”

The findings of the thesis showed that emissions savings are hugely dependant on demand and supply. The implementation of OPS faces various economic obstacles. The high capital cost, the possible need for retrofitting and the high electricity price (dependent on location) slows down implementation considerably as port authorities and cruise lines are not willing to invest. Other solutions, such as fuel switching are seen as more cost beneficial, thus supply of shore power is low. However, more cruise lines have invested in ship side shore power systems, although just a fraction of the global cruise fleet. From the 193 cruise ships analysed (70 % of the global fleet), 75 cruise ships possess the necessary ship side equipment. However, only 25 of those 75 cruise ships utilize the offer of shore power actively.

The number of cruise ships using OPS has been used as the lower estimate for the calculation of the reduction potential. Based on these findings, the reduction potential is expectably low, as it only represents 30 % of the 78 ships berthed in Bergen in 2017. The preferred outcome would therefore be the higher estimate, representing the total number of ships able to receive shore power. Yet, with the current trajectory in terms of ships outfitted and ships actively utilizing OPS, this number will be hard to reach as it represents a near hundred percent of the ships that berthed in bergen harbour in 2017.

The LCA ultimately revealed that a near 100 % in emissions reduction is not achievable in the case of Bergen, as the electricity mixture is still causing emissions. Furthermore, the emissions from the energy usage depend on OPS utilization, increasing with less utilization and conversely decreasing with more utilization. The indirect emissions from the implementation of OPS in Bergen are considered small in comparison to the emissions reductions. This is regarded as positive, as the emissions from the implementation are fixed rather than dynamic, meaning they can be distributed over the lifespan of the facility.

In conclusion, the implementation of shore power is steered by demand and is hugely depended on electricity mixture, especially in terms of CO_2 reductions. If the electricity mixture is regarded as non-renewable, emissions are ultimately relocated and not reduced or nullified. Though seen through the lens of air pollution, ports and port cities gain from the implementation one way or another as air pollution decreases in the area around the dock, which is ultimately the essence of onshore power supply and its implementation.

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7.1 References: Pictures

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7. Appendix

The Appendix includes the entirety of the calculations done in Excel and as such would be too long to be include in the thesis itself. Hence, the Excel sheet can be accessed online under this link: https://hvl365-my.sharepoint.com/:x:/g/personal/161486_stud_hvl_no/ET0DKA0gwoZJuXr0bqReCdYBDPZPihFWldVJ6JbLbEfjJQ?e=WZE5W4

In addition to the excel sheet, the AIS database used throughout this thesis is also accessible here:

http://fling.jostedal.no/Cruise/Default.aspx