CHALMERS
UNIVERSITY OF TECHNOLOGY

Benchmark for Reduction of Anchored Vessels Emissions – Enabling Change of Operations

Research on air pollution management in The Port of Gothenburg, Sweden

Master's thesis for the degree of Master of Science in Maritime Management

CARLOS FLOREZ - VALERIA BETANCUR

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021
www.chalmers.se

Master's thesis 2021

Benchmark for Reduction of Anchored Vessels Emissions Enabling Change of Operations

Research on air pollution management in The Port of Gothenburg, Sweden

CARLOS FLOREZ - VALERIA BETANCUR

Department of Mechanics and Maritime Sciences
Division of Maritime Studies
Maritime Environmental Science
Chalmers University of Technology
Gothenburg, Sweden 2021

Benchmark for Reduction of Anchored Vessels Emissions Enabling Change of Operations
CARLOS FLOREZ - VALERIA BETANCUR

Supervisor: Elin Malmgren, Department of Mechanics and Maritime Science
Examiner: Kent Salo, Department of Mechanics and Maritime Science

Master's Thesis 2021
Department of Mechanics and Maritime Science
Division of Maritime Studies
Maritime Environmental Science
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Anchorage photograph provided by the Port of Gothenburg in the 400-year anniversary.

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2021

Benchmark for Reduction of Anchored Vessels Emissions Enabling Change of Operations
CARLOS FLOREZ - VALERIA BETANCUR
Department of Mechanics and Maritime Sciences
Chalmers University of Technology

Abstract

While air emission inventories can be calculated for distinct levels of accuracy depending on the availability of primary data versus average data, there are hovering assumptions in the methodologies that lead to uncertainties in assessing CO_2 benchmarks for anchoring operational mode. Normally, well-grounded information is neither available for auxiliary engines nor boilers at anchor to estimate the fuel consumption and the CO_2 emission that stem from it. However, research can generate primary data, as in the Brave Eco Method for tanker vessels. This case study creates a benchmark of CO_2 emission for the vessel at anchor in the port of Gothenburg as well as qualitative information of energy management at anchor. The average CO_2 emission rate for vessels at anchor in the port of Gothenburg was approximately 1.84 metric tonnes per hour in 2019. A similar emission rate is calculated for a period of 2021 with 1.54 metric tonnes of CO_2 per hour. These emissions are calculated using a bottom-up and fuel-based inventory methodology consisting of estimating fuel consumption for all the port's calls. Comparisons are made for world-known emission inventory methods in terms of CO_2 emissions of the port calls. Spatial distributions of CO_2 are shown for the designated anchor areas in Gothenburg. Ultimately, this research suggests a course of action to reduce carbon intensity in the areas adjoining the bay.

Keywords: Air emissions, bottom-up, emission inventory, port, anchor, vessel type, CO_2.

Acknowledgements

I would like to thank Kent Salo from Chalmers University, Fredrik Rauer and David Falk from the Port of Gothenburg, and Rasmus Parso from IVL for the trust placed on us to conduct this research. I am grateful to our supervisor Elin Malmgren for her invaluable advice and encouragement and to Valeria, my thesis partner, for her contribution and dedication. I would also like to express gratitude to my parents, it is my greatest honour to make them proud. Finally, I thank the Swedish Institute, this journey would not have been possible without its support. *This publication is part of my research work at Chalmers University of Technology, funded by a Swedish Institute scholarship.*

Carlos Florez, Gothenburg, August 2021

I would like to express my gratitude to Fedrik Rauer and David Falk from the Port of Gothenburg for giving me the opportunity to work in this project and supporting us in every way. I am also grateful for my thesis partner, Carlos Florez, for making me laugh everyday and for his dedication. Furthermore, I want to thank our supervisor Elin Malmgren from Chalmers University for her invaluable support, insightful comments, and suggestions at every step of the project. My gratitude extends to our examiner Kent Salo from Chalmers University for his comments and support. Lastly I would like to thank my family, friends and Jonas for their encouragement, support and love throughout the project.

Valeria Betancur, Gothenburg, August 2021

Contents

List of Figures

List of Tables

Acronyms and Nomenclature

Acronyms

IMO4	Methodology and average data at anchor of the Fourth IMO GHG Study 2020
POLA19	Methodology and average data at anchor of Port of Los Angeles Inventory of Air Emission 2019
BE	Methodology and average data at anchor of Brave Eco from Port of Gothenburg
AE	Auxiliary engines
BO	Boilers
EI	Emission inventories
FC	Fuel consumption
VBP	Vessel boarding program
GHG	Greenhouse gases
MT	Metric tonnes
ECA	Emission control area

1

Introduction

Since the industrial revolution the world's international trade has increased dramatically. Shipping is fundamental for international trade representing 90% of the global trade volume, around 11.08 billion tons [2, 3]. As a result, the exhaust emissions due to shipping have exponentially grown [4]. Emissions stemming from shipping are expected to continue growing since 95% of the world's fleet uses diesel engines [5], the global commercial fleet has increased by 4.1%, and vessel size has escalated over the last four years [3].

Even though maritime transport can be an energy efficient way of transportation, its emissions have a significant impact on human health and the environment [4, 2, 5, 3], contributing to global warming and climate change representing between 1.6% and 4.1% of the global CO_2 emissions [5]. The technical, economic, and social development in the past 250 years has been at the cost of the Earth's long-term stability [4]; therefore, the reductions of marine emissions are major concerns on a regional and global basis.

Ports play an essential role in the maritime industry as they represent the connection between ships and shore. Ports serve as a hub for shipping infrastructure, they provide services such as supplying ships with goods, fuel, means to perform other tasks, reception of sludge and other waste, among other activities [4]. Although ports are an important part of the maritime industry, their activities have a negative impact on the environment due to emissions from vessels operating in port [4]. About 70% of emissions from maritime transport are emitted within 400 km of land, causing health problems, acidification and eutrophication of the water and soil [4]. Furthermore, shipping emissions in port are estimated to be ten times greater than the emissions produced by the port operations [6]. This is an incentive to take action that limits emissions and their effects, not only because ports are located near cities affecting large populations, but also because there is greater potential in decreasing emissions from ships than from port activities [6]. Consequently, recently ports have started to adopt measures to reduce GHG emissions by initiating programs and creating policies [6].

To explore solutions, it is imperative to investigate the cause and scale of the issue [7]. Beig defines emission inventory as "an important tool for identifying the source of pollutants and quantitative expression of pollution load in a defined area at a particular time" [8]. The information obtained from an inventory of emissions has several applications, such as creating benchmarks, assessing compliance with regulations, and most important anticipating future trends. Consequently, over the last years the production of a reliable ship emission inventory has gained importance for creating appropriate regulation and policies related to air pollution management in port [7].

Within the bottom-up approach, the literature shows that emission inventories are compatible with at least two forms to estimate emissions; through the calculation of fuel consumption and the measurement of exhaust gases as depicted in the Jahangiri study[9].

Previous emission calculations methods for fuel consumption considered the demanded auxiliary power with ratios in proportion to installed main engine power [10]. In contrast, recent emission calculation methods use targeted vessel boarding surveying to collect auxiliary machinery data binned against ship type and district operating profiles [10]. Since 2014, the bottom-up approach for emission inventories has increasingly become popular among researchers as it can estimate and detach fuel consumption from different ship activity conditions" [11] like manoeuvring, berthing, and anchor.

The emission calculation to assess power and fuel consumption is easy and straightforward with the use of a couple of equations [9]. However, the data collection for specific data at anchor is scarce data in shipping [1, 11, 12] which proves the value of small endeavours to collect specific data through vessel boarding programs.

This case study intends to create an emission inventory for ships at anchor in the Port of Gothenburg during 2019 and the first quarter of 2021. Port of Gothenburg is located in the west cost of Sweden just 90 minutes from open sea to berth, 70% of the Nordic region's population and industry is located within a radius of 500 km from the port [13]. It is considered the largest port in Scandinavia handling around 800,000 TEU per year, 70 departures of RORO vessel every week. The case study will focus on the CO_2 emissions that stem from ships at anchor in the port. To do so a bottom-up approach is used to calculate emission based on fuel consumption for boilers and auxiliary engines. This research focuses only on air emissions, specifically CO_2, not other type of emissions such as water or noise. It focuses only on the anchor operational mode.

The case study uses primary and secondary data, where qualitative and quantitative questionnaires are used for data collection. Secondary data is provided by the Port of Gothenburg- Traffic Control Department. Moreover, 2019 and 2021 follows very similar methodologies, but the difference in the inventories lies within the data collection. 2019 uses average data from IMO4 and POLA19. 2021 uses specific data for tanker vessels and average data from IMO4 for the rest of the ship type.

The thesis is structured in two parts: Emission inventory for a CO_2 benchmark and potential solutions to address the CO_2 emission goal at the port. The first part relates to CO_2 emissions and energy usage onboard. Part I is divided into sections that describe state of the art in shipping emission inventories, the methodology, data collection, analysis, results, and discussion. Part II is an attempt to move forward with the port's goal to reduce CO_2 emission, and therefore certain requirements for a mobile prototype are provided from our qualitative and technical research. In addition, it is portrayed the motivation to constitute a vessel boarding program for the port of Gothenburg linked to CO_2 reduction capability.

1.1 Purpose of the Thesis

The purpose of this thesis is to contribute with a benchmark for reducing CO_2 emissions of vessels at anchor in the Port of Gothenburg for 2019 and part of 2021 and make a small contribution to the port goal to reduce CO_2 emissions by 70% by 2030. The study also aims to provide general understanding on energy generation, usage, and management onboard to help contemplate possible solutions linked to reducing energy use onboard. The information generated would enable change of operations in the hands of the Port of Gothenburg administration.

Based on the stated purpose, the following research questions have been formulated:

What is the amount of CO_2 emission from vessels at anchor in the port in 2019 and 2021?

- How is this energy generated onboard?
- What systems is this energy used in?
- What are the parameters to accurately calculate power demand and analyze emissions?
- How to make a small contribution to the port goal to reduce CO_2 emissions by 70% by 2030?

2

Background

This section provides the readers with context to the information undertaken throughout this research. It includes relevant aspects regarding air pollution, GHG in shipping, CO_2 emission inventories, diesel engines, and fuels used.

2.1 Air Pollution and Green House Gases

Air pollution consists of various gases released into the atmosphere at concentrations that can harm and cause health, economic and aesthetics effects when the concentrations outreach the natural capacity of the environment to dissipate them [14]. Greenhouse gases (GHG) excessive emissions have been considered as the main contributor to climate change [15], and therefore an environmental issue. Since the industrial revolution when the burning of fossil fuel began, the levels of GHG have been increasing [4]. Moreover, due to the human population growth rate and energy demand, the impact on the natural environment has also increased, causing loss of biodiversity, deforestation and overfishing [4].

The GHG gases directly contribute to the greenhouse effect, which is a process where the sun's energy reaches the Earth's atmosphere, some radiation is reflected back to space and other is absorbed by greenhouse gases [16]. GHG high concentration is reaching a level that exceeds the planet's natural capacity, raising its average temperature affecting human health and the climate system, among other consequences [14].

GHG gases consist of natural gases and anthropogenically produced gases [15] like water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3) and others [17, 14, 15]. Carbon dioxide is not the most potent of the gases but is considered the main contributor to GHG due to the great amount of volume emitted to air as a result of the combustion of fossil fuels [4, 17] .

The concentration of greenhouse gases is estimated considering all gases and forcing agents using the CO_2 equivalent as a unit of measure (CO_2e). CO_2 equivalent is defined as "an equivalent amount to the concentration of CO_2 that would cause the same amount of radioactive forcing as a mixture of CO_2 and other forcing agents (greenhouse gases and aerosols)" [18]. The total CO_2e considering all gases and other forcing agents reached 457 parts per million - ppm in 2018 [18], moreover the CO_2 concentration in 2018 reached 408 ppm. Since 1990 the total radioactive forcing has increased a 43% by greenhouse gases, 80% of this is due to CO_2 [19]. However, it is important to acknowledge that this study focuses on carbon dioxide, and therefore it is the only greenhouse gas considered.

2.2 GHG in Shipping

Greenhouse gas emissions constitute the largest contributor to climate change [15] and therefore have drawn much attention from the international community to mitigate and reduce GHG emissions on a global scale, not only for their climate impact but also for the harmful potential risks they impose to health and air quality [15].

Shipping plays an important role in reducing GHG emissions as it represents 1,076 million metric tons of CO_2-e, accounting for 2.89% of global anthropogenic emissions in 2018 [1]. The greenhouse gases coming from shipping listed in the IMO 4th study are CO_2, CH_4, N_2O. The main contributor is CO_2 1,056 million metric tonnes of emissions in 2018 [1]. CO_2 shipping emissions are concerning due to the following reasons. Carbon dioxide emissions have increased by 9.3% from 2012 [1] and are expected to keep growing as 95% of the world's fleet uses diesel engines [5]. In addition, the global commercial fleet has increased by 4.1%, while the vessel sizes have escalated over the last four years [3].

Endeavours to reduce environmental impacts from shipping had not focused on climate change from the beginning due to the omission of the sector in the inventories under the Kyoto Protocol. Some reasons not to include shipping are; its reputation as the most energy-efficient type of transportation and the difficulty regulating GHG globally due to its transboundary nature [20]. However, due to the growing contribution of shipping to climate change during the past years, efforts have been made to reduce emission and develop policies and regulations [15, 20]. The primary inter-governmental administration is the International Maritime Organization (IMO), responsible for regulating air pollution and GHG from international shipping. In April 2018, IMO introduced the Initial IMO Strategy on Reduction of GHG Emissions from Ships [21], which aims to lower greenhouse gas emissions from international shipping by at least 50% by 2050 compared with 2008. IMO has adopted technical and operational measures through the Annex VI of its MARPOL Convention [2]. From these measures is worth mentioning the establishment of emissions control areas that sets limits for SO_x and NO_x. NO_x is regulated through IMO Tier limits that depend on the engine speed and age. Sulphur is regulated under a maximum allowance of sulfur fuel content (SFC) of 0.5% on a global limit since January 2020, while for the Sulphur Emissions Control Areas (SECAs) like the North Sea and Baltic Sea applies 0.10% since 2015 [2]. Additionally, IMO has incorporated mandatory regulation for all ships, such as the Ship Energy Efficiency

Management Plan (SEEMP) that determines a tool to improve ships' operational energy efficiency and uses data collection for fuel consumption [2].

In addition to intergovernmental organizations, other private and national organizations are adopting measures to reduce emissions by imposing compulsory measurements or promoting voluntary initiatives [2].

Specifically, port authorities are developing various policies and incentives to reduce emissions as they are considerable and noticeable. Around 70% of the emissions from shipping are emitted within 400 km from shore [4], and an important part of the CO_2 emissions from ships comes from the time ships stay in ports [20]. Winnes, states that ships are a source that causes approximately ten times greater emissions than other sources from the ports' own operations [6]. Moreover, ports are usually located near cities, and therefore emissions directly impact the health of large populations. Data from the Los Angeles County Health Survey shows that communities close to Port of LA experience higher rates of asthma and coronary heart disease than other communities in Los Angeles [22]. The fact that ports are located near cities affecting large populations, current political and social demand to reduce GHG emissions, and that there is greater potential in decreasing emissions from ships than from port activities [6] constitute strong incentives to take action that limit emissions and their effects. Consequently, in the last years, ports have started to adopt measures to reduce GHG emissions by initiating programs and creating policies [6].

To undertake this challenge, port authorities can influence GHG emissions by the implementation of emission reduction plans, for example, environmentally differentiated harbor dues, managing and administrating the supply of alternative fuel and onshore power connections, or a speed reduction program like the one implanted in Port of Long Beach and Port of Los Angeles [6].

2.3 Emission Inventory

To explore solutions is imperative to investigate the cause and scale of the issue [7]. Reporting of emissions plays an essential part in ports nowadays, as it supports the decision making for emissions reduction plans, assessing compliance with regulations, and most important anticipating future trends [17]. The emission reporting can be achieved through an emission inventory (EI). Beig defines emission inventory as "an important tool for identifying the source of pollutants and quantitative expression of pollution load in a defined area at a particular time" [8]. The reasons and resources to create an EI would influence the scope and other aspects like level of accuracy, operational domain, emission type, emission sources, time period, etc. [17]. The methodology behind the development of EI would include the approach, emission estimation method, and emission factors [17]. Moreover, IMO provides the Port emissions Toolkit to help develop emission reduction strategies and the creation of port EI [23]. Toolkit also differentiates between different approaches depending on the accuracy level; the scaled approach extrapolates external data produced from other ports using scaling factors, assuming that operation between ports is comparable. The screening approach increases the level of detail of the scaled approach by including specific data, assumption, or external data but still using a simplified emissions quantification method. Finally, the comprehensive approach has the highest level of accuracy based on detail and specific data from every emission source category and use sophisticated emissions estimating methods [23].

There are several methods to estimate shipping emissions, the most commonly used are top-down and bottom-up approaches. The Top-down method is a fuel-based approach, meaning that the emissions are calculated based on the statistical analysis of fuel consumption directly linked to the marine fuel sales and fuel-related emission factors. This data is published by the Energy Information Administration, the International Energy Agency, and the United Nations Framework Convention on Climate Change. On the other hand, the bottom-up (activity-based) method uses statistical analysis of the vessel-specific activity and specific emission factors to calculate emissions based on ship type, size and or operational mode (cruising, hoteling, manoeuvring, berthing, or anchoring). Therefore, this method requires technical ship-specific data such as ship characteristics (vessel type, engine type and age, fuel type, fuel consumption and so on) and depends on several variables, making it a challenging and expensive approach [11, 7, 24]. Even though the top-down approach would be the most accurate method to estimate emissions, it has been found some inconsistencies between the fuel used by the global fleet and the bunker fuel sales statistics [7]. Therefore, since 2014 the bottom-up approach has been mostly used by researchers, despite the complexity of gathering or finding accurate specific data.

Therefore, the complexity of emissions calculation lies in the accuracy of specific data for each vessel. When analyzing different studies from ports, the results are vague, incomplete, or inaccurate due to the use of surrogate data (proxy data, data from other ports or assumptions) [17]. To evaluate emissions from ship operation, it is needed the specific emission factor (EF) that varies with engine type, fuel consumption, fuel type, and the use of abatement technologies [4].

2.4 Auxiliary Machinery and Fuel Type

Shipboard conventional electrical power is produced by a prime mover coupled with a current generator. The alternating current generator follows the physics of electromagnetism on the grounds that when a magnetic field changes around a conductor, a current is induced in the conductor [25]. For example, an auxiliary diesel engine and a current alternator together act as a generating set. However, steam turbines are an alternative used as the prime mover to drive generating sets [26].

Diesel engines are internal combustion engines that ignite fuel in a high-pressured combustion chamber [27] to “convert some of the chemical energy, contained by the diesel fuel, to mechanical energy through combustion" forces, and then the mechanical energy rotates a crank in the alternator to produce electric power [28]. Diesel engines are built to operate within a fixed sequence of strokes that can be either two or four(Taylor, 1996a). Diesel engines are equipped with fuel injection systems that manage the timing and amount of fuel to grant adequate combustion, and thereby it must be some sort of measurement for the fuel supply [27].

Four-stroke engines are usually medium speed (250 to 750 revolutions per minute - RPM) and are used in auxiliary systems rather than two-stroke for propulsion [27]. Not only medium-speed but also high-speed diesel engines are principally used as prime movers for generating sets. Moreover, they can deliver direct drive for heavy machinery such as large pumps or transversal thrusters.

Boilers are found onboard every ship type, even if the main propulsion systems is not steam-powered. On vessels with diesel engine prime movers, boilers are installed to provide steam for numerous services [29]. All boilers have a combustion chamber where the fuel releases energy while being burnt [29]. Accordingly, boilers boil feedwater to produce steam, and the energy released by combusting fuel in the boiler's furnace is accumulated in the steam flow. Such energy is thermodynamically stored using temperature pressure [29].

There are multiple designs of boilers that come within a water-tube or fire-tube arrangement. Moreover, boilers can be equipped with heat recovery from exhaust gases [29]. Water-tube boilers are installed for high temperature and high-pressure systems such as propulsion steam turbines and cargo pump turbines. On the other hand, fire-tubes boilers are used for systems with lower intensity of temperature and pressure, such as the supply of low-pressure steam on diesel propulsion vessels [29].

Currently, fossil oil is still the source of most of the fuels used in shipping [30]. Through refining (heating and distillation), it is possible to obtain several fractions of the oil, for instance marine diesel could be used in both medium and high-speed diesel engines [30]. Marine diesel oil falls into the distillates category and has features of being free-flowing and could be injected without treatment, while heavy fuel oils are viscous and thick, requiring centrifugal treatment and heating before injection [30]. The refining of crude oil has supplementary treatment to detach harmful chemicals like sulphur, which is required for certain refined products [30].

A rise in environmental demands has led to a transition for the standardization of marine fuels that stem from petroleum crude [31]. ISO 8217: 2017 is a standard for petroleum products, it specifies the requirements for energy carriers used in marine diesel engines and boilers before they are treated onboard. ISO 8217: 2017 defines classifications of distillate fuels and six categories of residual fuels [32]. Marine diesel oil – MDO and marine gas oil -MGO, both distillate energy carriers, have the nearest equivalent in the ISO classification as DMB and DMA respectively.

3

State of the Art

As this research aims to create a CO_2 emission inventory of vessels at anchor, a literature review is undertaken to portray major works and publications previously done in this field. Moreover, the ideas presented hereunder try to construct knowledge on results and methodologies. Furthermore, it is discussed our remarks in relation to the creation of emissions inventories.

General Overview

Emissions to air have increasingly become a focal point in terms of sustainability [6]. This is why endeavours have been undertaken at different strategic levels such as academia, private port industries, and shipping intergovernmental organizations.

To develop an inventory of emissions, the literature shows two different methodologies, top-down and bottom-up. The top-down methodology is based upon the marine fuel sales in combination with fuel-related emissions factors [24], while bottom-up aggregate the emissions based on the emissions emitted by the ship, the calculation of emissions is based on fuel consumption that depends on ship type, size and or operational mode[1] [11, 24].

Even though the top-down approach would be the most accurate method to estimate emissions, it has been found some inconsistencies between the fuel used by the global fleet and the bunker fuel sales statistics [7]. Therefore, since 2014 the bottom-up approach has been mostly used by researchers, despite the complexity of gathering or finding accurate specific data and because "it can estimate ship fuel consumption by accounting for ship activity conditions" [11]. Accordingly, relevant literature is screened through bottom-up approaches.

Previous emission calculations methods considered that "the installed auxiliary engine power increased in proportion to installed main engine power" [10]. In those earlier approaches, the calculation was in function of ratios between main engine and auxiliary machinery for different ship types and load factors obtained through operational profiles [10].

In contrast, contemporaneous emission calculation methods deploy detailed surveying and provide "auxiliary engine and auxiliary boiler power binned against ship

[1] Cruising, hoteling, maneuvering, berthing, or anchoring.

type, ship size and operating mode" [10]. Hulskotte et al. used questionnaires to directly collect fuel consumption and FC rates from 89 different ship types at berth in the port of Rotterdam, in this way the only form to differentiate between boilers and auxiliary engines is with a fraction used by type of machinery [33], this information might not be simply to get. Goldsworthy also mentions that matching approaches are worldwide employed for at least three different publications; (e.g., Jalkanen et al., 2009; Olesen et al., 2010; Smith et al., 2015; Chen et al., 2017).

Review of Calculation Methodologies
Relevant literature arrays different initiatives to comprise shipping emission inventories within the last two decades. Consequently, such literate accounts for major works accomplished on shipping inventories and peer-reviewed publications.

Academic papers encompass emissions inventories at ports and methods to assess auxiliary power and fuels. The papers reviewed pursue their research in Korea, Greece and Australia. On the other hand, some private initiatives produce distinct port studies for emissions inventories, for example, Starcrest in the United States. In addition, the Environmental Protection Committee of IMO recently developed a thoroughly greenhouse gases study for the world's fleet including anchoring and a fuel-based methodology for CO_2 .

Consistently among the reviewed sources it is determined two characteristics that steer CO_2 emission inventories: data collection and emission calculation. Le state that "studies that use datasets of a large number of vessels and voyages usually rely on assumptions from prior studies" [11]. Even one of the studies states that "different assumptions were observed to provide biased estimates, especially for auxiliary engines" [9]. Therefore, a common concern is that every study carries along multiple assumptions that are difficult to relate to one another as they do not state their level of accuracy when calculating emissions. Another remark is that multiple studies are based on average data from the same sources to a certain extent.

The literature is consistent with two distinct forms to estimate emissions. Either through the measurement or calculation of fuel consumption [33, 1], or the analysis and measurement of exhaust gases, that analyses the chemical composition and physical properties of a specific fuel [9]. When it comes to fuel consumption, in all the Starcrest studies [2] it is found that the emissions are comprised as a "function of vessel power demand with energy expressed in kW-hr multiplied by an emission factor, where the emission factor is expressed in terms of grams per kilowatt-hour (g/kWhr)" [12]. On the other hand, when the fuel consumption is measured the total amount of fuel is known, and therefore it is assumed that the 100% of the combustion rate. Conversely, it was found a different approach consisting of the measurement of CO_2 emissions directly from exhaust gases, although it is usually for CH_4, PM, and NO_x. The emission calculation is based upon the "specific fuel consumption (SFOC) and formed CO_2 to provide the exhaust gas flow" and then it analyses the "chemical composition and physical properties of HFO" [9].

[2]Port of: LA, Long Beach, NY & NJ, Everglades.

Since bottom-up is directly linked to the vessel's activity, it is important to clearly understand what anchor means for emissions inventories. In this study, anchoring contemplates fuel consumption of generating sets and boilers, as only "auxiliary engines are used to provide electricity to equipment onboard the vessel [34, 35].

Fuel consumption methodologies are carried out by determining the amount of fuel combusted through distinct auxiliary machinery, as in the Fourth IMO GHG Study 2020. Another way is to measure the amount of fuel consumed from tanks, as seen in [11]. However, both emission calculation have in common a bottom-up approach as it is "becoming increasingly popular because it can estimate ship fuel consumption by accounting for ship activity conditions" [11].

In accordance with the amount of fuel burned, the literature appoints that it could be accomplished via either specific fuel consumption (SFC) or specific emission factor (SEF). In IMO4, the emissions are estimated as a function of the output power, service time, SFC linked to a particular engine, and emissions factors linked to the fuel used. On the other hand, POLA19's emissions are comprised as a function of vessel power demand, service time, and a specific emission factor which is linked to fuel type, engine speed and the IMO Tiers [12].

Emission calculation "for evaluating power and fuel consumption are fairly simple [9]. However, data collection for specific data, especially at anchor, constitute a great proportion of the strains. IMO clearly states that fuel consumption linked to power demand for generating sets and boilers constitute not only scarce data in shipping but also the access to Ship Performance Monitoring Systems of the world fleet is very limited as of today [1].

Data Collection Methodologies

The HIS [3] database is one of the most significant sources of data for ocean-going vessels, but it "contains limited auxiliary engine installed power information or information on use by mode, because neither the IMO nor the classification societies require vessel owners to provide this information" [12]. Moreover, Goldsworthy states that "Reliable information is usually available for main engines" but not for auxiliary systems [10].

One of the main remarks is that pristine data lacks standardization [4] and there is a gap between the main source (shipping) and research for data collection. The lack of standardization could relate to the display of multiple electrical plant arrangements. Starcrest states that one factor that presents challenges for obtaining auxiliary power demand is the different generating set arrangements onboard and "the lack of relatively complete data sets on installed equipment and numerous other factors that make determining auxiliary power requirements a challenge without input from the vessel operators" [12].

[3]HIS Fairplay is a maritime database that evolved from the Lloyd's Register of Ships published since 1764

[4]Reaching an agreement which specifies what information shall be collected.

Onboard surveying could be more accurate, but it is not always practical to do so from a resource perspective, as “time and human resources may be limited” [9]. Vessel boarding programs are often undertaken in an attempt to procure reliable information on onboard energy consumption. The vessel boarding concept has vital utility for generating sets emissions calculations, on the grounds that the HIS [5] “contains very limited installed power information for auxiliary engines and no information on use by mode” [36]. Specific auxiliary data is expensive and challenging to collect, and in broad terms, it is not gathered from private shipping lines [11].

Among the different studies, it is used either specific data or average data. The Starcrest studies use VBP data “to determine auxiliary engine and boiler loads, by the various operational modes. The discrete vessel operational data collected during VBP is confidential, but the averages used for defaults” [36]. VBP data can also be retrieved from ship-shore connections. Actual engine data from ship-shore connections at berth is also collected to estimate emissions as well as actual loads from engines; when the data is not available, defaults are used after sister ships data [12, 37].

Additionally, IMO has a power demand model that begins with Starcrest’s VBP and afterwards this data is upgraded by building operational profiles, using relevant literature, accessing published data, and consulting experts on auxiliary power demand [1]. It can be deduced that if standardization were accomplished, the process and its assumptions to build a methodology (such as IMO’s) would dwindle considerably, and it would be possible to keep track of the accuracy of the data collected and results. VBP are not indifferent to this remark.

Energy consumption data has to do with a wide range of ship types, size, and other factors. The different reviewed studies show that depending on the resources, aim, and scope, the collected data could correspond to different levels of variety (ship type, size, operational modes, geography). For example, the 4th GHG study of IMO has access to the whole fleet’s demographics, meaning that there is data for almost every ship type and size. A similar but in a smaller scale approach is The Hellenic Chamber of Shipping - HCS that retrieves data from 375 vessels of its members within a vast spectrum covering multiple ships and sizes [24]. HCS database comprised horsepower, engine type, fuel type, total fuel consumption at port, among other data.

On the other hand, there are studies appointing specific ship type. In the study developed by [11], specific data on container vessels was directly recorded “at the end of each voyage for all container ships operated by a shipping company. 38,687 voyages were collected from 100–143 container ships between 2012 and 2016” [11]. It is found that some studies use limited data from small local surveys to compare specific data with average data from larger studies like IMO4 or POLA19.

Brave Eco research stands in a fuel-based bottom-up approach to develop a

[5] HIS Fairplay is a maritime database that evolved from the Lloyd’s Register of Ships published since 1764

CO_2 emissions inventory. It also undertakes the first steps towards a vessel boarding program to generate specific fuel consumption data for ships at anchor in the Port of Gothenburg. Although BE initially aimed to collect information from multiple ship types, it ended up receiving data mostly from tankers, constituting a medium sample for tankers between 3,000 and 62,000 GT at anchor in an ECA area. These demographics are compared with the auxiliary power average data from the 4th GHG IMO study.

In the end, the final remark lies with regard to the reliability and accuracy of emission inventories because we have not found traceability in the process of constituting average data from specific data in the reviewed literature.

4

Research Method

This section explains the method to conduct this research. Figure 4.1 shows the research methodology implemented through a labelled hierarchy.

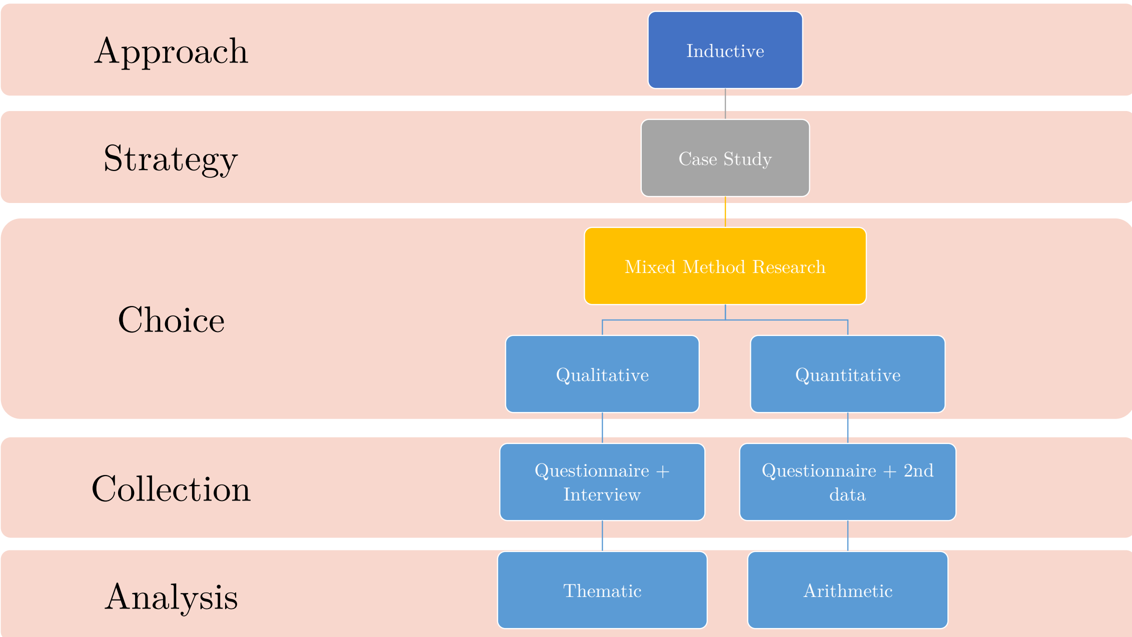


Figure 4.1: Research method labeled hierarchy

4.1 Approach

This study undertakes a bottom-up method using resources provided by the Port of Gothenburg, enabling the collection of specific data. The literature also exposes the relationship between the bottom-up and the inductive method, being a type of inductive research [38]. By undertaking an inductive approach is expected to provide a conclusion or an understanding of why something is happening from the collected data. This research takes on a relatively new and constantly open topic for debate, and therefore the literature proposes to proceed inductively by “generating data and analyzing and reflecting upon what theoretical themes the data are suggesting” [39].

4.2 Strategy

The research strategy is aborded as a case study. A case study is defined as 'a strategy for doing research which involves an empirical investigation of a particular contemporary phenomenon within its real-life context using multiple sources of evidence' [39]. A case study is appealing to this research because it intends to explore existing theories and provide new insights of the phenomenon within its context, trying to answer the question of how energy is generated onboard. Also, a case study is interesting because it allows the use of different data collection techniques (Section 6.3).

4.3 Research Choice

Moreover, the study uses a multiple method approach where qualitative and quantitative data is collected and analyzed following mixed-method research. The mixed-method research is characterized by the use of quantitative data analyzed quantitatively and qualitative data analyzed qualitatively [39]. Furthermore, it allows the use of qualitative and quantitative data collection and analysis simultaneously, which could be helpful to verify and complement findings [39]. This method facilitates studying different aspects of the dataset, having a more significant overview with the quantitative data and specific aspects with the qualitative.

4.4 Data Collection

Research questions will be answered using secondary and primary data. Secondary data is provided by the Port of Gothenburg- Harbor Master Office retrieved from the software Portit linked to AIS. The dataset comprises information of anchored vessels at Port of Gothenburg. During 2019, the dataset is comprised of 285 different vessels accounting for 1109 port calls at anchor. While from January up to April 2021, the database shows 121 vessels accounting for 309 port calls. The data gathered from Portit is general information of the vessel and time at anchor, more details are listed in Table 4.1. The information retrieved is fairly complete, nonetheless missing information is individually collected from Marine Traffic, an online database that provides real-time information regarding vessel general information.

Table 4.1: Main inputs of secondary data from Portit

Inputs for the Methods
Type of vessel
Designated anchor area
Deadweight DWG and gross tonnage GT

Table 4.1 continued from previous page
Inputs for the Methods
Year of built
Time at anchor

The primary data is collected through questionnaires for both qualitative and quantitative data, which are efficient ways to collect responses from a large sample and analyze the relationship between variables, especially cause and effect [39].

A semi-structured online interview was conducted with follow-up questions to a liquified gas tanker prior to the questionnaires. Together with a general technical auxiliary machinery background, all this contributed to assembling well-defined and clear questions for the questionnaires.

The general idea behind the design of both questionnaires is trying to ensure that the questions are interpreted in the same way by the respondents using clear wording and terms that are likely to be familiar in the questions, to enhance the quality of the data. The form is intended for the engineering departments of the vessels as the questions demand technical knowledge. Initially, the idea was to site-survey the vessels, but the public health emergency Codiv-19 forced the research to adapt to non-presential data collection tools. Therefore, the questionnaires are internet-mediated and self-administered[1]. Henceforth, with the intend to validate if the retrieved data is reliable, the questionnaire includes an entry for the position onboard of the respondent. Furthermore, both questionnaires complement each other, filling gaps of missing information in the research field.

For the qualitative questionnaire, one version (QQV01) digital and paper-based were held throughout this research, from February to April 2021 (Appendix A). The questionnaire comprises four blocks: general information about the ship, energy generation & usage, onboard data collection on energy matters, and energy efficiency & emission reduction. Aiming to provide the following knowledge linked to research questions:

- A better understanding of how the energy is generated onboard
- A better understanding of how the energy used onboard
- Factors that increase energy use linked to anchor activity
- An onboard perspective concerning energy management
- As support to the paired technical questionnaire for the quantitative method 2021

[1]Completed by respondents.

A few versions digital and paper-based were developed for the quantitative questionnaire based on the response rate, from February (week 8) to mid-May (week 18). The first version (TQV01) runs for the first two weeks of 2021, but due to the low response level the second version (TQV02) was produced and run for a week. Finally, the third version (TQV03) held until the end of the research for eight weeks. All these versions can be found in Appendixes A to C. The technical questionnaire comprises three blocks:

- General information of the ship
- Average energy consumption at anchor and energy capabilities
- Machinery on service at anchor

The information it intends to achieve is the following, linked to the research questions:

- The machinery used while anchor and the operating time
- Ship-shore connection availability
- Average consumption per hour

5

Analysis Method

This section undertakes the methodologies for the qualitative analysis of the qualitative questionnaires and the quantitative analysis to comprise the CO_2 emissions inventories at anchor.

5.1 Qualitative Analysis

The qualitative analysis methodology adheres mostly to the thematic approach. More than a specific method, the thematic approach is perceived as a flexible research tool giving freedom to decide how to pursue the analysis [40]. This method is characterized by identifying, analyzing, and reporting themes, making it useful to synopsize key aspects of large data [41].

The analysis of data to produce results consist of different stages. The first one is familiarization with the data and initiation of a general evaluation and thoughts of potential themes within the dataset [40, 41]. The themes are defined as important findings within the data that have a strong connection with the research questions and show some pattern level [40]. During this process, the raw data was archived and transfer to an excel sheet to convert the raw data into text, which would be afterwards analyzed in a word document.

The second stage of the analysis consists of creating codes to structure the data. Coding is a tool that enables the researchers to simplify and concentrate on specific characteristics of the data [40]. The codes are based on the different topics touched upon in the questionnaire; energy generation and usage, onboard data collection, and energy efficiency and emission reduction. From here, each question was analyzed looking for consistency in the answers to identify patterns to create themes. This was done by relating the different entries to one another and discussing probable explanations from a technical side.

It was decided after discussions and data analysis that themes will be created based on each question. Each question is analyzed separately, bringing together fragments of the most currents answers creating themes and highlighting interesting comments that enrich the results. A theme needs to apprehend something important related to the research question rather than depend only on the quantifiable measures [40].

5.2 Quantitative Analysis

This section shows how fuel consumption and CO_2 emissions are estimated during 2019 and 2021 for vessels at anchor in Gothenburg, following an arithmetic calculation. The year 2020 is excluded for reasons related to the Covid-19 pandemic, which diverted regular port operations and maritime traffic in the area as stated by the port administers.

For the analysis two inventories have been developed for 2019 and 2021. The inventory of 2019 is based on the 4th IMO GHG Study 2020 (IMO4) and parallelly with The Port of Los Angeles Inventory of Air Emission 2019 (POLA19). On the other hand, the inventory of 2021 is partially developed with specific data gathered during this research. The emissions are calculated within the boundaries of Gothenburg's bay following a methodology for emissions calculation similar to the IMO4.

5.2.1 CO_2 Emissions Average Inventory Method 2019

The emissions inventory of 2019 comprises secondary data provided by the Port of Gothenburg from the software Portit, linked to AIS. The analysis and development of the inventory is based on the comparison between the average data and methodology of the 4th IMO GHG Study 2020 and the Port of Los Angeles inventory of Air Emission 2019.

This section exposes the process of data sorting and assumptions made to obtain the total amount of fuel that each vessel burned in designated anchor areas during 2019 for each approach (IMO4 and POLA19). Therefore, when calculating emissions with both methodologies, the results obtained can be compared validated against each other.

5.2.1.1 2019 Inventory Based on the IMO 4th GHG Study

The 4th IMO GHG Study includes a global emission inventory of greenhouse gases and relevant substances emitted to the air from vessels larger than 100 GT [1]. Considering an anchor operational mode, IMO4 appoints a fuel-based bottom-up estimation for CO_2 emissions, where the calculation depends on the intrinsic amount of pollutants in a particular fuel and engine type [1]. Basically, this section shows the assumptions made to comprise an inventory using average data and its method.

The secondary data provided by the Port of Gothenburg is used to obtain information such as ship identification, designated anchor area and time at anchor. The information is fairly complete, but part of the information required to follow the IMO4 study to be generated or assumed. 99.8% of vessels in the Portit database are directly matched with IMO4 equivalent. However, the remaining 0.2% vessel in Portit are adapted and matched trying to find the most similar vessel type from IMO4. Basically, this is done to homogenize the entire data and categorize vessels that did not take part in IMO4 like; special vessels, survey vessels, and navy vessels.

Table 5.1 shows the type of vessel from the retrieved data 2019 (Gothenburg, Sweden) and IMO4 (worldwide) as well as the relation between them. Vessels labelled as "no data" means that such vessels were not at anchor during 2019. Additional, "as if" is assigned when a symmetrical match is not attained, following a pairing criterion based on the mission and crew size. For example, naval vessels are to have redundant systems and thereby redundant power [42] consumption, plus numerous crews to uphold standby warfare capabilities, which could be roughly approximated to be almost equivalent to a cruise ship providing hospitality services for multiple passengers rather than an oil tanker for instance. Nonetheless, there are only four entries for naval vessels out of 1109 port call for anchor, so any discrepancies regarding vital machinery data are imperceptible.

Table 5.1: Vessel type equivalent IMO4

Type of vessel Portit	Match	IMO4
Bulk Carrier	data	Bulk Carrier
Chemical Tanker	data	Chemical Tanker
Container Vessel	data	Container
General Cargo	data	General Cargo
Gas Tanker	data	Liquefied Gas Tanker
Tanker DH	data	Oil Tanker
Other liquid tankers	no data	Other liquid tankers
Ferry pax only	no data	Ferry pax only
Cruise	no data	Cruise
Ferry RoPax	no data	Ferry RoPax
Refrigerated Bulk	no data	Refrigerated Bulk
RoRo Vessel	no data	RoRo
Car Carrier	no data	Vehicle Car Carrier
Yacht	no data	Yacht
Service, tug	no data	Service, tug
Miscellaneous, fishing	no data	Miscellaneous, fishing
Offshore Vessel	no data	Offshore Vessel
Service, other	no data	Service, other
Miscellaneous, other	no data	Miscellaneous, other
Special Vessel	as if	Ferry RoPax
Survey Vessel	as if	Ferry RoPax
Naval Vessel	as if	Cruise

IMO4 categorizes the type of vessel reflecting solely upon the size in term of the cargo capacity. Thus, the size of the vessel can be established by deadweight – DWG if the vessels transport cargo, by gross tonnage – GT if the vessels transport passengers or a combination of passengers and cargo, by TEU if it is a container vessel, or by cubic meters if it is a liquefied gas tanker.

The retrieved data provides gross tonnage (GT) and deadweight (DWT) information of most vessels. However, missing data, 1.16% of vessels were completed using the online platform Marine Traffic, 18 vessels missing DWT and 23 container vessels missing TEU information.

As machinery information neither for main propulsion nor auxiliary systems is available in the retrieved data. The fuel consumption and the auxiliary generated power are imported from IMO4. Accordingly, the auxiliary engine and boiler power output is determined by look-up tables provided in the fourth GHG IMO Study in Table 5.2. These values only depend on the ship type and size; therefore, it is a straightforward correlation using previous assumptions on vessel type.

Table 5.2: Summary of IMO Table 17

Type of vessel	**Size Range**	**Boiler Output (kW)**	**Genset Output (kW)**
Bulk carrier	$0 < DWG \leq 9,999$	70	180
Bulk carrier	$10,000 < DWG \leq 34,999$	70	180
Bulk carrier	$35,000 < DWG \leq 59,999$	130	250
Bulk carrier	$60,000 < DWG \leq 99,999$	260	400
Bulk carrier	$100,000 < DWG \leq 199,999$	260	400
Bulk carrier	$200,000 < DWG \leq +200,000$	260	400
Chemical tanker	$0 < DWG \leq 4,999$	160	170
Chemical tanker	$5,000 < DWG \leq 9,999$	160	490
Chemical tanker	$10,000 < DWG \leq 19,999$	240	490
Chemical tanker	$20,000 < DWG \leq 39,999$	320	550
Chemical tanker	$40,000 < DWG \leq +40,000$	320	550
Container	$0 < TEU \leq 999$	250	450
Container	$1,000 < TEU \leq 1,999$	340	910
Container	$2,000 < TEU \leq 2,999$	450	910
Container	$3,000 < TEU \leq 4,999$	480	1,350
Container	$5,000 < TEU \leq 7,999$	580	1,400
Container	$8,000 < TEU \leq 11,999$	620	1,600
Container	$12,000 < TEU \leq 14,499$	630	1,800
Container	$14,500 < TEU \leq 19,999$	630	1,950
Container	$20,000 < TEU \leq +20,000$	700	1,950
General cargo	$0 < DWG \leq 4,999$	0	50
General cargo	$5,000 < DWG \leq 9,999$	110	130
General cargo	$10,000 < DWG \leq 19,999$	150	370

Table 5.2 continued from previous page

Type of vessel	**Size Range**	**Boiler Output (kW)**	**Genset Output (kW)**
General cargo	$20,000 < DWG \leq +20,000$	150	370
Liquefied gas tanker	$0 < CBM \leq 49,999$	200	240
Liquefied gas tanker	$50,000 < CBM \leq 99,999$	200	1,700
Liquefied gas tanker	$100,000 < CBM \leq 199,999$	300	2,000
Liquefied gas tanker	$200,000 < CBM \leq +200,000$	600	7,200
Oil tanker	$0 < DWT \leq 4,999$	100	250
Oil tanker	$5,000 < DWT \leq 9,999$	150	375
Oil tanker	$10,000 < DWT \leq 19,999$	250	500
Oil tanker	$20,000 < DWT \leq 59,999$	270	520
Oil tanker	$60,000 < DWT \leq 79,999$	360	490
Oil tanker	$80,000 < DWT \leq 119,999$	400	640
Oil tanker	$120,000 < DWT \leq 199,999$	500	770
Oil tanker	$200,000 < DWT \leq +200,000$	600	770
Other liquid tankers	$0 < DWT \leq 999$	200	500
Other liquid tankers	$1,000 < DWT \leq +1,000$	200	500
Ferry-pax only	$0 < GT \leq 299$	0	190
Ferry-pax only	$300 < GT \leq 999$	0	190
Ferry-pax only	$1,000 < GT \leq 1,999$	0	190
Ferry-pax only	$2,000 < GT \leq +2,000$	0	520
Cruise	$0 < GT \leq 1,999$	950	450
Cruise	$2,000 < GT \leq 9,999$	950	450
Cruise	$10,000 < GT \leq 59,999$	950	3,500
Cruise	$60,000 < GT \leq 99,999$	950	11,500
Cruise	$100,000 < GT \leq 149,999$	950	11,500
Cruise	$150,000 < GT \leq +150,000$	950	11,500
Ferry-RoPax	$0 < GT \leq 1,999$	250	105
Ferry-RoPax	$2,000 < GT \leq 4,999$	250	330
Ferry-RoPax	$5,000 < GT \leq 9,999$	250	670
Ferry-RoPax	$10,000 < GT \leq 19,999$	380	1,100
Ferry-RoPax	$20,000 < GT \leq +20,000$	380	1,950
Refrigerated bulk	$0 < DWG \leq 1,999$	270	570
Refrigerated bulk	$2,000 < DWG \leq 5,999$	270	1,200
Refrigerated bulk	$6,000 < DWG \leq 9,999$	270	1,650
Refrigerated bulk	$10,000 < DWG \leq +10,000$	270	3,100
Ro-Ro	$0 < DWG \leq 4,999$	250	430
Ro-Ro	$5,000 < DWG \leq 9,999$	250	680
Ro-Ro	$10,000 < DWG \leq 14,999$	380	950
Ro-Ro	$15,000 < DWG \leq +15,000$	380	950
Vehicle/Car Carrier	$0 < DWG \leq 9,999$	300	500
Vehicle/Car Carrier	$10,000 < DWG \leq 19,999$	300	550
Vehicle/Car Carrier	$20,000 < DWG \leq +20,000$	300	550

Table 5.2 continued from previous page

Type of vessel	**Size Range**	**Boiler Output (kW)**	**Genset Output (kW)**
Yacht	$GT > 0$	1	130
Service - tug	$GT > 0$	1	80
Miscellaneous - fishing	$GT > 0$	1	200
Offshore Vessel	$GT > 0$	1	320
Service - other	$GT > 0$	1	220
Miscellaneous - other	$GT > 0$	110	150

To determine the specific fuel consumption - SFC (gr/kWh) for the auxiliary machinery, IMO4 presents a look-up Table 5.3, that depends on the engine type, fuel type and the year build of the ship.

Table 5.3: Summary of IMO Table 19: SFC (gr/kWh) for auxiliary machinery based on fuel type

Engine type	**Year of Built Range**	**HFO**	**MDO**	**LNG**
Gas Turbine	[1900 , 1983]	305	300	N/A
Gas Turbine	[1984 , 2000]	305	300	N/A
Gas Turbine	[2001 , 2020]	305	300	203
Steam Turbine/Boiler	[1900 , 1983]	340	320	285
Steam Turbine/Boiler	[1984 , 2000]	340	320	285
Steam Turbine/Boiler	[2001 , 2020]	340	320	285
Auxiliary Engine	[1900 , 1983]	225	210	N/A
Auxiliary Engine	[1984 , 2000]	205	190	173
Auxiliary Engine	[2001 , 2020]	195	185	156

The year-built information is missing from the retrieved data for 76% of the entries. Thus, for those entries it was assumed to be 2007 as the year built; the reason is that the median value of year built indicated in the qualitative results is 2007 for the ships that came to Gothenburg between January and May 2021.

An important assumption has to do with the type of fuel used in auxiliary engines and boilers. There is inexistent information with regards to the burned fuel at anchor for 2019. The port of Gothenburg lies in the North Sea which is nominated as an Emission Control Area – ECA under Annex VI MARPOL – in the category of Prevention of air pollution by ships [43]. SECA regulation for SO_X entered into force in November 2006 in the North Sea, so that the 285 vessels are to meet the convention in 2019. Although SO_X are not considered for this study, their regulations enable a shift to a lower sulfur content fuel that alters the CO_2 emission inventory because of the change of fuel. Moreover, the results from the qualitative research appoint MDO as the only fuel combusted. Therefore, it is assumed that all vessels are using MDO when anchor at the port of Gothenburg.

Even though Table 5.3 differentiates between HFO, MDO and LNG. The liquefied gas tankers are assumed to burn also MDO when anchor, based on results of the qualitative questionnaires, where a vessel stated that "only ME is running on LNG and AEs are running only on very low sulfur gasoil".

To calculate the fuel consumption (FC), both the third and fourth IMO GHG study assumes that the load factor has no dependency on the fuel consumption for auxiliary machinery [1]. This provides a simplified formula that does not consider any load factor for boilers or generating sets. Therefore, the rate between the fuel consumption and the operating time (Equation 5.1) is the product of specific fuel consumption [SCF] and the demanded power [W]. This ratio can be used for boilers and auxiliary engines, the dimensional analysis in Equation 5.1.

Fuel consumption equation 5.1

$$FC = SFC \times W \tag{5.1}$$

FC dimensional analysis of Equations 5.1

$$FC = \frac{gr.}{kW \times h} \times \frac{kW}{1} \tag{5.2}$$

$$FC = \frac{gr.}{\cancel{kW} \times h} \times \frac{\cancel{kW}}{1} \tag{5.3}$$

$$FC = \frac{gr.}{h} \tag{5.4}$$

After the calculation of fuel consumption, the CO_2 emissions rate per hour (EM) is estimated by obtaining the product between fuel consumption [FC] and the fuel-based emission factor [EFF] that depends on the fuel type, as shown in Table 5.4. Given that it has been assumed to be MDO for all vessels, the EF is a constant value all along this case study.

Table 5.4: Fuel-based emissions factors - IMO Table 21

Fuel type	**Carbon Content**	**EF gr. CO_2 per gr fuel**
HFO	0.8493	3.114
MDO	0.8744	3.206
LNG	0.7500	2.750
Methanol	0.3750	1.375
LSHFO 0.01	0.8493	3.114

The equation to calculate the CO_2 emissions is shown below as well as the dimensional analysis for Equation 5.5.

CO_2 Emission Equation 5.5

$$EM = FC \times EF \tag{5.5}$$

Emissions dimensional analysis of Equation 5.5

$$EM = \frac{gr.(fuel)}{h} \times \frac{gr.(CO_2)}{gr.(fuel)} \tag{5.6}$$

$$EM = \frac{\cancel{gr.(fuel)}}{h} \times \frac{gr.(CO_2)}{\cancel{gr.(fuel)}} \tag{5.7}$$

$$EM = \frac{gr.(CO_2)}{h} \tag{5.8}$$

5.2.1.2 POLA19

Starcrest produces annual activity-based emission inventories that serve as a tool to track the port effort to reduce emissions to air that stem from the maritime activity and related sources [35]. The bottom-up inventory is estimated based on the vessel power demand and pollutants linked to specific engine types.

For this methodology, the secondary data is also sorted out and categorized to match the vessel type of POLA19. In this case, 4.5% of the vessels are adapted and matched. The remaining are symmetrically match with POLA19 equivalent vessel type as shown in Table 5.5. It is important to highlight that POLA19 does not have gas tankers in the vessel type classification.

Table 5.5: Vessel type equivalent POLA19

Type of vessel	**Match**	**POLA19**
Bulk Carrier	data	Bulk
Chemical Tanker	data	Tanker Chemical
Container Vessel	data	Container
General Cargo	data	General Cargo
Gas Tanker	as if	Tanker
Tanker DH	data	Tanker
Other liquid tankers	as if	Tanker Chemical
Ferry pax only	as if	Cruise
Cruise	data	Cruise
Ferry RoPax	as if	RoRo
Refrigerated Bulk	data	Reefer
RoRo	data	RoRo

Table 5.5 continued from previous page

Type of vessel	Match	POLA19
Car Carrier	data	Auto Carrier
Yacht	as if	Miscellaneous
Service, tug	as if	Miscellaneous
Miscellaneous, fishing	as if	Miscellaneous
Offshore Vessel	data	Ocean Tug
Service, other	as if	Miscellaneous
Miscellaneous, other	data	Miscellaneous
Special Vessel	as if	Miscellaneous
Survey Vessel	as if	Miscellaneous
Naval Vessel	as if	Miscellaneous

Table 5.6 of POLA19 average data only differentiate between output power for auxiliary engine and boilers, respectively. Only containers and tankers are differentiated by size. For the tankers, it has been associated the ranges of DWT based on tanker type (Handymax, Panamax, Aframax). Even though the retrieved data provides GT and DWT data, missing data of 0.99% of the vessels are completed using the online platform Marine Traffic.

The auxiliary generating power is estimated with the look-up tables developed by POLA19. These values are based on the ship type and size, and therefore it is a straightforward correlation with previous assumptions on vessel type.

Table 5.6: Summary of Table 3.2 and Table 3.5 of Port of LA

Vessel Type	Size Unit	AE power [KW]	BO power [KW]
Auto Carrier	DWG	622	305
Bulk	DWG	253	125
Cruise	DWG	na	306
General Cargo	DWG	180	160
Ocean Tug (ATB/ITB)	DWG	79	0
Miscellaneous	DWG	200	96
Reefer	DWG	828	285
RoRo	DWG	434	251
Tanker - Chemical	DWG	402	255
Tanker Handymax	DWG	560	144
Tanker Panamax	DWG	379	451
Tanker Aframax	DWG	474	375
Container 1000	TEU	1000	270
Container 2000	TEU	942	350
Container 3000	TEU	559	416
Container 4000	TEU	1124	446
Container 5000	TEU	967	572
Container 6000	TEU	1464	595

Table 5.6 continued from previous page

Vessel Type	Size Unit	AE power [KW]	BO power [KW]
Container 7000	TEU	884	677
Container 8000	TEU	1055	703
Container 9000	TEU	996	618
Container 10000	TEU	1051	511
Container 11000	TEU	1684	694
Container 12000	TEU	2000	790
Container 13000	TEU	1224	560
Container 14000	TEU	1156	495
Container 17000	TEU	1000	585
Container 19000	TEU	1600	761

POLA methodology does not use SFC, instead it provides a Specific Emission Factor (SEF [grCO_2/kW*h]). This value is estimated from the look-up Table 5.7, based on the engine speed, fuel type and IMO Tier.

Table 5.7: Summary GHG Emission factor auxiliary engines, Table 2.10 San Pedro Port

Engine Category	IMO Tier	Model	CO_2	N2O	CH4
Medium speed AE	Tier 0	1999 and older	686	0.029	0.0120
Medium speed AE	Tier I	2000 to 2011	686	0.029	0.0120
Medium speed AE	Tier II	2011 to 2016	686	0.029	0.0120
Medium speed AE	Tier III	2016 and newer	686	0.029	0.0120
High speed AE	Tier 0	1999 and older	656	0.029	0.0100
High speed AE	Tier I	2000 to 2011	656	0.029	0.0100
High speed AE	Tier II	2011 to 2016	656	0.029	0.0100
High speed AE	Tier III	2016 and newer	656	0.029	0.0100

For the fuel type burned in the auxiliary machinery for POLA19, the same assumptions than the IMO4 method are considered. All vessels are assumed to burn MDO as Gothenburg port is considered an SECA area, so in order to comply with the IMO regulations, ships have to shift to lower sulfur fuels.

Another assumption made in order to estimate the SEF is that all ships have a medium-speed engine. Emissions were calculated considering medium speed or high speed, the results were very similar with a difference of 4%. Therefore, medium speed was assumed for all ships, which has higher emissions than high speed, according to Table 5.7.

For the estimation of the SEF following POLA19 methodology is necessary to consider the IMO Tiers, that are directly linked to the age of the machinery, assumed to be the same as the build year of the ship. However, the specific emission factor for CO_2 is constant for all Tiers, in accordance with Table 5.7, and therefore the age of the ship is irrelevant.

The CO_2 emissions are calculated as the product of a specific emission factor (SEF), the demanded power for the auxiliary machinery (W), and the time at anchor (AT) as shown in Equation 5.9.

CO_2 Emission Equation 5.9

$$EM = SEM \times W \times AT \tag{5.9}$$

Emissions dimensional analysis of Equation 5.9

$$EM = \frac{gr.(CO_2)}{kW \times h} \times kW \times h \tag{5.10}$$

$$EM = \frac{gr.(CO_2)}{\cancel{kW} \times \cancel{h}} \times \cancel{kW} \times \cancel{h} \tag{5.11}$$

$$EM = gr.(CO_2) \tag{5.12}$$

5.2.2 CO_2 Emissions Hybrid Inventory Method 2021

This section describes the methodology used for the development of the inventory of 2021, and assumptions made to obtain the total amount that each vessel burned in designated anchor areas in 2021. Additionally, it details the arithmetic process to establish output power, consumption, and the CO_2 emissions for BRAVE ECO method (BE) and a comparison of a particular demographics of tankers between BE and IMO4.

The emissions inventory of 2021 is comprised of all the vessels that visited the port of Gothenburg from January 1st 2021 to April 30th 2021. This secondary data is provided by the Port of Gothenburg from the software Portit, the data is used to obtain information such as ship identification, designated anchor area and time at anchor. The inventory is developed with specific data from this research and average data from the IMO4.

In an attempt to use the least average data possible, a hybrid[1] inventory is created. The output power and fuel consumption for auxiliary engines are comprised through the following hierarchy.

1. Specific data of a vessel
2. Specific data by sister ship

[1]Specific data from this research (BRAVE ECO) plus average data from IMO4.

3. Non-linear logarithmic regression

4. Average data from IMO4

The output power and fuel consumption for all boilers is comprised through IMO4 average data. Once the output power and the fuel consumption are attained for the vessels at anchor, it is possible to estimate a hybrid CO_2 inventory.

5.2.2.1 BRAVE ECO Inventory

The retrieved specific data, obtained through the technical questionnaires, is reviewed and discussed. It is also compared from a technical perspective against reference values such as the hourly energy consumption on the MSB[2] to be finally vetted or disregarded. Afterwards, the retrieved information is arranged depending on their hierarchy. Most tanker vessels are directly linked to the specific vessel and sister/like ship and some discrete values for liquefied gas tankers and containers. The hierarchy continues with a logarithmic model that only applies to tanker vessels, and finally, the last step on the hierarchy is the use of average data from IMO4.

A sensibility analysis is carried to determine the variation of the EI when incorporating a wider range of gross tonnage to allocate sister/like ships. This action maximizes the use of sister ships with BE specific data and minimizes average data. When assigning sister/like ship, it is considered two parameters from specific data; the ship type and a range of the gross tonnage. In the following bar chart, it is possible to appreciate the hierarchy distribution as the range changes. The sensibility analysis showed that with a range of +/-5% GT, it is possible to allocate 11 more port calls with SD within an acceptable similar GT than with a range of +/-3%. The variation in CO_2 emissions between using 3% and 5% is 0.47%, which is insignificant.

A sensibility analysis is carried to determine the variation of the EI when incorporating a wider range of gross tonnage to allocate sister/like ships. This action maximizes the use of sister ships with BE specific data and minimizes average data. When assigning sister/like ship, it is considered two parameters from specific data; the ship type and a range of the gross tonnage. In Figure 5.1 it is possible to appreciate the hierarchy distribution as the range changes. The sensibility analysis showed that with a range of +/-5% GT, it is possible to allocate 11 more port calls with SD within an acceptable similar GT than with a range of +/-3%. The variation in CO_2 emissions between using 3% and 5% is 0.47%, which is insignificant.

[2]Main switch board.

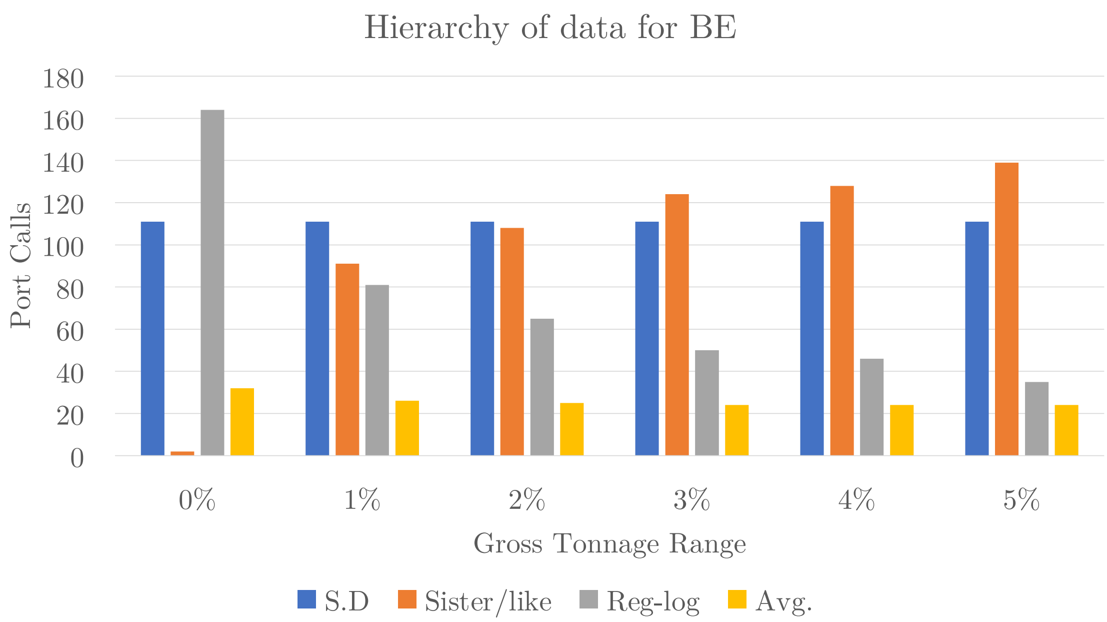


Figure 5.1: Hierarchy of data for Brave Eco inventory

When considering a range of +-/5% GT for the year 2021, 36% of the port calls are comprised by direct specific data, 45% by sister specific data, 11% by a logarithmic regression from specific data, and 8% by IMO4 average data.

For the non-linear logarithmic regression, the gross tonnage is selected as the independent variable to relate the dependent variables, output power and the FC. It does not mean that the GT is the only or most suitable variable to attain such relations. GT is chosen because it is an entry consistent in every port call of the Portit secondary data. Thus, the logarithmic equation is based on the ship type and size to estimate output power and fuel consumption only for generating sets but not for boilers due to scarce information. The logarithmic regression accounts only for oil tanker and chemical tanker between 2900 and 62500 gross tonnage.

Figure 5.2 shows the specific data generated through BE for auxiliary engines output power. There are a few data points from the specific data that appear to be elevated values (SD.2), these are not disregarded from the dataset. Such values may correspond to auxiliary engines output powers that point to be reference values instead of operational values at anchor. Figure 5.2 also presents the non-linear logarithmic regression for the output power of the genset with r-squared values of approximately 80%, the SD.2 values are not used to create the regression.

For the fuel consumption, Figure 5.3 shows the specific data generated through BE for auxiliary engines fuel consumption. There is also data that has a lower fuel consumption rate for the ship size compared to similar ships among our data. For the non-linear logarithmic regression for fuel consumption these values are not considered, presenting a r-squared values of approximately 80%.

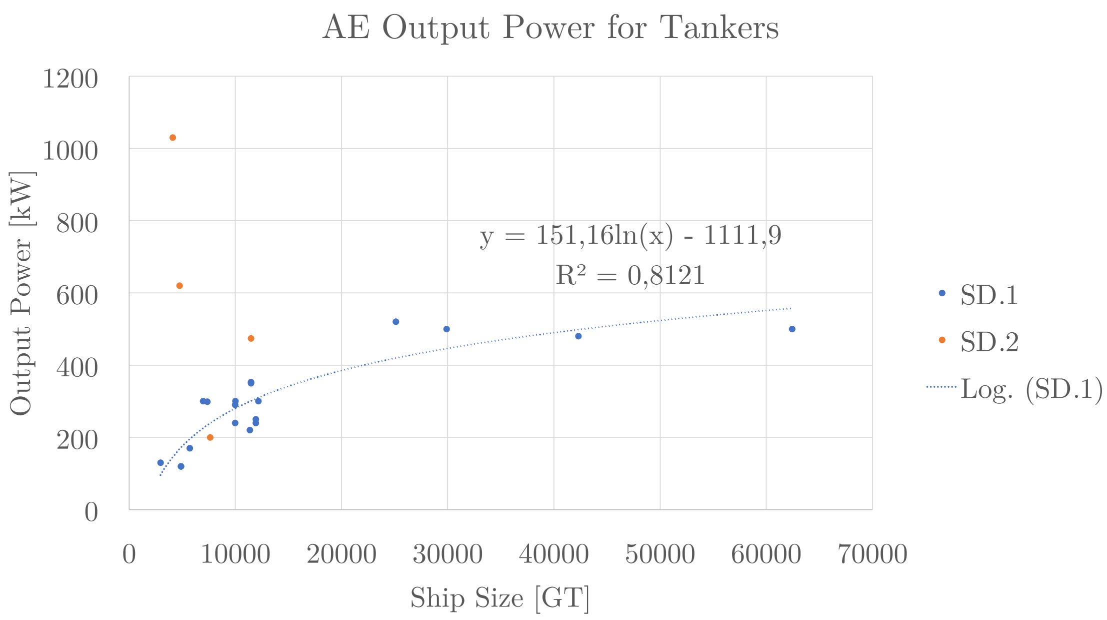


Figure 5.2: Output power for tankers auxiliary engines at anchor

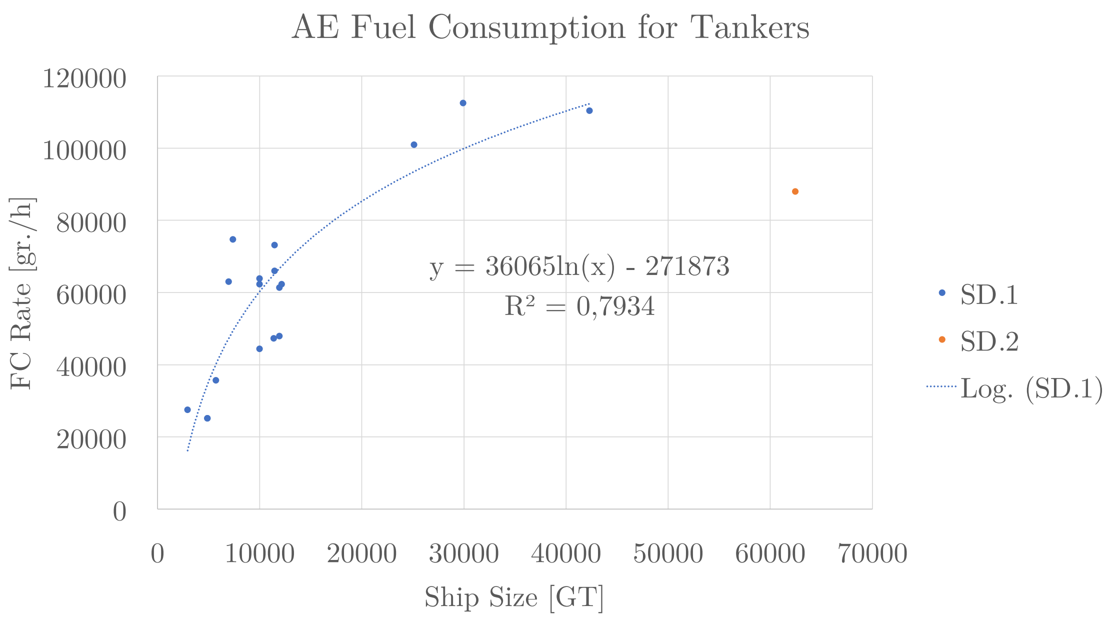


Figure 5.3: Fuel consumption for tankers auxiliary engines at anchor

The coefficient of determination still lacks a bit of precision to portrait a reliable proportion of the variance for the dependent variables output power and FC. That is why the BE method prevails specific data to sister/like vessels over the regression.

It shall be noted that the specific data is a bit scattered, but it is still possible to identify a tendency for output power and FC in Figure 5.2 and Figure 5.3 respectively.

To calculate the output power (W), Equation 5.13, discrete output powers are plotted against the ship size. It is assumed that the load factor is not taken into account; this provides a simplified formula for the non-linear regression of output power as a function of the natural logarithm of the gross tonnage.

Equation 5.13 for AE output power in BE

$$W = 151.16 \times \ln(GT) - 1111.9 \tag{5.13}$$

Dimensional analysis of Equation 5.13

$$W = kW \tag{5.14}$$

To calculate the fuel consumption (FC), Equation 5.15, the product of discrete output powers and discrete SFC is obtained and plotted against the GT. This provides a non-linear regression for the fuel consumption rate in terms of the natural logarithm of the gross tonnage. The consumption rate is multiplied with the anchor time (AT) to calculate FC.

Fuel consumption Equation 5.15

$$FC = (36065 \times \ln(GT) - 271873) \times AT \tag{5.15}$$

FC dimensional analysis of Equation 5.15

$$FC = \frac{gr.fuel}{h} \times h \tag{5.16}$$

$$FC = \frac{gr.fuel}{\not{h}} \times \not{h} \tag{5.17}$$

$$FC = gr.fuel \tag{5.18}$$

After the calculation of fuel consumption, the CO_2 emissions rate per hour (EM) is estimated by obtaining the product between fuel consumption (FC) and the fuel-based emission factor (EFF) that depends on the fuel type, 3.206 gCO_2/gfuel as shown in Table 5.4. As the fuel consumed while anchor has been assumed to be MDO for all vessels, the EF is a constant value all along this research.

Equation 5.19 to calculate CO_2 BE emissions

$$EM = FC \times EF \tag{5.19}$$

The vessels that do not fit with the logarithmic regression, sister ship or identical ship are calculated using average data. Part of the information required to import IMO4 average data had to be generated or assumed, such as DWT or TEU.

For 2021 all the 309 port calls at anchor it is found a symmetrical match with the 4th IMO GHG Study's equivalent. Table 5.8 shows vessel types considered for 2021.

Table 5.8: Vessel types for 2021 EI

Type of vessel Portit
Bulk Carrier
Chemical Tanker
Container Vessel
General Cargo
Gas Tanker
Tanker DH
Car Carrier

As mentioned in section 4.5.2.1.1 the IMO4 categorizes the type of vessel reflecting solely upon the size in term of the cargo capacity. Thus, the size of the vessel can be established by deadweight – DWG if the vessels transport cargo, by gross tonnage – GT if the vessels transport passengers or a combination of passengers and cargo, by TEU if it is a container vessel, or by cubic meters if it is an liquefied gas tanker.

The retrieved data provides gross tonnage (GT) and deadweight (DWT) information for most vessels. However, missing data, 1.16% of vessels were completed using the online platform Marine Traffic, 18 vessels missing DWT and 23 container vessels missing TEU information.

The fuel consumption and the auxiliary engine powers are imported from IMO4 for most vessels other than the tankers. However, for tanker vessel out of the range of 2900-62500 GT, information is taken from IMO4. Moreover, the boiler power output for all ships is determined by average data. Accordantly, the auxiliary engine and boiler power output is determined by look-up tables provided in the IMO 4 Study, Table 5.2. These values only depend on the ship type and size; therefore, it is a straightforward correlation using previous assumptions on vessel type.

To determine the specific fuel consumption (SFC (gr/kWh)) for the auxiliary machinery, the IMO4 presents a look-up Table 5.3 that depends on the engine type, fuel type and the year build of the ship.

The year-built information is missing from the retrieved data for 76% of the entries. Thus, for those entries it was assumed to be 2007 as the year built; the reason is that the median value of year built indicated in the qualitative results is 2007 for the ships that came to Gothenburg between January to April 2021.

An important assumption has to do with the type of fuel used in auxiliary engines and boilers. There is inexistent information with regard to the burned fuel at anchor for 2021. MDO is chosen because of the emission control area, explained in Section 5.2.1.1, and the qualitative results.

To calculate the fuel consumption (FC) and CO_2 emissions (EM), the arithmetic follows the same assumptions and equations than Section 5.2.1.1.

5.2.2.2 Tanker Comparison Between BE and IMO4

The quantitative method also proposes a partial comparison between BE and IMO4. This intends to assess inaccuracies within the statistical calculations that create average data from specific data, and possibly to point out systematic errors. Thereby, the results of the CO_2 emission are presented and analyzed for the oil tankers and chemical tankers in the range of 2900 and 62500 gross tonnage.

The comparison method undertakes a graphical display with a parallel boxplot and scatter plot to compare the two mentioned datasets in terms of the center distribution, the interquartile ranges, and the spread. Moreover, the comparison shows the percentual deviation to each other and description of outliers.

6

Qualitative Results 2021

This section presents the results from the qualitative questionnaire (Annex D). The results contemplate the demographics, energy generation and usage, data collection onboard and energy efficiency matters. These results aim to give a holistic perspective on energy use linked to fuel consumption for vessel at anchor. The results hereunder are limited to the surveyed ships at anchor in Gothenburg during the first quarter of 2021.

6.1 Demographics

From the 75 questionnaires sent to all vessels at anchor in Gothenburg, 64 were tankers and the rest were vehicle carriers, containers, LNG, and general cargo. The retrieving rate is 24%, equivalent to 18 vessels, from which 94% are tankers and a container vessel. Therefore, the qualitative results mostly depict energy generation, usage, and management among tankers. Table 6.1 shows the demographics of the ships.

Table 6.1: Demographics of the sample

Type of Vessel	Sample Number	Percentage
Chemical Tanker	7	39%
Oil tanker	5	28%
Oil/Chemical Tanker	3	17%
LNG	2	11%
Container	1	6%

Most of the respondents of the qualitative questionnaire have technical knowledge. 61% of the addressees are chief of engineers and 21% shipmasters. The remaining 18% was not noted.

For the year built (Figure 6.1), the interquartile range specifies that 50% of the vessels are between 2005 to 2009. The spread of the data is relatively concentrated, except for one ship that was built in 2016. The median for the year built is 2007.

The deadweight (Figure 6.2) of the vessels has an interquartile range between 7000 MT and 17000 DWT with a median of 12000 DWT. Among the results, a couple of crude oil tankers (47000 and 11200 DWT) are much larger than the median. These vessels are not outliers, on the contrary, they account for valuable data retrieved on energy matters from large crude carriers.

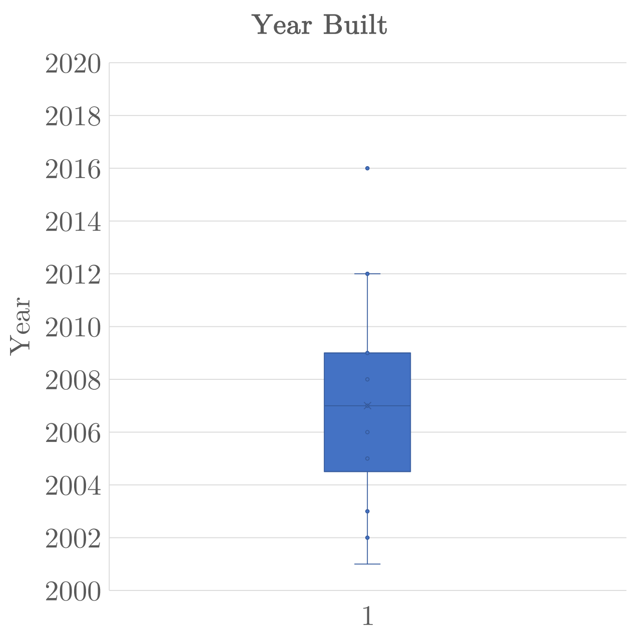


Figure 6.1: Year built all vessels retrieved (94% tankers)

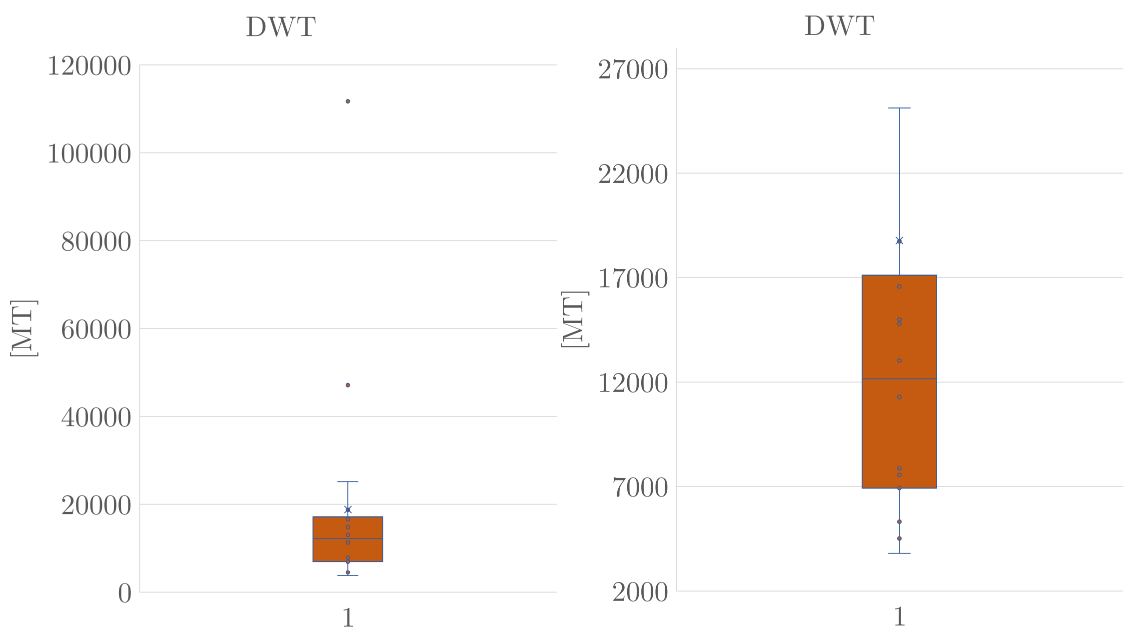


Figure 6.2: Ship capacity all vessels (94% tankers)

6.2 Energy Generation and Usage

The auxiliary machinery is all machinery onboard that is not the main engine. Therefore, for this study auxiliary machinery is divided into auxiliary engines (generators) to generate electrical power and boilers for heat power onboard.

6.2.1 How is the energy generated on board at anchor?

The majority of the ships state that the electrical power comes from just one auxiliary engine on service. The vessels in the survey indicate that such power is being generated through auxiliary engines; to be more precise via generating sets.

Regarding the procedure to generate energy among the ships, all onboard processes relate to energy transformation from an energy carrier to electric energy. Additionally, surveyed ships in this study are burning low sulfur MDO which in most cases is said to be initially retained in the storage tanks and then pumped out to a settling tank to be sedimented by gravity. After that, the MDO is filtered and purified through a centrifugal separator. The final step is to transfer the fuel to a service tank from which the generating set feeds from. A 16500 DWT Oil/Chemical tanker even mentioned that the fuel is sent through a fuel booster module before being used.

Regarding the heat generated onboard, little information was collected. 15000 DWT Chemical tanker explained that heat energy is generated by “catamiser[1]utilizing auxiliary engine exhaust gas waste heat”. Additionally, two tanker vessels answered that heat power at anchor comes from boilers with start-stop sequences used simultaneously while running the auxiliary engine.

6.2.2 How is the energy used on board at anchor?

Once the generated power is available, the energy is used in different areas according to the results. Although this study does not intend to quantify the electrical load attached to the fuel consumption, it can identify relevant sources of power consumption at anchor; meaning where the produced energy might go. To better understand the results, the answers are grouped by engine room, crew facilities, bridge, and cargo related.

Engine rooms allocate about 60% of the services mentioned in the results. The most popular service within this group is the HVAC systems (Heating Ventilation Air Conditioning), followed by the cooling plant. The data reports that HVAC systems

[1]A catamiser “is a combined unit for waste heat recovery and NOx reduction of exhaust gases” (GESAB, 2021)

are also very popular for accommodation services. The list below is a compilation of additional services used in the engine room (ER) mentioned in the results.

- Boiler's supply systems. In the quantitative questionnaire, no vessel has provided electric boilers data, just conventional oil-fired boilers
- Heating for bunkers tanks and lube oil
- Centrifugal purifiers and filtering units of the generator fuel system
- Electric motors of ship systems
- Various pumps and systems in the engine room
- Exhaust and supply fans
- Air compression
- LNG process room fans and glycol pumps
- Pipe heating
- Main engine preheating, before it is put on service before shifting
- Engine room lighting

Crew facilities are the second area with the most services. The most common services are HVAC and the hoteling load for accommodation on the crew. The hoteling load mainly includes the electric sockets disposed of for the crew, galley equipment, and cold rooms to store supplies.

Lightning is a complex load-balance group to sectorize as it extends over almost every single space onboard and relates to other load balance groups, for example, safety lighting at anchor. It can also be categorized as a general ship service. Lighting is one of the most frequent answers retrieved regarding how energy is used. A distinction is noticeable within the answers between general interior lighting and external lighting for cargo decks at night and regulatory positioning/navigating lights.

The bridge was also identified as a sector that consumes energy while anchoring. 15 vessels stated that the energy is used to supply electrical energy for control and standby navigation systems for positioning, communications, and it could be inferred that other function necessary to enable an operative bridge.

Surprisingly, the cargo sector is mentioned in a single entry as cargo equipment for a liquefied gas tanker. However, cargo electrical loads cannot be generalized for all tanker vessel due to lack of information. Regarding liquefied gas tanker, the insulation of storage tanks does not sustain the cargo conditions at the boiling point of the liquified gas [44].Therefore, auto refrigeration is undertaken onboard to vent out the excess of heat [45], so in this case at anchor, active equipment aboard

LNG carriers is likely used to retain and adapt the pressure and temperature of the liquified cargo inside the tanks. Table 6.2 summarizes the main sectorization of load grouts at anchor during 2021.

Table 6.2: Energy sectorization load groups at anchor

Load group	**ER**	**Crew Fac.**	**Bridge**	**Cargo Sys.**
Navigation and safety services			X	
Lighting	X	X	X	
Auxiliary engine support systems	X			
Other engine room systems	X			
HVAC	X	X	X	
Galleys, refrigeration		X		
Accommodation services		X		
Cargo loads				X

6.3 Performing of Data Collection Onboard

With the purpose of preparing the path for future studies, this part aims to analyze the feasibility of specific data collection onboard, the level of technology of fuel consumption measuring, and how often it is delivered to shore. Additionally, these results mention current analytical tools for energy management.

6.3.1 How is energy-data collected and registered onboard?

This question aims to look at how the data is collected onboard in general, while the technical results intend to assess how digitalized the collection is among other aims. Therefore, any information regarding data collection onboard for fuel consumption is valuable.

Among the sample, it is possible to identify several options to collect data related to fuel consumption onboard. Therefore, three categories of different collection techniques are defined based on the answers received to create themes to analyze the data. The bins are defined as follow:

- Analog: when the fuel consumption and/or power are measured with analogue meters or catalogue curves and then externally computed
- Mixed: when the fuel consumption and/or power are measured with digital meters and then externally computed
- Digital: when the fuel consumption and power are automatically measured by digital meters collected in monitoring software.

Vessels with analogue technology account for 50% of the answers. Multiple combinations are reported to collect fuel consumption onboard. Some answers state that the analogue measurement is accomplished through analogue fuel meters on each genset which measure the inbound fuel flow to the generator, and then the crew use it for noon-reports. However, other vessels point that the fuel consumption can be recorded by sounding the service tank. Tank sounding is defined as the measurement of "height of the fluid from the surface of the fluid to the bottom of the tank" [46]. Another possible way inferred from answers is to attain fuel consumption via specific fuel consumption (SFC), which utilizes an additional gauge for the generated power. It is technically assumed that the performance curves of the generating sets are being checked for this purpose. After measuring the fuel consumption onboard, the dataset shows that this information is registered in different ways such as excel sheet, logbook, or report.

Vessels with digital technology represents 28% of the answers. Among the answers it is consistent the use of integral monitoring and performance ship systems such as LeanMarine[2] fleet analytics, KYMA system[3](KDU300), and in Kongsberg K-Fleet which are used onboard for energy data collection coming from digital meters and sensors. After that, the data is analyzed in the system and reported.

Data shows combined procedures[4] and mixed levels of technology[5] to attain collection and register of fuel consumption onboard. Among the answers is consistently found vessels with digital electronic gauging that provides ullage for the fuel tanks and monitoring through a software. Some vessels have reported the use of PPM footnote PPM Protection and Power Management by DEIF, is a Power Management System install onboard [49] to make measurements and management of power, but not for data collection.

As before mentioned, mixed technologies for measuring fuel consumption are depicted to be analogue or electronic, collecting data such as fuel flow or SFC. This data is afterwards registered into excel datasheets as well with other parameters for example, the specific gravity of the fuel to calculate fuel consumption. Additionally, to obtain a more detailed register, analogue flow meters are installed for each fuel consumer, which is mentioned to yield a satisfactory control over energy consumption.

The energy consumption of more than 70% of the vessels is recorded daily using the mentioned procedures (analogue or digital). The rest of the vessels have not specified when the data collection is done.

Regarding data reporting, data is sent in more than 50% of the cases online using reporting software, the rest of the vessels do not give information about it. In

[2]Fleet Analytics is a Lean Marine reporting and data analysis tool that manages data generated by a vessel while operating [47]

[3]KDU300 is a ship performance and monitoring tool with an integrated power meter system and features for energy management, noon-reports, and atmospheric emission reports [48]

[4]Such as digital and analogue.

[5]Such as digital gauge with or without software processing or other combinations.

terms of reporting frequency, several vessels deliver fuel information at the end of the charter, every departure or arrival, or on a weekly or monthly basis. Nevertheless, data shows that vessels with digital technologies tend to report to shore daily.

6.3.2 What are the parameters to estimate an accurate energy consumption with the information available onboard?

The question hereunder intends to capture crew insights on what parameters are used to estimate accurate energy consumption.

The answers show that vessels that are not installed with digital or automatic collection usually estimates energy consumption by measuring the fuel consumption and output power (kW). Additionally, the crew described another approach, such as the fuel's energy content provided by laboratories[6], to increase accuracy.

Among the crew's opinions regarding the level of accuracy and easiness of data collection, a couple of vessels using analogue technologies state that, if more accuracy is needed it has to be done manually and is very time-consuming as there is a considerable lack of technology. Conversely, vessels with mixed or digital technologies do not address the additional parameter to increase accuracy or data collection. A chemical tanker with digital tank reading and monitoring system points out that "all consumption is based on tank readings and will never be as accurate as, for example, flow meters or mass flow meters". Moreover, other tankers have stated that it is enough with considering just one parameter; fuel consumption, as there is no other power production or consumption onboard. Complementary, other insights introduce new parameters to be considered, such as the "heat energy consumption evaluation" and to have "kW/h counter on each generator to know how effective fuel was used" in every machine.

6.4 Efficiency and Emission's Reduction

6.4.1 What direct approaches have been used onboard to reduce energy consumption and/or emissions?

For the analysis hereunder, a direct approach is defined as an isolated activity carried out to save or reduce consumption or emissions, respectively. For example, an energy management plan can be formed by multiple isolated activities. The answers are allocated in three different themes, reduction of electrical consumption, abatement technologies, fuel- based carbon intensity. These results intend to give a general

[6]Technical laboratory certification of the bunker by the supplier.

insight and summarize the different approaches undertaken from different vessels to reduce energy consumption, rather than to analyze each particular vessel.

Almost 34% of the vessels undertake activities to reduce electric consumption by using the absolute minimum required. The main approaches can be summarized and listed as follows:

- Minimize the running equipment
- Turning off unnecessary lights
- Reducing heating on bunker tanks
- Operation in low speed the pumps and using of frequency converters
- Load reduction on generators
- Reducing the use of fans
- Using power management systems - PMS
- Waste heat recovery
- Optimizing the number of auxiliary engines and pumps

Around 28% of the vessels pursue activities to reduce emissions from a rigorous fuel-related stance, for instance using distillate marine fuels Grade- A “DMA 0.10%” and “DMA 0.07%” as the main fuel. Additionally, a 15000 DWT chemical tanker is equipped with fuel optimizers from Lean Marine and use “the full capability of the propeller by utilizing its combinator mode function. It lowers the engine RPM but raises the propeller pitch angle to achieve maximum output with less fuel consumption”. Although there is not specific information on the dataset accounting for the optimization through Lean Marine at anchor, it is possible to infer that generating sets could be optimized through the AE RPM (as in the main engines), but in the function of the electrical load.

Regarding abatement capabilities to reduce emissions, the answers accounts for about 16% of the ships. CO_2 direct abatement technologies, such as in-funnel carbon filters or carbon capture equipment, are not mentioned at all. However, some of the respondent identify heat recovery and low sulfur fuel as CO_2 abatement technologies. For example, an LNG vessel states that “only ME is running on LNG and AEs are running only on very low sulfur gasoil”. However, the dataset indicates that selective catalytic reduction – SCR are in place to reduce nitrogen oxides – NO_x.

On the other hand, about 20% of the vessels has no direct approaches to reduce energy consumption or emissions.

6.4.2 Are there external factors that might increment energy usage when anchored?

There are external factors that might increase the energy usage linked with fuel consumption at anchor. More than 90% of the respondents conceive the weather as the factor that produces most of the variations on the electrical load. "During very cold weather, we normally use more heating, so that it is an additional energy use" and a chemical tanker adds that the "boiler will increase fuel consumption". Additionally, extreme bad weather may impose a risk upon safety, and this is evidenced by an answer of a 16500 DWT chemical tanker that put on-service the main engines for drifting maneuvers at anchor.

Besides drills and the safety reasons exposed above, there are also listed considerations regarding ship operation and the cargo. Within ship operation are mentioned bunkering and tests included in the Planned Maintenance System – PMS that "requires the use of a system that are normally not used at anchor". Cargo operation increments energy usage at anchor by conditioning the cargo and performing "tank cleaning/ventilation or inertization".

6.4.3 Is there any management plan onboard to reduce energy consumption?

Almost 80% of the vessels answer The Ship Energy Efficiency Management Plan – SEEMP as the most used scheme to reduce energy consumption onboard. However, SEEMP does not limit additional company commitments as stated by one vessel, meaning that it can be used simultaneously with other procedures to reduce energy consumption. For example, SEEMP is mentioned to be actionable with the European Monitoring, Reporting and Verification Systems – EU MRV.

A couple of entries have in place ISO 50001 – Energy Management System, a conservation policy that aims to minimize energy use of all electrical consumers. ISO 50001 could be considered an equivalent of SEEMP, as both are energy management systems. Other vessels give detailed information of actions undertaken to reduce energy consumption such as "switching off the lights if you are leaving your cabin".

6.4.4 What are the factors to consider in a CO_2 reduction service

In the foreseeable future, if the Port of Gothenburg were to facilitate the energy used at anchor (low-carbon or renewable), almost 20% of the vessels are positively drawn to use such service as long as it is low cost, safe, and easy to connect without any loss of time of seamanship. Another important factor that concerns some of the vessels is if the system would enable enough capacity for extra activities to be performed while anchoring, such as tank cleaning operation, cargo conditioning, and HVAC systems for general services. Fuel-saving and environmental awareness are briefly mentioned.

However, around 10% of vessels disclose a different stand where they cannot picture how the port electrical cables can reach the vessel at the anchor designated areas considering that strong winds and currents can slightly drift the vessel. Over and above, it is stated by one ship that it is prohibited to drop anchor on the places where there are power cables in the seabed. This reinforces the hypothesis of having a modular prototype that can be mobilized and moored side by side with the main vessel. Thereby, the mooring shall hold drifting changes and re-positioning to a safer anchor location due to weather.

7

Quantitative Results

This section presents the results of the 2019 and the 2021 CO_2 emission inventory for the vessels at anchor in the Port of Gothenburg.

7.1 CO_2 Emissions Inventory Results 2019

This section presents the results of CO_2 emission inventory in the port of Gothenburg for 2019 based on IMO4 methodology. To comprise the most accurate inventory of emissions using average data, a comparison between the results of IMO4 and POLA19 is made and presented hereunder. Uncertainties and thoughts regarding the methodologies applied are presented in the discussion Section9.

From the 1109 port calls of vessels at anchor in Gothenburg, 81% are tankers corresponding to 214 unique ships. The second most significant group is 6% of the port calls by chemical tankers. Table 7.1 shows the whole 2019 demographics involved in the emission inventory considering ship type, port calls, and the number of different ships anchored in Gothenburg.

Table 7.1: Vessels' demographics 2019

Type	Number of Port Calls	Number of Ships
Oil tanker	897	214
Chemical tanker	69	23
Cruise	4	3
Liquefied gas tanker	47	12
General cargo	24	4
Ferry-RoPax	4	2
Container	60	23
Bulk carrier	0	0
Vehicle/Car Carrier	3	3
Ro-Ro	1	1
Total	**1109**	**285**

7.1.1 Fuel Consumption

The fuel consumption results are fuel-based to every port call. Fuel-based means that the CO_2 is estimated proportionally to the amount of pollutants found in a specific fuel type and engine [1]. In this case study, the consumption of diesel auxiliary engines and fuel-fired boilers is estimated from marine diesel oil. As evidenced in (6.2.1 of the qualitative results6.2.2), the operational anchor mode enables auxiliary systems such as generating sets and boilers, both run on MDO.

Due to the large demographics of oil tankers[1] attending port calls, the more significant amounts of MDO consumption are linked particularly to this type of vessel. Figure 7.1 evidence that in Gothenburg during 2019 oil tankers had by far the greatest fuel consumption at anchor with about 3900 MT of MDO. In contrast, liquefied gas tankers, containers and chemical tankers are clustered ranking underneath with about 1100 MT of MDO.

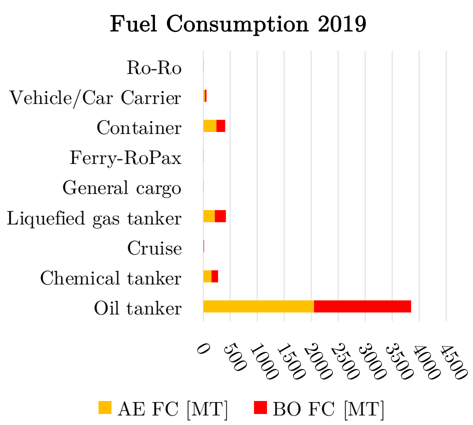


Figure 7.1: MDO consumption based on data from 2019

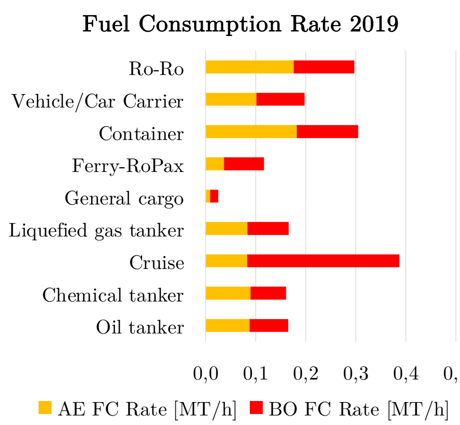


Figure 7.2: MDO consumption rates 2019 based on IMO4

The results of Figure 7.2 indicate that Ro-Ro, vehicle carriers, and cruise vessels have the most outstanding total[2] fuel consumption rates, almost over 0.2 MT/h. However, this set of vessels account for the least number of port calls, and therefore the least anchor hours. Conversely, vessel types with several port calls and anchor hours depict a different trend below 0.2 MT/h. Accordingly, tankers including oil, chemical, and liquefied gas tankers have total fuel consumption rates around 0.164 MT/h. Container vessels have the greatest total fuel consumption rate, for vessel types with multiple port calls, with 0.305 MT/h during 2019.

Figure 7.2 also shows the relation between fuel consumption rates for auxiliary

[1] 987 out of 1109 port calls.

[2] Auxiliary Engine + Boiler.

engines and boilers. On average, during 2019 the auxiliary engines consumed 13.4% more MDO than the boilers while anchoring. Regarding average fuel consumption rates, the boilers had 12.4% more MDO consumption per hour than the auxiliary engines among all the port calls.

Table 7.2 summarizes the numeric results sorted out by ship type and distinct MDO consumption for boilers and generating sets with IMO4 average data:

Table 7.2: Summary of fuel consumption by ship type

Ship Type	**AE FC [MT]**	**AE [MT/h]**	**BO FC [MT]**	**BO [MT/h]**
Oil tanker	2052.128	0.088	1797.655	0.077
Chemical tanker	152.296	0.090	120.212	0.071
Cruise	3.069	0.083	11.207	0.304
Liquefied gas tanker	210.762	0.083	208.353	0.083
General cargo	0.313	0.009	0.542	0.016
Ferry-RoPax	0.700	0.037	1.517	0.080
Container	241.567	0.182	162.882	0.123
Vehicle/Car Carrier	30.149	0.102	28.445	0.096
Ro-Ro	0.334	0.176	0.231	0.122
Total	**2691.318**		**2331.044**	

7.1.2 CO_2 Emissions – General Overview

As a general overview, during 2019 it was discharged into the air about 16,102 metric tonnes of CO_2 in a period of 29,238 anchor hours linked to 1109 distinct port calls, these results are based on IMO4 method. The results presented hereunder related to anchor operational mode, this means that the ship is not moving, and therefore the metric to comprise emissions is "Time", defined as CO_2 emissions per hour. In 2019 CO_2 was emitted at a rate of 0.55 MT per anchor hour, considering total amount of anchor hours or 1.84 MT per hour, considering the hours of a year. These CO_2 emission rates from IMO4 are 3% lower when compared with the POLA19 method. Table 7.3 contrast the results and differences obtained with both approaches.

Table 7.3: CO_2 emissions by IMO4 and POLA19

	IMO4	**POLA19**
Total Emissions [CO_2 MT]	16101.69	16614.09
Anchor hour EM. rate [CO_2 MT / h]	0.55	0.57
Hour EM. rate [CO_2 MT / h]	1.84	1.90

All port calls during 2019 are traced back to 6 designated anchor locations by Portit secondary data. Henceforth it is possible to attribute with certainty each port call to its pairing anchoring area and determine clusters. The results show that the two main areas with the highest on-coming cluster traffic are TRU B and TRU C, which account for 65% of the port calls. TRU B accounts for 57% of the total anchor hours, and TRU A is second with 12% of the anchor hours (Figure 7.4). Dana and Rivö N-S have a stable trend with regard anchor hours and port calls. Figure 7.3 present the complete distribution of port calls and anchor hours within the six designated anchor areas respectively.

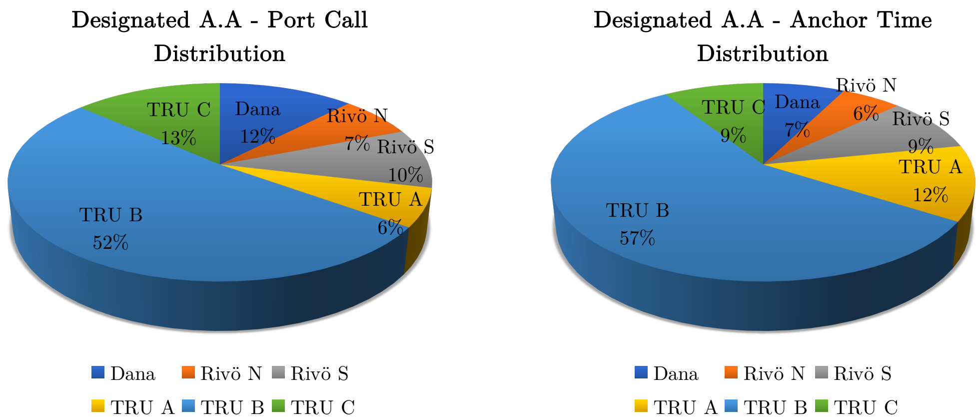


Figure 7.3: 2019 port calls and anchor hours distribution

The direct allocation of CO_2 emissions to every designated anchor area for both IMO4 and POLA19 depict similar percentages. IMO4 registers TRU B and TRU A as the areas with the highest concentration of CO_2 as well as POLA19. The POLA19 calculation yields higher carbon intensity in TRU B than IMO4, and IMO4 yields higher carbon intensity for TRU A than POLA19 considering the same port calls and anchor hours. It is possible to appoint TRU B as the highest CO_2 emission anchor area with 55%. On the other hand, Rivö presents the lowest emissions with 5% of the total emissions. Figure 7.4 shows the emission percentage that was matched with every anchor area during 2019.

Figure 7.5 maps out the geographical distribution of the CO_2 emissions in Gothenburg Bay. Larger circles are associated with more CO_2 emissions across the bay where the ships cast anchor. The radios of the dot size are proportional to the CO_2 emissions. It can be appreciated that the designated areas with the highest emissions are slightly far out into the sea, while low carbon intensity areas are affiliated closer to the islands and the shore.

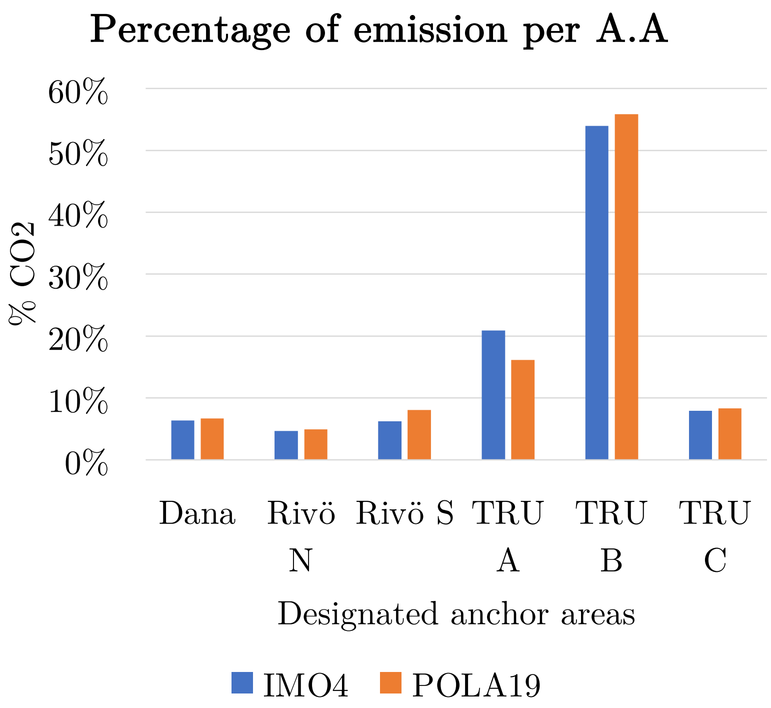


Figure 7.4: Emission distribution per AA

Figure 7.5: CO_2 mapping for 2019

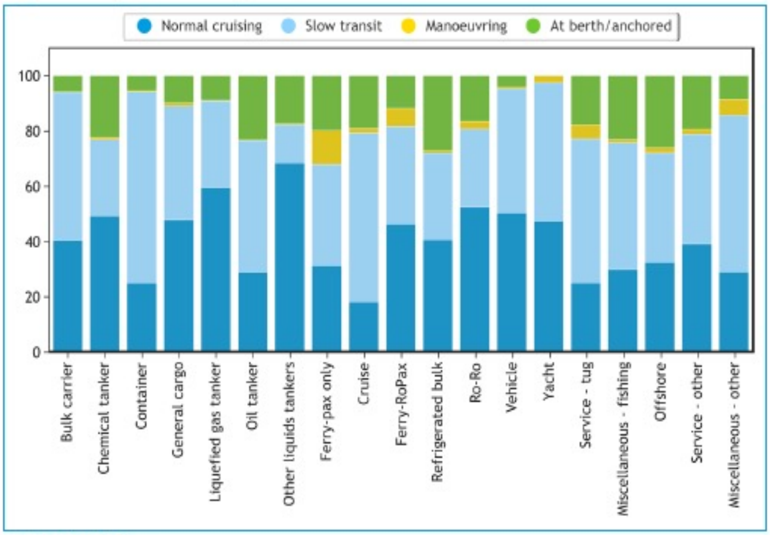


Figure 7.6: Proportion of international GHG EM CO_2e 2018, [1]

Table 7.4 summarizes the numeric results sorted out by designated anchor areas:

Table 7.4: Summary of CO_2 Emissions by anchor area

Anchor Area	Port calls	A.A	EM IMO avg [MT]	EM POLA avg [MT]
Dana	136	2175	1022.7	1113.5
Rivö N	75	1594	754.4	813.2
Rivö S	108	2604	1007.9	1342.0
TRU A	69	3589	3360.1	2682.6
TRU B	572	16629	8684.1	9280.9
TRU C	149	2648	1272.5	1381.9
Total	**1109**	**29238**	**16101.7**	**16614.1**

TRU B is further broken down to explore why it allocates the most significant CO_2 emissions. The results show that this area allocates the most port calls and the most anchor hours, as shown in Figure 7.3. Furthermore, TRU B is comprised in 78% by port calls from oil tankers which, according to Figure 7.6 of [1], ranges among the highest proportions of CO_2e at berth/anchored.

7.1.3 CO_2 Emissions by Ship Type

Both methods, BE and IMO4, display similar trends in the emission inventory throughout the first four months of 2021. Consistently, the IMO4 gathers more elevated emissions than BE.

The results point out September 2019 is the month with the highest CO_2 emissions in Gothenburg, it was released 2500 MT of CO_2 to the air from anchor activity. On the other hand, a seasonal aggrupation rank summer and autumn (June to November) as seasons with substantial CO_2 emissions. On the other hand, in the period from January to May and December the emissions decrease 38% in comparison with summer and autumn, it is also possible to observe a 35% decrease in the anchor hours. Figure 7.7 shows the CO_2 emission distribution throughout 2019.

The CO_2 emission inventory carried out for 2019 is summarized by vessel type in Figure 7.8. The results show that the vessel types that emit the most CO_2 are oil tankers, other types of tankers, container, and general cargo. Other vessel types present fewer emissions because their anchor time and port calls were brief and infrequent in Gothenburg during 2019.

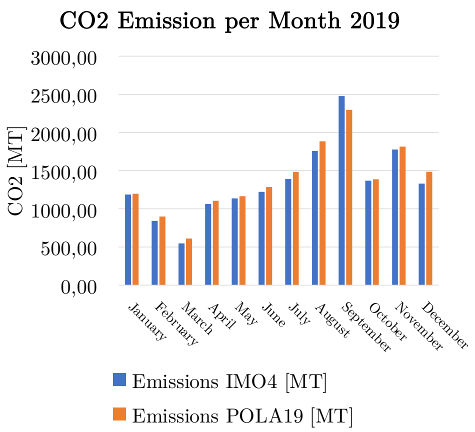


Figure 7.7: CO_2 emissions per month 2019

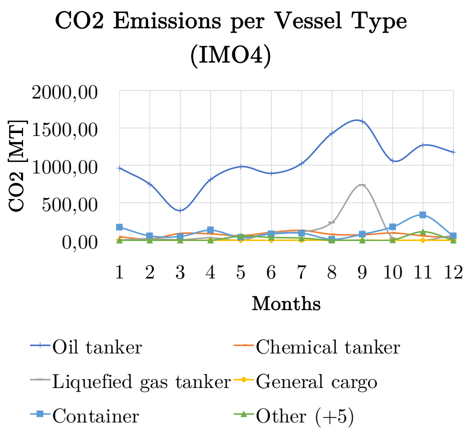
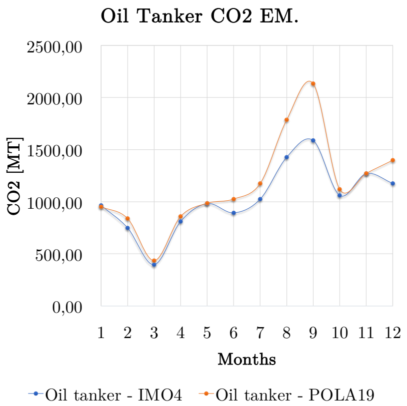
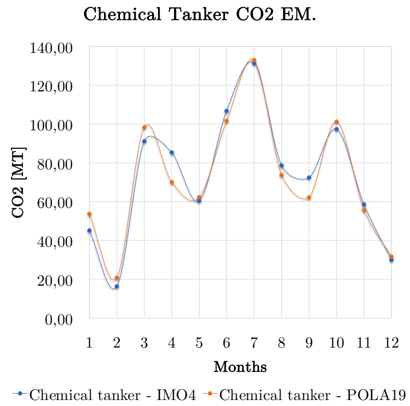


Figure 7.8: General emission plot per vessel type 2019

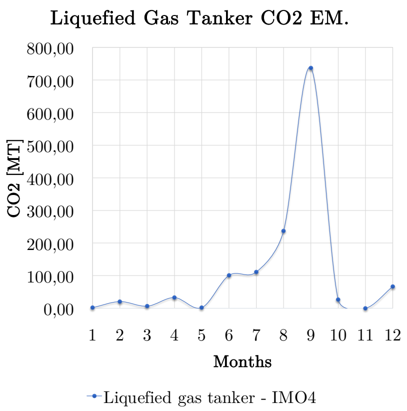
Figures 7.9a to 7.9f present isolated results of CO_2 emissions for the most predominant ship types that attended port calls in Gothenburg during 2019. Different curves are shown for IMO4 and POLA19. Please note that the POLA19 study does not incorporate LNG carriers, therefore LNG are only presented with the IMO4 method.



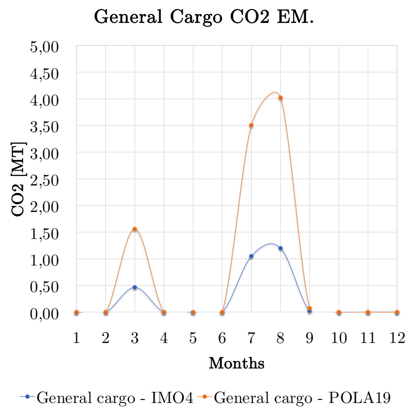
(a) Oil Tanker CO_2 EM. 2019



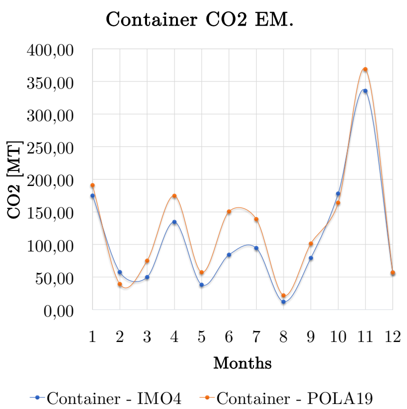
(b) Chemical Tanker CO_2 EM. 2019



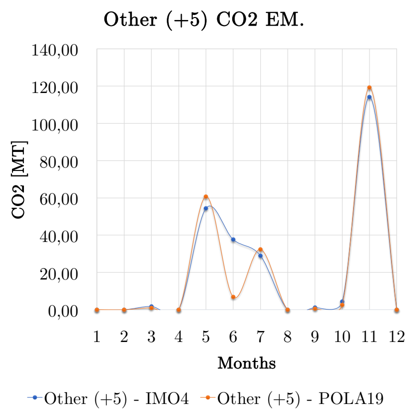
(c) Liquefied Gas Tanker CO_2 EM. 2019



(d) General Cargo CO_2 EM. 2019



(e) Container CO_2 EM. 2019



(f) Other vessel types (+5) CO_2 EM. 2019

Figure 7.9: CO_2 emissions per Vessel type during 2019

Table 7.5 and Table 7.6 summarize the emission results sorted out by ship type and for every month in 2019 calculated with IMO4 and POLA19 average data.

Table 7.5: 2019 CO_2 emission by vessel type and month with IMO4 average data

Month	**Oil tanker**	**Chemical tanker**	**LNG**	**General cargo**	**Cont-ainer**	**Other (+5)**
January	964.38	45.12	1.87	0.00	174.94	0.00
February	748.87	16.40	20.48	0.00	57.72	0.00
March	396.14	91.18	6.39	0.47	50.04	1.81
April	811.30	85.35	32.84	0.00	134.51	0.00
May	982.41	60.39	1.98	0.00	38.35	54.40
June	893.07	106.84	100.93	0.00	84.24	37.66
July	1024.66	131.29	111.27	1.05	94.49	28.99
August	1427.14	78.67	237.39	1.20	12.26	0.00
September	1587.63	72.43	737.16	0.02	79.46	1.21
October	1060.54	97.37	26.75	0.00	177.92	4.32
November	1270.19	58.60	0.01	0.00	335.63	114.15
December	1176.04	30.02	66.61	0.00	57.09	0.00
Total	**12342.36**	**873.66**	**1343.68**	**2.74**	**1296.66**	**242.54**

Table 7.6: 2019 CO_2 emission by vessel type and month with POLA19 average data

Month	**Oil tanker**	**Chemical tanker**	**General cargo**	**Cont-ainer**	**Other (+5)**
January	951.31	53.70	0.00	190.80	0.00
February	839.20	20.82	0.00	39.23	0.00
March	434.83	98.34	1.56	75.22	1.01
April	859.00	70.14	0.00	174.71	0.00
May	985.04	62.35	0.00	57.47	60.74
June	1025.56	101.70	0.00	150.48	6.85
July	1174.72	132.95	3.51	138.90	32.37
August	1785.57	73.78	4.02	21.91	0.00
September	2132.80	62.26	0.08	101.54	0.60
October	1119.40	101.26	0.00	164.00	2.56
November	1271.38	55.76	0.00	368.70	119.23
December	1397.98	31.76	0.00	56.98	0.00
Total	**13976.78**	**864.82**	**9.17**	**1539.93**	**223.36**

7.2 CO_2 Emissions Inventory Results 2021

This section provides the estimated vessel-based results of the 2019 CO_2 emissions inventory attained through BE method. The results are divided in fuel consumption and carbon intensity.

From January to April 309 port calls of vessels at anchor in Gothenburg were registered, 121 port calls correspond to unique vessels. Oil tankers represents 84% of the port calls and the second most significative group is liquefied gas tankers and chemical tankers with 5% each. Table 7.7 shows the 2021 anchor demographics involved in the emission inventory considering ship type, port calls, and the number of ships that anchored in Gothenburg.

Table 7.7: Vessels' demographics 2021

Type	**Number of port calls**	**Number of Ships**
Oil tanker	261.0	91
Chemical tanker	14.0	9
Liquefied gas tanker	14.0	5
General cargo	6.0	5
Container	12.0	9
Vehicle/Car Carrier	2.0	2
Total	**309.0**	**121.0**

7.2.1 Fuel Consumption

The fuel consumption results are fuel-based to every port call. In this case study, the consumption of diesel auxiliary engines and fuel-fired boilers is estimated from marine diesel oil. The results show a time operational factor of 100% for all the generating sets, for boilers 56% of the vessels at anchor range between 5-20% time operational factor, 10% of vessel ranges between 80-100% time operational factor, and for the rest of ships, there is no information available. However, all information regarding boilers is obtained by means of average data from IMO4 as there is not enough specific data available for the fuel consumption and power of the boiler.

Due to the large demographics of oil tankers[3] attending port calls, the greater amounts of MDO consumption are linked particularly to this type of vessel. Figure 7.10 shows that in Gothenburg during 2021, oil tankers had the most significant fuel consumption at anchor with about 998 MT of MDO. In contrast, liquefied gas tankers, containers and chemical tankers are clustered, ranking underneath with about 393 MT of MDO.

[3] 261 out of 309 port calls

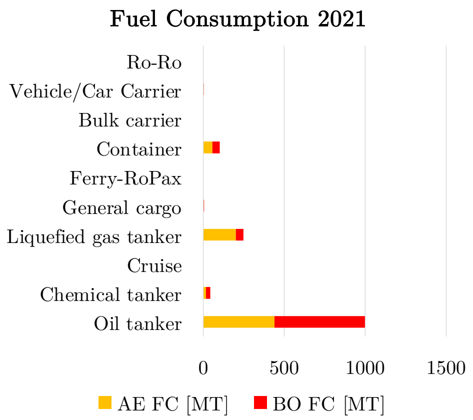


Figure 7.10: MDO fuel consumption at anchor 2021

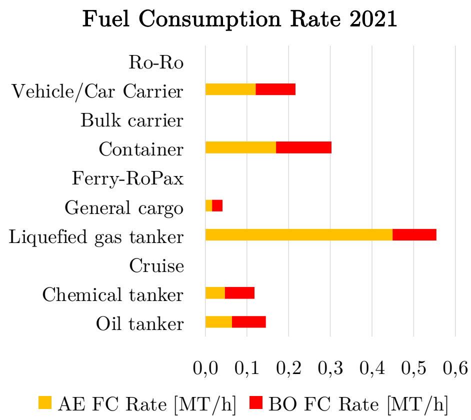


Figure 7.11: MDO fuel consumption rate at anchor 2021

The vessels types with the higher fuel consumption rates for auxiliary engines are liquefied gas tankers with 0.449 MT/h, container vessels with 0.170 MT/h, and car carriers with 0.121 MT/h. The lowest consumption rates on auxiliary engines are for general cargo ships, oil tankers, and chemical tankers with less than 0.100 MT/h.

Figure 7.11 shows the relation between fuel consumption rates for auxiliary engines and boilers. On average, during 2021 the auxiliary engines consumed 5.1% more MDO than the boilers while anchoring. The AE had 41% more MDO consumption per hour than the boilers among all the port calls regarding average fuel consumption rates.

Table 7.8 summarizes the numeric results sorted out by ship type and distinct MDO consumption for boilers and generating sets.

Table 7.8: Summary of fuel consumption by ship type

Ship Type	**AE FC [MT]**	**AE [MT/h]**	**BO FC [MT]**	**BO [MT/h]**
Oil tanker	439.17	0.064	559.38	0.081
Chemical tanker	17.18	0.047	25.96	0.071
Liquefied gas tanker	201.08	0.449	46.94	0.105
General cargo	2.19	0.016	3.36	0.025
Container	56.98	0.170	44.61	0.133
Vehicle/Car Carrier	1.58	0.121	1.26	0.096
Total	**718.18**		**681.52**	

7.2.2 CO_2 Emissions – General Overview

As a general overview, during the first four months of 2021, it was discharged into the air about 4,488 metric tonnes of CO_2 in a period of 8,168 anchor hours linked to 309 distinct port calls, based on the results obtained from BE. The results presented hereunder relate to anchor operational mode, this means that the ship is not moving, and therefore the metric to comprise emissions is "Time", defined as CO_2 emissions per hour. In 2021 CO_2 was emitted at a rate of 0.55 MT per anchor hour, considering the total amount of anchor hours, or 1.54 MT per regular hour, considering the hours of a year. The CO_2 emission rates using BE is 13% lower when compared with the IMO4 method for the same time span. Table 7.9 contrasts the results and differences obtained with both approaches.

Table 7.9: CO_2 emissions by BE and IMO4

	BE	**IMO4**
Total Emissions [CO_2 MT]	4487.41	5160.74
Anchor hour EM. rate [CO_2 MT / h]	0.55	0.63
Hour EM. rate [CO_2 MT / h]	1.54	1.77

All port calls during 2021 are traced back to six designated anchor locations based on Portit secondary data. Henceforth it is possible to attribute with certainty each port call to its pairing anchoring area and determine clusters. The results show that the two areas with the highest anchored vessels are TRU B and TRU C, which account for 64% of port calls (Figure 7.12). TRU B represents 47% of the total anchor hours, and TRU A is the second biggest area with 24% of the total anchor hours. Dana and Rivö N-S have similar trends with regard anchor hours and port calls. Figure 7.12 presents the complete distribution of port calls and anchor hours within the six designated anchor areas respectively.

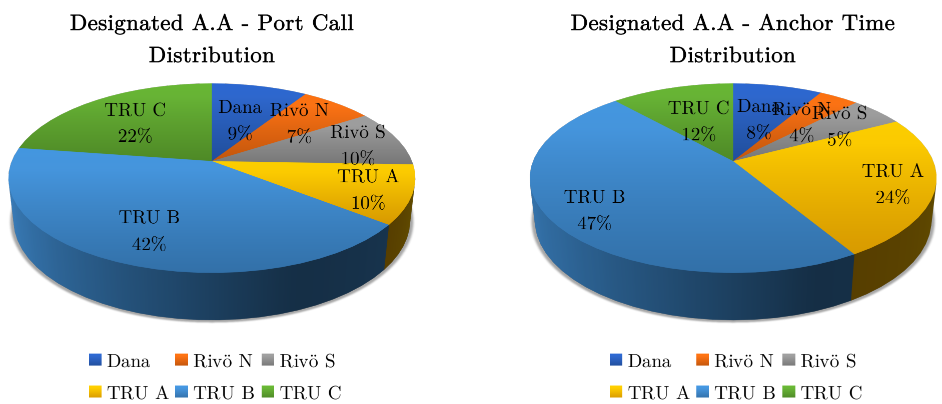


Figure 7.12: Port calls and anchor hours distribution 2021

The direct allocation of CO_2 emissions to every designated anchor area for both BE and IMO4 depict similar percentages. TRU B and TRU A are the areas with the highest concentration of CO_2 . BE yields a greater percentage of emissions than IMO4 for TRU B and TRU A, but the opposite happens for Dana, Rivö N-S, and TRU C, considering the same port calls and anchor hours. It is possible to appoint TRU B as the highest CO_2 emission anchor area with 47%. On the other hand, Rivö-N presents the lowest CO_2 emissions with 4% of the total emissions. Figure 7.13 shows the emission percentage that was matched with every anchor area during 2021.

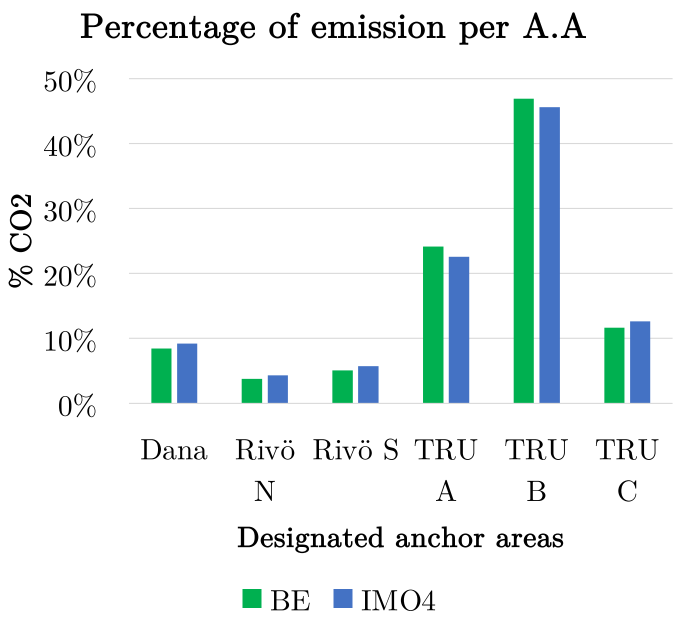


Figure 7.13: 2021 Emission distribution per AA

Figure 7.14 maps out the geographical distribution of the CO_2 emissions in Gothenburg Bay. Larger circles are associated with more carbon intensity across the bay where the ships cast anchor. The radios of the dot size are proportional to the CO_2 emissions. It can be appreciated that the designated areas with the highest emissions are slightly far out into the sea, while low CO_2 emission areas are affiliated closer to the islands and the shore.

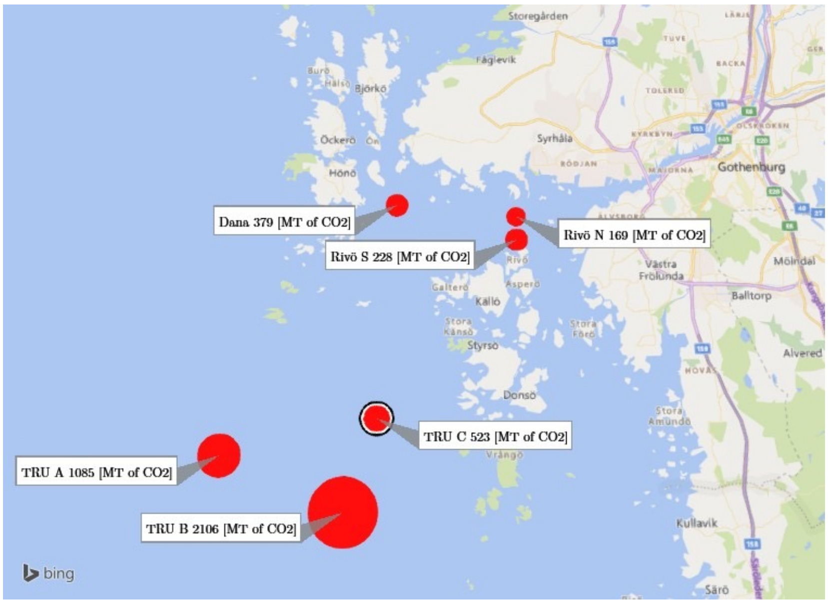


Figure 7.14: CO_2 mapping January to April 2021

Table 7.10 summarizes the numeric results sorted out by designated anchor areas:

Table 7.10: Summary of CO_2 emissions by anchor area

Anchor Area	Port calls	A.A	EM BE [MT]	EM IMO Avg. [MT]
Dana	28	866	378.88	474.61
Rivö N	21	447	168.70	222.55
Rivö S	30	859	227.32	294.58
TRU A	31	1421	1084.85	1164.71
TRU B	129	3258	2105.09	2353.66
TRU C	70	1316	522.57	650.62
Total	**309**	**8168**	**4487.41**	**5160.74**

TRU B is further broken down to explore why it allocates the most significant CO_2 emissions. The results show that this designated anchor area allocates the most port calls and the most anchor hours, as shown in (Figure 7.12). Furthermore, 74% of the port calls that comprise TRU B come from oil tankers which have the greatest fuel consumption at anchor in 2021.

7.2.3 CO_2 Emissions – Ship Type

Both methods, BE and IMO4, display similar trends in the emission inventory throughout the first four months of 2021. Consistently, the IMO4 gathers more elevated emissions than BE.

The results point out February 2021 as the month with the highest emissions. During the latest, it was released 1,569 MT of CO_2 to the air from anchor activity. The first two months of the year had higher CO_2 emissions than the subsequent two months, with a decrease of 34% in the CO_2 emissions that stem from ships at anchor in Gothenburg. Figure 7.15 contrasts the emission per month in 2021 between BE and IMO4.

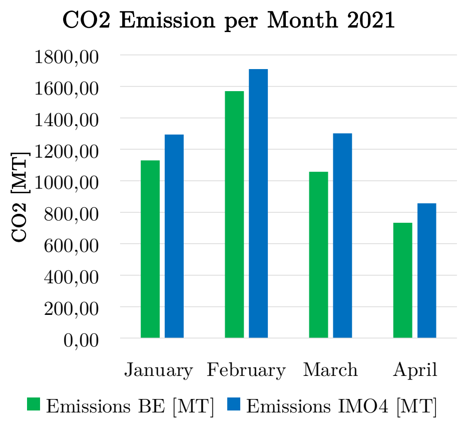


Figure 7.15: 2021 CO_2 emissions by month

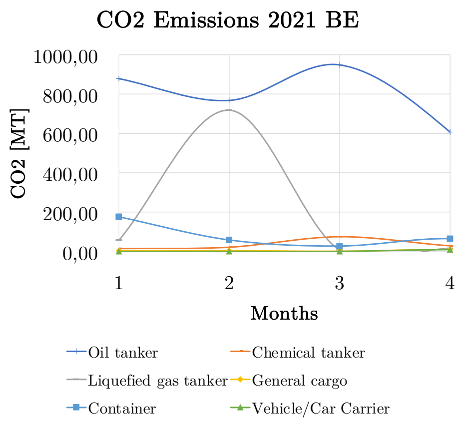
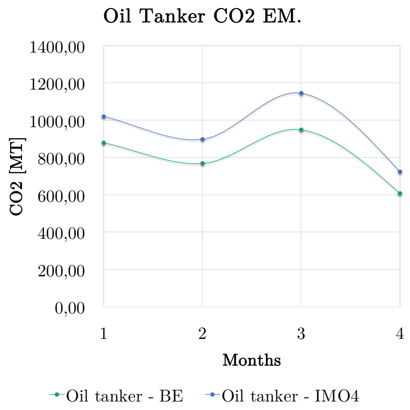


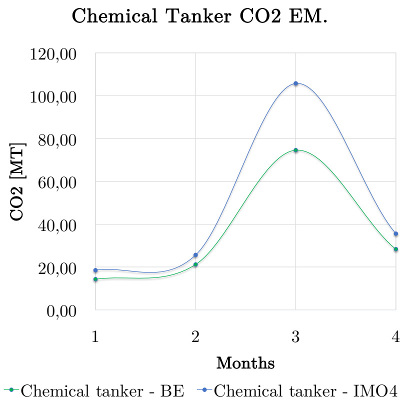
Figure 7.16: 2021 CO_2 general emission plot

The CO_2 emission inventory carried out for 2021 is summarized by vessel type in Figure 7.16. The results show that the vessel types that emit the most are oil tankers and liquefied gas tankers. Other vessel types present fewer emissions because their anchor time and port calls were brief and infrequent in Gothenburg during 2021.

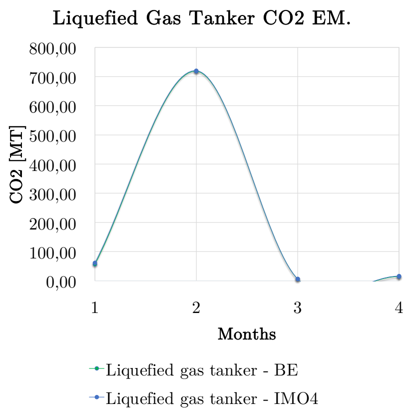
Figure 7.17a to Figure 7.17f present isolated results of CO_2 emissions for the most predominant ship types that attended port calls in Gothenburg during 2021. Different curves are shown for BE and IMO4.



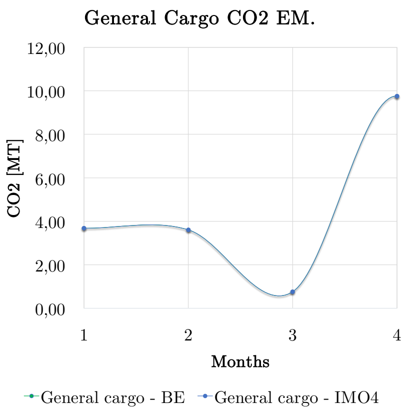
(a) Oil Tanker CO_2 EM. 2021



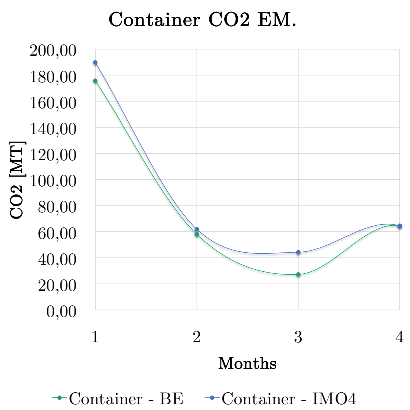
(b) Chemical Tanker CO_2 EM. 2021



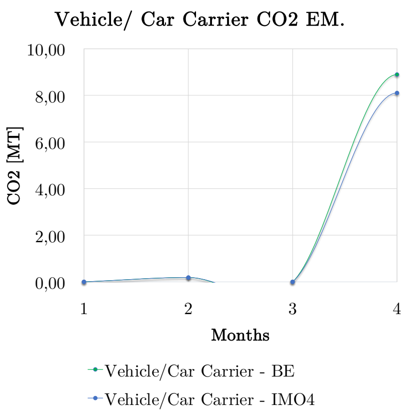
(c) Liquefied Gas Tanker CO_2 EM. 2021



(d) General Cargo CO_2 EM. 2021



(e) Container CO_2 EM. 2021



(f) Other vessel types (+5) CO_2 EM. 2021

Figure 7.17: CO_2 emissions per ship type for 2021

Table 7.11 and Table 7.12 summarize the emission results sorted out by ship type and for every month in 2021 with BE and IMO4 average data:

Table 7.11: CO_2 emissions by vessel type and month with BE

Month	Oil tanker	Chemical tanker	Lqf. gas Tk.	G. Cargo	Container	Car Carrier
January	878.46	14.28	56.45	3.68	175.83	0.00
February	767.79	21.17	718.11	3.61	58.06	0.19
March	948.34	74.56	6.04	0.76	27.27	0.00
April	606.77	28.31	14.54	9.76	64.53	8.89
Total	**3201.36**	**138.32**	**795.14**	**17.81**	**325.70**	**9.08**

Table 7.12: CO_2 emissions by vessel type and month with IMO avg.

Month	Oil tanker	Chemical tanker	Lqf. gas Tk.	G. Cargo	Container	Car Carrier
January	1019.49	18.54	61.68	3.68	189.77	0.00
February	897.64	25.60	720.15	3.61	61.92	0.19
March	1144.12	105.73	6.40	0.76	44.28	0.00
April	723.12	35.61	16.05	9.76	64.53	8.10
Total	**3784.37**	**185.48**	**804.29**	**17.81**	**360.49**	**8.29**

7.2.4 Tanker Comparison BE and IMO4

BE inventory, as explained in Section 5.2.1.1, is comprised of specific data and average data. The specific data gathered during the study was mostly from oil/-chemical tankers between 2900 and 62500 GT. Therefore, a comparison between BE and IMO4 for this vessel type within the mentioned range is made to contrast the method and the differences in emissions between an inventory comprised of specific data (BE) and another with average data (IMO4).

Results from the BE method does not show outliers that can be disregarded due to lack of information, and therefore all data collected is considered, 269 port calls of oil/chemical tankers. For comparing both methods, a scatter plot between the port calls and the CO_2 emissions is done (Figure 7.18). This graph reveals that both methods yield similar distribution of CO_2 emissions below 20 MT, but the emissions from BE are lower than IMO4. On the other hand, above 20 MT the values from both methods are scattered but still showing more emissions from the IMO4 method.

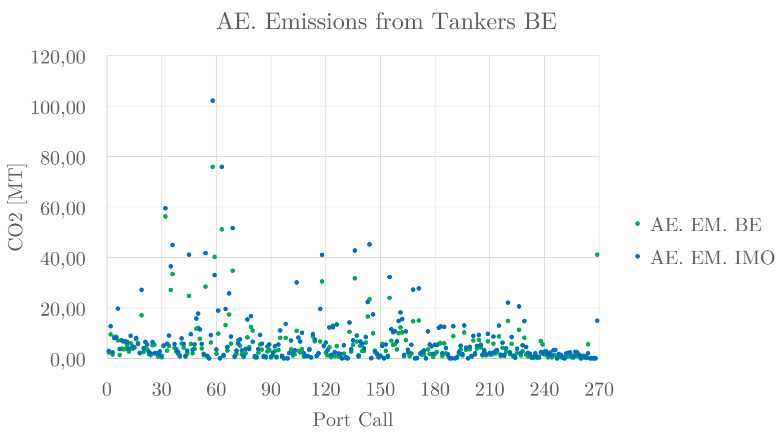


Figure 7.18: Scatter plot of CO_2 AE emissions for tankers at anchor

The emissions rate per anchor hour is similar for both methods, 50% of the emission rate from BE lies between 0.1-0.23 CO_2 MT/h while 50% of the emission rate from IMO4 fall into a range of 0.22-0.30 CO_2 MT/h for auxiliary engines of tankers at anchor. IMO4 shows a slightly higher range than BE. Figure 7.19 shows the box plot for CO_2 emission rates comparing the two mentioned methods.

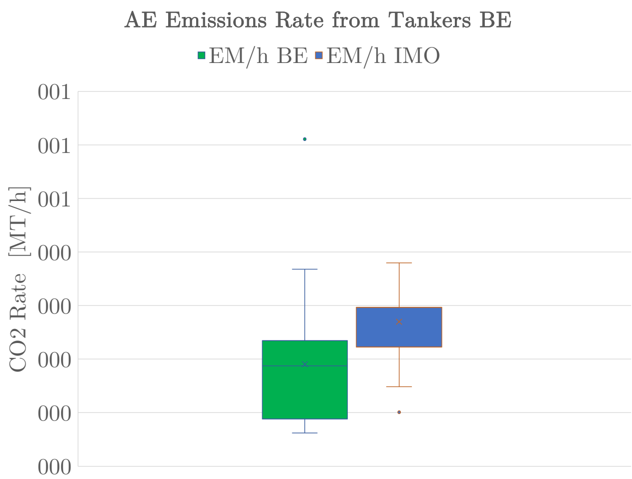


Figure 7.19: Box plot of CO_2 AE emission rate for tankers at anchor

Moreover, the results of CO_2 emissions from both methods are presented in Table 7.13

Table 7.13: CO_2 emissions for tankers BE and IMO4

	BE	**IMO4**
Total Emissions [CO_2 MT]	1406.65	2036.82

8

Course of Action

This section briefly presents a possible course of action for the port to reduce CO_2 emissions. The possibilities are laid within a research and a technical perspective.

8.1 Research Side

Throughout this case study, it is noticeable the significance of primary data collection in shipping. Gathering and analyzing specific data became the most important aspect of this research because it is not possible to ensure how reliable the average data is. Consequently, it is logical to think that more reliable primary data is to yield more reliable bottom-up emission inventories that are pointed as "the most predominant method to estimate emissions and thereby to assess compliance with the emissions regulations" [50]. Moreover, some studies have found "significant variations between the estimates and the actual fuel consumptions informing implications of unrealistic cost and emission estimates", which is another of the downsides of average data [50].

Consistent with the port strategic goals to reduce CO_2 emissions, it is essential to attain bottom-up emission benchmarks based merely on specific data. It could guarantee higher levels of accuracy and enable more reliable decision making in the hands of the port administration. Thus, a vessel boarding program is presented as an indirect way to reduce carbon intensity in the areas adjoining the port.

It is recommended that the port has an own or outsourced "energy brigade" to board the vessels and collect the required primary data on fuel consumption coming from onboard equipment. Collaterally, gathering such data would contribute to comprise more accurate emission inventories, and therefore to make more informed decisions in order to reduce carbon intensity. An example of existing vessel boarding programs can be evidenced in some US ports since 2003. Port of Los Angeles and Port of Long Beach collect specific data from a VBP and use it as primary data for the port's emission inventories [12].

Vessels are boarded to collect data "on auxiliary engine and boiler loads and other aspects of OGV engine operations needed to verify or refine OGV emissions inventory estimation" [12].It is recommended that Port of Gothenburg undertakes extensive vessel survey not only for vessels at anchor but also at berth. Nowadays, there is an increasing demand for this information from research communities and IMO, ports are prefect hubs to obtain it. A VBP could be enforced by the port authority in the form of port tariff incentives for the vessels willing to participate.

Although there is no information in the literature on how to design a standard vessel boarding program in shipping, it could be valuable to acknowledge the following characteristics to draw up a VBP.

- Adhering to quality and risk standards
- Aligning with the ISPS code regulations
- Aligning with the EU-MRV system, EU Regulation 2015/757

Regarding qualifications and training, it is recommended that the VBP personnel has deep knowledge in marine engineering, especially in the following areas:

- Marine machinery parts and combustion for main engines, auxiliary engines, turbines, boilers
- Relevant energy management equipment in the engine room
- Marine fuels
- Marine technologies
- Data collection, data analysis
- Experience to adapt surveyed data on-site to match the parameters of the analysis

Safety certifications may mitigate the risk associated with conducting task onboard. Thus, VBP personnel is advised to undertake some of the STCW 2010 courses for seafarers. Some recommended courses are listed hereunder:

- Basic safety training - BST
- Environmental related training
- Firefighting course
- Maritime security courses
- Ship survey and port state control PSC

- Additional requirements to come aboard tankers and liquified gas tankers.

A good start exemplification of what data should be gathered is shown in TQV01 in Appendix A. In broad terms, it is essential to collect operational data for distinct operational profiles (in this case, anchor, berthing, perhaps shifting), machinery reference data, and electricity meters to compare and validate. Implementing real-time data collection technologies is highly recommended as these processes would be extensive throughout many years. Real-time analytics enables the preparation and measurement of data, meaning that the “users get insights or can draw conclusions immediately (or very rapidly after) the data enters their system”[51].

8.2 Technical Side

On the technical side, it would be worth exploring alternatives to reduce CO_2 emissions at anchor in a direct approach. As of today, the only suitable way to counterpart the fuel consumption and linked emissions of auxiliary machinery at anchor would be either mobile units or through an energy terminal with multiple shore connection as a new anchor area.

The mobile units reaching anchoring positions could be barges or modular floating platforms. There would be logistics involved, for instance, to target vessels at anchor with the highest fuel consumption (information could be assessed by VBP). In addition, tug operations would be required to deploy, attach, and retreat the floating platforms to the anchor locations. Operation and maintenance are also foreseen. As mentioned in Section 6.4.4, the system shall be at least safe, affordable, and time-consuming for the crew. Regarding carbon intensity reduction capabilities, the units shall undertake, if possible, one or a combination of the following options to provide a desired electrical capacity for the time used:

- Energy generation by renewable energy sources (solar panel, wind rotor, or others)
- Energy supply by batteries charged for renewable sources
- Energy generation by generating set using non-fossil or low-carbon energy carriers

In addition, the floating devices shall have the capabilities to monitor and record electrical consumption while operating through a ship-mobile connection in order to generate specific data for further research on energy consumption. The prototype itself shall include communications, positioning, regulatory lights as well as deck, and safety equipment and electric emergency system. It is not recommended that the fuel tanks are structural tanks. These requirements can be observed in Figure 8.1 and Figure 8.2.

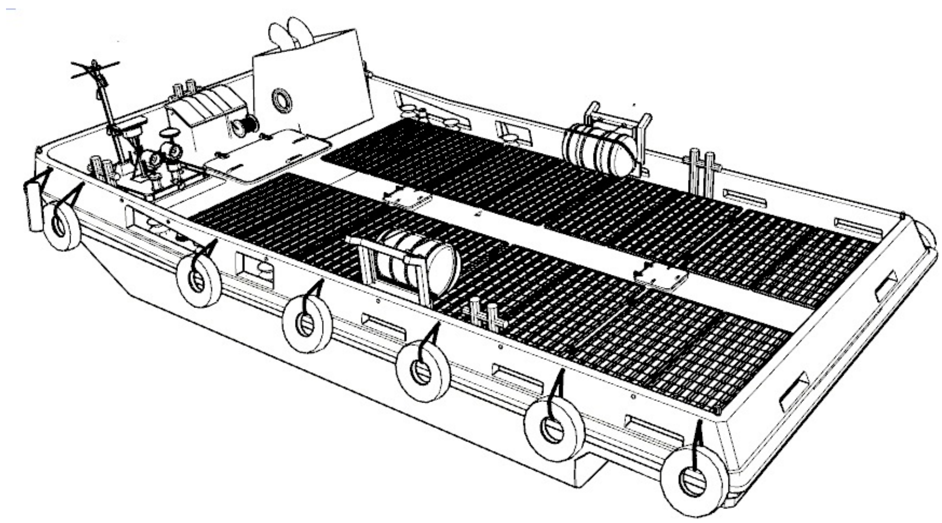


Figure 8.1: Deck view of solar panels and deck general arrangement

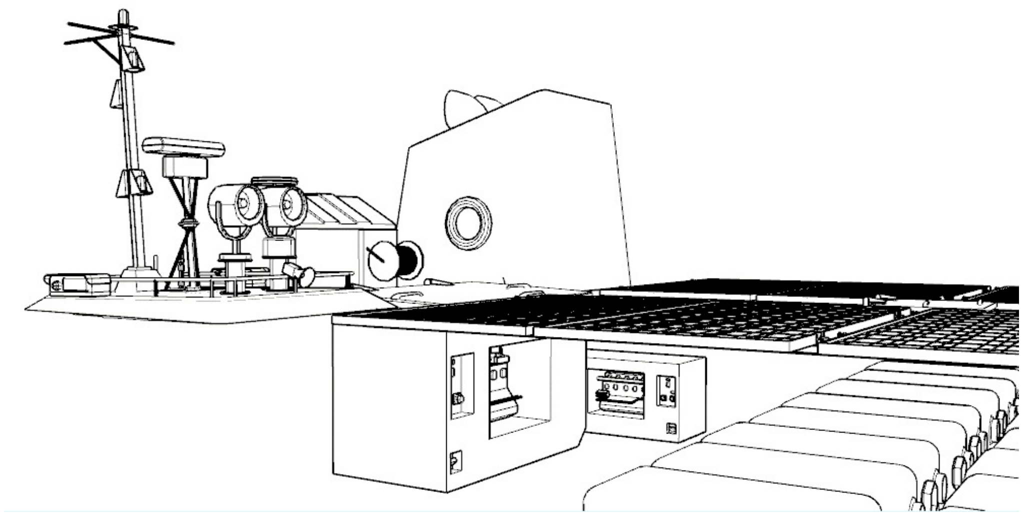


Figure 8.2: Below deck view with generating sets and battery bank

Another direct action to reduce carbon intensity is to provide ship-shore connections for vessels at berth. Although it does not encompass emissions at anchor, it could substantially contribute to reducing CO_2 emission at the port. From the qualitative results is known that 75% of the surveyed vessel are equipped with a ship-shore receptacle.

Ship-mobile or ship-shore connection shall operate within a frequency between 50 and 60 hertz in accordance with the results. However, 86% of the survey vessels operate at 60 Hz. Its electrical current, voltage and average electrical consumption (measured at the MSB) are shown in Table 8.1.

Table 8.1: Electric characteristics required for ship-shore system at anchor

	MSB kw/h	Voltage V.	AMP
Min	100	230	32
Max	560	450	800
Mode	300	440	250
Average	278	432	285
Median	250	440	250

It is advised to additionally apply design and growth margins for electric losses in the system.

Figure 8.3 shows a scatter distribution of the hourly electrical consumption at anchor for district surveyed vessels during 2021 in Gothenburg. Mainly, chemical and oil tankers present the higher rates, which points a demographics to target for solutions in order to reduce carbon intensity to a further extent.

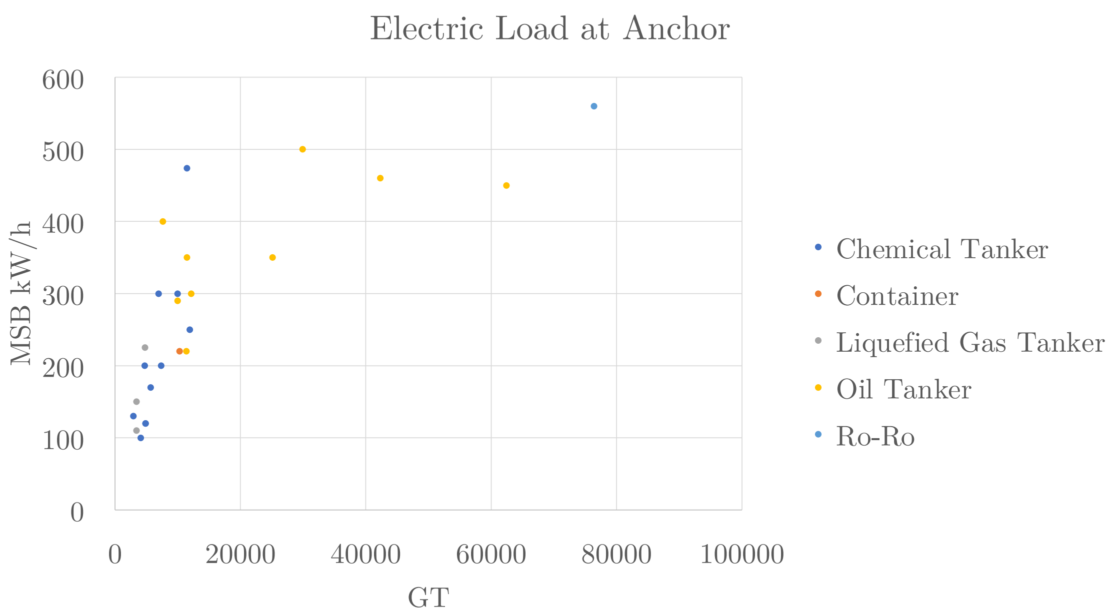


Figure 8.3: Specific data of power consumption at anchor by vessel type 2021

9

Discussion

This section discusses the distinct methodologies, data collection, results, relevant aspects, and recommendations for further studies in an attempt to provide a better understanding, and provide perspective on this case study.

To our knowledge, this case study has provided a perspective on energy generation and usage and a crew insight on how data is collected onboard for fuel consumption. Moreover, we created a bottom-up CO_2 emission inventory for ships at anchor in the Port of Gothenburg during 2019 and part of 2021. To comprise the emissions, we conducted different methodologies to calculate fuel consumption for boilers and auxiliary engines. The BRAVE ECO (BE) methodology is developed through a hierarchy model using specific data and average data.

This case study has also generated unique specific data primarily for tanker vessels in anchor operational mode, using bottom-up, fuel-based, and vessel-based approaches. To our cognition, as of today, this study may be the first attempt to make a comparison of CO_2 emission results, using real anchor port calls from the Port of Gothenburg between two world well-known methodologies; the Port of Los Angeles Inventory of Air Emissions 2019 and the Four GHG Study 2020 released July 2020.

Methodologies

Known EI methodologies such as IMO4 and POLA19 undertake similar aims. However, there are important aspects that should be mentioned as some of their assumptions regarding CO_2 emissions from vessels at anchor using auxiliary machinery are perceived to generate uncertainties when obtaining CO_2 emissions.

IMO4 and POLA19 comprise a reliable bottom-up method for emission inventories using multiple inputs, among them specific data gathered from VBP. However, the manner such specific data is internally treated in both methods is unknown from a statistical perspective. The way IMO4 presents the average data for other users to apply the same EI methodology is very satisfactory, unlike POLA19. IMO4 has greater subdivision levels; IMO states that it reduces discrepancies and proportionally raises the precision of the fuel consumption estimation and thereby the reliability of the subsequent carbon inventory [1]. On the other hand, POLA19 average data is a bit scanty regarding the vessel size for specific vessel types (Table 5.2).

Only tankers and container vessels are subdivided by size, and the number of bins to categorize the ships is fewer than IMO4 (Table 5.6). The implication of this is the deviation in the emissions, producing either too high or too low emissions if the vessel has low GT or high GT, respectively. This has been proven with the inventories of 2019, where POLA19 produced 3% higher CO_2 emissions than IMO4 (Table 7.3) and this difference is due to the size of the bins for ship type and size. That is why IMO4 is used to compare against BE, as IMO4 tends to be more accurate than POLA19.

Initially, we considered that the fuel consumption was mostly associated with the vessel type and its auxiliary machinery. However, during the research it became evident that FC is better connected with the ships' age. For instance, IMO4 (Table 5.3) and POLA19 introduce such parameters to estimate fuel consumption using lookup tables. Although POLA19 for estimating the CO_2 specific emission factors differentiates between IMO Tiers for engines type, the value for all of them is the same (Table 5.7). The implication of it is an unrealistic estimate for the specific emission factor on AE. Moreover, for a more realistic estimation, other aspects shall be considered, such as abatement technologies and overhaulings, where auxiliary machinery could be upgraded and linked to the SEFs for every IMO Tiers (0, I, II, III).

Regarding BE, if needed the specific data from oil/chemical tankers within range of 2900-62500 GT could be extrapolated and adapted for other vessel types by analyzing similarities and particularities in terms of the electric load used at anchor. For instance, if scaling factors for different ships types were developed, our specific data or non-linear logarithmic regression could be adjusted to fit bulk carriers in a lower electrical load or liquefied gas tankers for higher loads. The specific generated data and method could be directly used for tankers at anchor in different ports.

Data Collection
It can be agreed upon that data collection is crucial for the research as the primary data itself uphold more substantial weight in the methodologies than average data. The scarce and incomplete data made it meaningful to obtain raw data to contrast average data and technical knowledge. The use of average data over specific data can lead to contrasting CO_2 inventories, as seen in the 2021 tanker comparison for AE (Table 7.13). In addition, collecting the specific data ourselves gives us a direct context with the FC data and the CO_2 emissions. On the other hand, if the specific data had been provided, we would have lost some context within the case study.

To our knowledge, a substantial breakthrough in terms of data collection is the concept of vessel boarding programs (VBP). However, neither IMO4 nor POLA19 display specific data from VBP, even though they used it. Such information is concealed and only presented as average data without stating how it has been treated and analyzed and how accurate the average data is. The displayed sets of average data (Table 5.2 and Table 5.6) could be more useful if something were stated about their traceability. This would enable other methods to adapt average data (by scaling or extrapolating) in a more precise way to other vessels rather than just allocating it by default categories, ending up in EI with increased precision. In our opinion, it would be helpful to make available or accessible VBP primary information for research because it can reduce the uncertainties and increase the level of accuracy and reliability of studies. On the other hand, a downside is that VBP requires additional financial resources, so it is understandable that this data is concealed, but it could be sold and make revenue from it.

For the data collection in this research, three versions of the technical questionnaires were adapted. The first version, in our opinion, is the most complete and intuitive. The first version counted with information about abatement technologies and reference data (maximum values of RPM and output power) of the machinery, making it more straightforward when answering the specific data. One of the limitations is the retrieving rate of the questionnaires for vessels other than tankers. The reasons for this could be that most of the inbound maritime traffic of the Gothenburg area is comprised of tankers, and the rest of vessel types have specialized areas for cargo operations and therefore will not need to wait at anchor prior berthing, for instance, the APM terminal for containers. In order to increase the retrieving rate a tradeoff is made, renouncing to reference data of the machinery that is a way to validate data when analyzing. If it was not for the main switchboard average electric consumption reading, we would not have had any mark to compare or validate the specific data that was being generated.

Results

The growing concern of tackling emissions coming from shipping due to their impact on climate change and human health mobilizes endeavours to implement operational changes in the maritime industry. In order to explore solutions, it is imperative to investigate the cause and scale of the problem. Therefore, this case study aims to create a benchmark for the port of Gothenburg that would enable decision making on this matter and address CO_2 emissions from ships at anchor. During 2019 the CO_2 emissions from ships at anchor in the port of Gothenburg reached approximately 16102 MT, using the IMO4 method. The CO_2 emissions from January to April of 2021 are approximately 4488 MT, calculated with the BE method. To give perspective, the total bottom-up CO_2 emissions for the world fleet reached 1,056 million MT in 2018 (IMO, 2020), about 20% of this emission correspond to anchor and berthing activity [1]. Therefore, CO_2 emission from the port of Gothenburg at anchor in 2019 represents approximately 0.008% of the total anchor emissions in the world in 2018. The emissions of Port of Los Angeles in 2019 for vessels at anchor reached 15,444 MT [35], this value differs little from the emissions in the port of Gothenburg.

The case study also intends to give a general understanding of how the energy is produced and used onboard while anchoring. The energy used is directly linked to the fuel consumption and its emissions, and therefore understanding this process from the ship perspective would allow the port or other entities to gain perspective and think of solutions to reduce energy use. Additionally, the qualitative questionnaire also touches upon data collection onboard and energy efficiency matters, which would be helpful when collecting data, to know how the data is collected and treated onboard.

The impact of the results is not only creating awareness of the actual situation regarding CO_2 emissions but also enabling change of operation from the port side to reduce emissions. This will positively impact society as the air quality increases with the implementation of reduction plans in the following years. A different angle is portrayed within the 2030 UN Sustainable Development Agenda. Future plans to reduce CO_2 emissions may resemble upon, by wording, Goal 3 – Good health and well-being, Goal 9 – Industry innovation and infrastructure, Goal 11 – Sustainable cities and communities, and Goal 13 – Climate action. Furthermore, it reinstates where the port stands in terms of corporate social responsibility by showing influence and leadership to find a sustainable operation.

Relevant Aspects
Relevant aspects should be kept in mind while reading the case study, as they can influence the perspective on energy management at anchor or EI results. It is also important to understand that every available method to comprise emission inventories counts with assumptions as of today. Although assumptions might influence the results, it does not mean that the result obtained is invalid or wrong. Therefore, it is imperative to be analytic when reading GHG studies. The validity of the results will depend on the data used and the type of assumptions made. This case study has several assumptions due to scarce data and difficulty gathering specific information such as load factors or output power for boilers. Within the limitation of this research, we cannot assess how much the assumption have influenced our results. However, the results lie within realistic values compared to other studies of GHG emissions and air quality.

The accuracy of the generated qualitative data is reasonably acceptable as 60% of the responses are from chief engineers and 21% of masters. This cognition can be extended to the specific data from the quantitative questionnaire. Therefore, it can be said that the results from the case study are accurate enough as most of the respondent have technical knowledge.

Although most of the responses come from oil and chemical tankers, the results are disclosed for every type of vessel considering the following reasons (Section 7.2.3). Firstly, having fewer answers of a specific type of vessel does not always mean that they are not valuable for data analysis. For instance, most merchant vessels show general design lineaments (auxiliary arrangements), which provides a general understanding of energy consumption of ships at anchor. Simultaneously, all the results provide distinct features on energy consumption regarding some specific types of cargo.

It must also be noticed that in the results obtained, we found a few values of AE output power and fuel consumption that do not correspond with values of similar vessels (Figure 5.2). They cannot be regarded as outliers as there is not enough information to do so, but it could be due to a lack of standardization to collect fuel consumption parameters. A possible solution would be to use standardized models to collect data for fuel consumption aided by digital data collection and analysis tools. For instance, it is reasonable to state that the accuracy of the energy consumption might depend on the measuring instruments and the crew's workload that can be lightened by digital technologies when undertaking MRV reporting tasks (Section 6.3). The lack of standardization also resembles upon different technologies, either digital or analogue, that could have different accuracy levels. However, it is depicted that every ship addresses energy management data collection with their available tools, but we cannot tell from the data if they are doing it in the most suitable way.

Furthermore, the obtained results show some differences when estimating the average fuel consumption rate (MT/h), dividing the fuel consumption by anchor hours per ship type (Figure 7.11). When making the average FCR, ship types with fewer vessels and fewer anchor hours show the biggest values because the IMO average data is considerably higher than BE specific data. We analyzed some of these vessels, showing that same ship type with lower GT have higher values of output power, which comes from IMO4. For example, a 3,999 GT containers vessel corresponds to 450 kW AE output power compared to a 10,318 GT container vessel giving 220 kW of output power by specific data. It is important to consider that for some large vessel that cannot be compared as there is no available specific data, IMO4 shows considerably high values that influence the results with higher FCR making a noticeable difference in the results compared with other vessels types.

The qualitative questionnaire shows that the efficiency and emission reduction parts' answers are concise but not elaborated. Specifically, regarding the use of SEEMP onboard (Section 6.4.3), most of the ships mentioned the energy management system, but nothing regarding how it is used. This might have direct implications on relevant information touching upon data collection and energy generation & usage. However, the answers regarding data reporting to onshore offices show that the frequency of the reports is not necessarily linked to the technology used to collect the data. It is logical to think it is associated with the policies and conditions of each shipping management company. Nevertheless, data has shown that vessels with digital technologies tend to report to shore daily.

Another interesting aspect of the qualitative research is that a liquefied gas taker was found to use energy at anchor for cargo equipment. It is reasonable to think that there is active equipment, while anchoring, on gas tankers to retain or adapt the pressure and temperature of the liquefied cargo inside the tanks. We could infer from this that other vessels, such as containers, could use additional energy at anchor to supply electricity to the reefer units.

In the case study, it is found a tendency that all the electric power at anchor comes from one of the generating sets to be working 100% of the time at anchor. Therefore, it is logical to conclude that even with multiple machinery arrangements available for generating sets, the electrical load at anchor is always low as it could be undertaken just by one genset. To the best of our knowledge, we have not found a similar argument that portraits this finding in the literature. Therefore, it may comprise new information regarding auxiliary generation at anchor. An opposite argument that is not mentioned within the generated information could be that some of the electrical load is undertaken by other sources combined with the genset, like solar panels.

On the other hand, the lack of retrieved information from boilers is noticeable. Few vessels indicated just the operating time at anchor, which ranges between 5 and 20% of the anchor time (Section 7.2.1). However, information to estimate fuel consumption is not given, which leads to thinking that boilers may not be considered a relevant fuel consumer at anchor or that they do not count with a measurement device. Nonetheless, boilers are important from a fuel consumption standpoint because the specific fuel consumption tends to be higher in comparison with the SFC of AE according to IMO4 average data. Lacking primary data of boilers has the direct implication of using average data for the boilers' consumption, and therefore the CO_2 inventory is compromised to a certain extent.

Regarding emissions at anchor, we thought they would vary within seasons due to HVAC systems for heating or air conditioning. Surprisingly, the results show that the emissions are influenced mainly by the incoming traffic and the ship types during the summer and winter. In order to obtain a trend between the emissions and the seasons, it would be better to survey the same group of vessels and see how the fuel consumption changes over the year.

Fuel Consumption Equation Terms
While analyzing the results and methodologies, we have found two terms that should be considered in the equations to calculate fuel consumption that might weigh over the veracity of the EI. These terms are time operational rating and engine load.

IMO4 and POLA19 do not distinguish between the number of generating sets, boilers, and their time operational ratings. Not stating the time ratings could lead to misinterpretation, as it is unclear if average data has a default time operational rating. BE does consider the number of generating sets, boilers, and their time operational ratings. For instance, through BE, it is assessed that the vessels have power generation capacities 100% of operating time at anchor. On the other hand, according to our results (Section 7.2.1), for boilers is very contrasting as they have lower time ratings at anchor, between 5-20%.

Regarding the second term, neither of the methods, including BE, consider the engine load for auxiliary engines. This comprises a simplified model for emission inventories that do not correct the emission factor regarding the engine load. The implication of this is not considering the amount of emissions that stem from variations in the combustion process due to the load. Nonetheless, we cannot assess how much the emissions would be affected by not considering a load correction. The load factor is not considered in this study because it is difficult to gather this information as it depends on the engine particularities while operating, which is even more scarce than specific data on FC.

The recommendations made in the second part of the thesis provide an insight into the course of action to reduce carbon intensity by 2030. The suggestion of implementing a VBP is based on the idea of comprising an accurate benchmark that would enable a change of operations and decision in the port. Collecting information for an EI could be automatically accomplished by several means, such as sensor reporting. However, the enforcement of a VBP conformed by an "energy brigade" with deep knowledge in marine machinery will ensure the precision of the information gathered as the maritime sector lacks standardization for data collection.

Moreover, a mobile prototype is suggested as an approach to achieve the port goal to reduce fuel consumption. The qualitative questionnaire obtained the vessels' point of view regarding the possibility of providing sustainable energy while anchoring. Some vessels cannot picture how this service could be accomplished, and they assumed that the method would be through submarine electrical cables. The vessels state some operational facts why this cannot be done. For instance, it is prohibited to drop anchor on places with power cables in the seabed. This reinforces the hypothesis of having a modular prototype that can be mobilized and moored side by side with the main vessel.

9.1 Limitations of the Case Study

Even though the results found in the study are interesting and satisfactory, the study presented some limitations. Firstly, the short timeframe and the small sample size, these reasons are interconnected, as the results of the BE method would have reached a higher level of accuracy with more time, and therefore data. The timeframe for the thesis was approximately 17 weeks, where literature review, development of questionnaires, collection of data and analysis of results was done.

Moreover, the current situation regarding COVID-19 has influenced the study. The idea was to collect primary data using onboard qualitative and quantitative semi-structured interviews with follow-up questions that would have guaranteed higher accuracy levels in the results. In our opinion, this might have avoided adapting the questionnaires during the research to increase the response rate, which can also be considered a limitation as the first versions are more complete with information regarding abatement technologies and reference data that might have improved the thesis results. Additionally, due to COVID-19, the year 2020 was excluded from the study due to changes in the port activity, which creates a gap in the traceability for the inventory of emissions.

The lack of information available regarding CO_2 emissions of vessels at anchor and data reliability is also considered a limitation. Very few studies have reliable information due to the difficulty of gathering the specific data, and therefore there is a need to use average data, which in most cases comes from the same sources. The available studies have little specific data that, in most cases, is not applicable to our study because the data or the operational mode are not comparable.

9.2 Further Studies

It is recommended for the port of Gothenburg to continue with the emission inventory from May until the end of 2021 to have a complete benchmark throughout the mentioned year, following the BE method (Section 5.2.2). This action secures a complete 2021 benchmark within a screening level (Section 2). In addition, the port should keep collecting primary data on fuel consumption to increase the BE specific data, which leads to an increment of the dependency footnoteR^2 value of the logarithmic regressions. within the variables of GT, output power, and fuel consumption. On the other hand, if the port were to upgrade its emissions inventories to the highest level of accuracy, the comprehensive level, it is suggested that the data collection is undertaken by a vessel boarding program (VBP) along with a more robust emission estimating method for more precise results (Section 2). In this case, a better mathematical model could incorporate a more precise hierarchy built upon specific data. For instance, an algorithm that automatically adapts the bins based on changeable parameters of FC, as the ship size increments, could be beneficial for the emissions results.

To raise awareness of air pollution, it is important to include a broader spectrum of pollutants. A more holistic comprehension is needed on GHG emissions that stem from shipping activity in the area, not only for CO_2 but also for SO_x, NO_x, and PM, as they impose the greatest danger on human health. Additionally, the EI should include other operational modes of the ship like berthing and operations, as anchor produces lesser emissions.

10

Conclusion

BE and known EI methodologies such as IMO4 and POLA19 undertake similar scopes. However, they adhere to certain assumptions regarding anchoring that are perceived to generate uncertainties for the EI. The mentioned methodologies are bottom-up and vessel-based. In this case study, the estimated inventories could be catalogue based on the level of accuracy as scaling for 2019 and screening level for 2021.

Regarding the data collection, it can be agreed upon that it becomes crucial for the IE. Inventories can be generated using average data, but there is no possibility to assess over statistical uncertainties among that data. On the other hand, specific data is extremely limited and concealed for auxiliary engines and boilers at anchoring. However, this data can be generated questionnaires like in this case study or vessel boarding programs that may secure more reliable emission inventories in the end. Both data collection options face their own limitations.

The accuracy of the BE data collection is satisfactory as most of the respondents hold technical knowledge either as chief engineers or shipmasters. This also reflects upon the precision of the qualitative results and the BE EI to a certain extent. There is an issue in terms of the standardization for data collection, as of today, the maritime community has not reached a declared consensus to collect fuel consumption information at anchor. The closes to standardization are the throughputs that different methodologies require.

Comprising benchmarks for CO_2 emissions at anchor for the Port of Gothenburg is a very important and perceptible endeavor towards a more sustainable industrial practice. The results of this research, relating to how energy is produced and managed onboard while anchoring, help to contemplate possible solutions to reduce energy use further on.

The CO_2 emissions from vessels at anchor in the port of Gothenburg were approximately 16102 metric tonnes in 2019. In the period January to April 2021, the emissions added up to 4,488 metric tonnes of CO_2. These emissions at anchor came from energy is generated onboard by one generating set on service and heat from boilers in start/stop mode. The principle stands for energy transformation via an energy carrier to electric energy. Due to the extensiveness of the results, the reader is referred to Section 6 for qualitative results and Section 7 for the quantitative results.

One of the main technical issues when comprising EI could be the engine load of auxiliary engines. Specially at anchor when the engine load is not considered, there is not a correction for the emission factor that is directly related to the CO_2 emissions. This is consistent among the methodologies in this study. The engine load is mostly attained for main engines, but not for auxiliary engines.

The course of action suggests a vessel boarding program to produce comprehensive inventories leading to a more informed decision making. Further studies are detailed in Section 8 which are aligned with the port endeavors to help reduce carbon intensity. A mobile prototype with sustainable energy capabilities is conceptually introduced in Section 8. To secure traceability for the 2021 benchmark, the port is advised to continue with the emission inventory from May to December.

Finally, the underlying values of this research encompass an effort to increase awareness on air quality and may impact a small group of the society positively. It also portraits active corporate social responsibility led by the Port of Gothenburg to adhere to more sustainable practices aiming to find an environmental, economic, and social equilibrium.

Bibliography

[1] IMO, "Fourth IMO GHG Study 2020: Reduction of GHG emissions from ships," tech. rep., IMO, July 2020.

[2] A. Christodoulou, M. Gonzalez-Aregall, T. Linde, I. Vierth, and K. Cullinane, "Targeting the reduction of shipping emissions to air: A global review and taxonomy of policies, incentives and measures," Maritime Business Review, vol. 4, pp. 16–30, Jan. 2019. Publisher: Emerald Publishing Limited.

[3] UNCOTAD, REVIEW OF MARITIME TRANSPORT 2020. UNITED NATIONS, 2021. OCLC: 1231956368.

[4] K. Andersson, S. Brynolf, J. F. Lindgren, and M. Wilewska-Bien, eds., Shipping and the Environment. Berlin, Heidelberg: Springer Berlin Heidelberg, 2016.

[5] G. P. Gobbi, L. Di Liberto, and F. Barnaba, "Impact of port emissions on EU-regulated and non-regulated air quality indicators: The case of Civitavecchia (Italy)," Science of The Total Environment, vol. 719, p. 134984, June 2020.

[6] H. Winnes, L. Styhre, and E. Fridell, "Reducing GHG emissions from ships in port areas," Research in Transportation Business & Management, vol. 17, pp. 73–82, 2015.

[7] H. Lee, H. T. Pham, M. Chen, and S. Choo, "Bottom-Up Approach Ship Emission Inventory in Port of Incheon Based on VTS Data," Journal of Advanced Transportation, vol. 2021, p. e5568777, Apr. 2021. Publisher: Hindawi.

[8] G. Beig, S. Maji, A. S. Panicker, and S. K. Sahu, "25 - Reactive Nitrogen and Air Quality in India," in The Indian Nitrogen Assessment (Y. P. Abrol, T. K. Adhya, V. P. Aneja, N. Raghuram, H. Pathak, U. Kulshrestha, C. Sharma, and B. Singh, eds.), pp. 403–426, Elsevier, Jan. 2017.

[9] S. Jahangiri, N. Nikolova, and K. Tenekedjiev, "An improved emission inventory method for estimating engine exhaust emissions from ships," Sustainable Environment Research, vol. 28, pp. 374–381, Nov. 2018.

[10] B. Goldsworthy and L. Goldsworthy, "Assigning machinery power values for estimating ship exhaust emissions: Comparison of auxiliary power schemes," Science of The Total Environment, vol. 657, pp. 963–977, Mar. 2019.

[11] L. T. Le, G. Lee, H. Kim, and S.-H. Woo, "Voyage-based statistical fuel consumption models of ocean-going container ships in Korea," Maritime Policy & Management, vol. 47, pp. 304–331, Apr. 2020. Publisher: Routledge _eprint: https://doi.org/10.1080/03088839.2019.1684591.

[12] San Pedro Bay Ports, "San Pedro Bay Ports Emission Inventory Methodology Report," tech. rep., San Pedro Bay Ports, Apr. 2019.

[13] Port of Gothenburg, "Expand your business: Call the gateway to Scandinavia." Available: `https://www.portofgothenburg.com/about-the-port/the-port-of-gothenburg/`. Accessed on: 2021-05-26 [Online].

[14] J. A. Nathanson, "Air Pollution." Available: `https://www.britannica.com/science/air-pollution`, Oct. 2020. Accessed on: 2021-05-07 [Online].

[15] Y. Shi, Climate Change and International Shipping: The Regulatory Framework for the Reduction of Greenhouse Gas Emissions. Brill Nijhoff, Nov. 2016.

[16] Australian Government, Department of Agriculture, Water and the Environment, "Green house effect." Available: `http://www.environment.gov.au/`. Accessed on: 2021-05-24 [Online].

[17] P. Cammin, J. Yu, L. Heilig, and S. Voß, "Monitoring of air emissions in maritime ports," Transportation Research Part D: Transport and Environment, vol. 87, p. 102479, Oct. 2020.

[18] European Environment Agency, "Atmospheric greenhouse gas concentrations." Available: `https://www.eea.europa.eu/data-and-maps/indicators/atmospheric-greenhouse-gas-concentrations-7/assessment`, May 2021. Accessed on: 2021-05-11 [Online].

[19] World Meteorological Organization, "Greenhouse gas concentrations in atmosphere reach yet another high," Nov. 2019.

[20] L. Styhre, H. Winnes, J. Black, J. Lee, and H. Le-Griffin, "Greenhouse gas emissions from ships in ports – Case studies in four continents," Transportation Research Part D: Transport and Environment, vol. 54, pp. 212–224, July 2017.

[21] IMO, "Reducing greenhouse gas emissions from ships." Available: `https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx`. Accessed on: 2021-05-25 [Online].

[22] O. Merk, "Shipping Emissions in Ports," International Transport Forum Discussion Papers, p. 37, Dec. 2014. Publisher: OECD.

[23] IMO, GEF-UNDP-IMO GloMEEP Project, and IAPH, "Port Emissions Toolkit- guide no. 1: assessment of port emissions," 2018.

[24] H. N. Psaraftis and C. A. Kontovas, "CO2 emission statistics for the world commercial fleet," WMU Journal of Maritime Affairs, vol. 8, pp. 1–25, Apr. 2009.

[25] R. Kantharia, A Brief Overview of Ship's Auxiliary Engine- Part 1. Marine Insight, Aug. 2016.

[26] H. D. McGeorge, Marine Auxiliary Machinery, vol. 7. Auxiliary Power. Elsevier, 7th ed., 1995.

[27] D. Taylor, Introduction to Marine Engineering, vol. 4. Boilers. Elsevier, 2nd ed., 1996.

[28] J. Hanania, J. Martin, K. Stenhouse, and J. Donev, "Diesel generator," Mar. 2015.

[29] D. Taylor, Introduction to Marine Engineering, vol. 2.1 Four-Stroke Cycle. Elsevier, 2nd ed., 1996.

[30] D. Taylor, Introduction to Marine Engineering, vol. 8.1 Fuel Oils. Elsevier, 2nd ed., 1996.

[31] ISO, "ISO 8217:2017 (E) Specification of marine fuels; Petroleum products-Fuels (class F)," Tech. Rep. 6th, International Organization for Standarization, 2017.

[32] SIS, "Petroleum products-Fuels (class F) Specifications of marine fuels ISO 8217:2017."

[33] J. Hulskotte and H. Denier van der Gon, "Fuel consumption and associated emissions from seagoing ships at berth derived from an on-board survey," Atmospheric Environment, vol. 44, pp. 1229–1236, Mar. 2010.

[34] Port of Long Beach, "Air Emission Innventory- 2019," technical Report, Port of Long Beach, Sept. 2020.

[35] The Port of Los Angeles, "Port of Los Angeles Inventory of Emissions 2019," thecnical report, Starcrest Consulting Group, LLC, Sept. 2020.

[36] Port Everglades, "Port Everglades 2015 Baseline Air Emissions Inventory," tech. rep., Port Everglades Broward country, Florida, Florida, Dec. 2016.

[37] The Port Authority of New York and New Jersey, "Multi-facility Emission Inventory 2017," p. 97, Jan. 2019.

[38] MasterClass, "What Is Inductive Reasoning? Learn the Definition of Inductive Reasoning With Examples, Plus 6 Types of Inductive Reasoning," May 2021.

[39] M. N. K. Saunders, P. Lewis, and A. Thornhill, Research methods for business students. New York: Prentice Hall, 5th ed ed., 2009.

[40] V. Braun and V. Clarke, “Using thematic analysis in psychology,” Qualitative Research in Psychology, vol. 3, pp. 77–101, Jan. 2006.

[41] L. S. Nowell, J. M. Norris, D. E. White, and N. J. Moules, “Thematic Analysis: Striving to Meet the Trustworthiness Criteria,” International Journal of Qualitative Methods, vol. 16, Dec. 2017.

[42] P. Van Staalduinen, “COGOG Propulsion Installations in Guided Missile and Standard Class Frigates of the Royal Netherlands Navy: A Review of the Development From the Specific Design Philosophies to the Actual Technical, Personnel and Maintenance/Logistic Management in Service,” in ASME 1977 International Gas Turbine Conference and Products Show, (Philadelphia, Pennsylvania, USA), p. V001T01A066, American Society of Mechanical Engineers, Mar. 1977.

[43] IMO, “Special Areas under MARPOL.”

[44] CH-IV, “All About LNG.”

[45] Rigzone, “How Does LNG Work?.” Available: https://www.rigzone.com/training/insight.asp?insight_id=322&c_id=. Accessed on: 2021-05-09 [Online].

[46] K. Chopra, “Understanding Sounding, Ullage, and Frequency of Sounding,” June 2019.

[47] LeanMarine, “Fleet Analytics – Lean Marine,” 2021.

[48] KYMA AS, “Ship performance | Monitoring, reporting and analysis Kyma,” 2021.

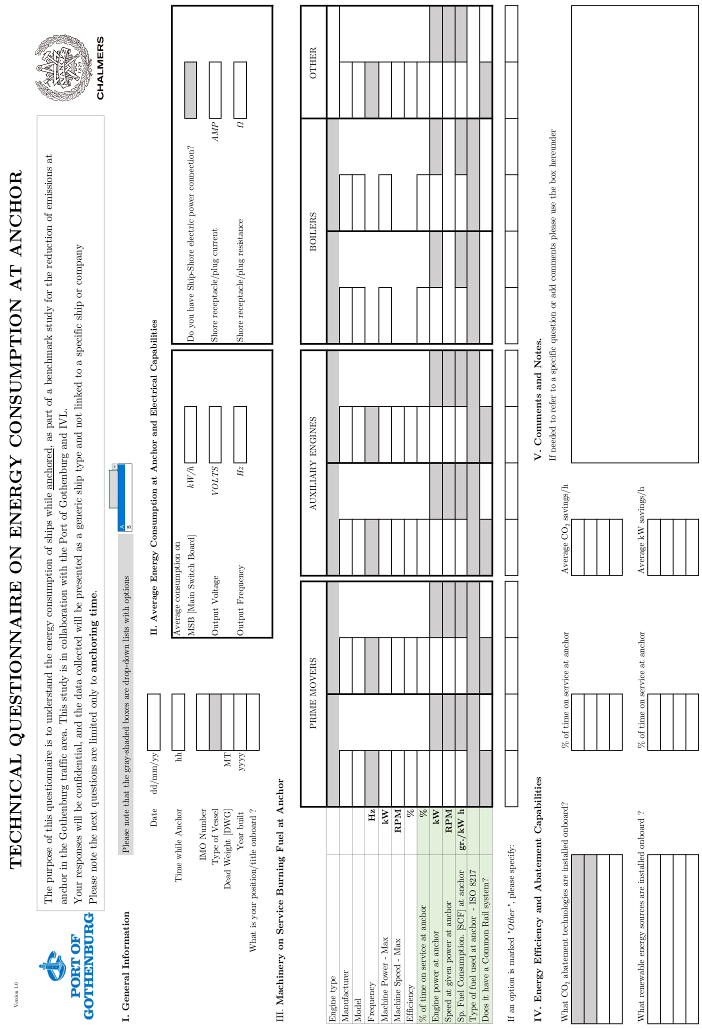
[49] DEIF, “PPM-3 Protection and Power Management.”

[50] R. H. Merien-Paul, H. Enshaei, and S. G. Jayasinghe, “In-situ data vs. bottom-up approaches in estimations of marine fuel consumptions and emissions,” Transportation Research Part D: Transport and Environment, vol. 62, pp. 619–632, July 2018.

[51] Sisense, “What is Real Time Analytics?.” Available: https://www.sisense.com/glossary/real-time-analytics/. Accessed on: 2021-05-16 [Online].

A

Appendix 1


Version 1.0

PORT OF GOTHENBURG

TECHNICAL QUESTIONNAIRE ON ENERGY CONSUMPTION AT ANCHOR

CHALMERS

The purpose of this questionnaire is to understand the energy consumption of ships while anchored, as part of a benchmark study for the reduction of emissions at anchor in the Gothenburg traffic area. This study is in collaboration with the Port of Gothenburg and IVL.
Your responses will be confidential, and the data collected will be presented as a generic ship type and not linked to a specific ship or company
Please note the next questions are limited only to **anchoring time**.

I. General Information

Please note that the gray-shaded boxes are drop-down lists with options

Date dd/mm/yy
Time while Anchor hh
IMO Number
Type of Vessel
Dead Weight [DWG] MT
Year built yyyy
What is your position/title onboard ?

II. Average Energy Consumption at Anchor and Electrical Capabilities

Average consumption on MSB [Main Switch Board] *kW/h*
Output Voltage *VOLTS*
Output Frequency *Hz*
Do you have Ship-Shore electric power connection?
Shore receptacle/plug current *AMP*
Shore receptacle/plug resistance *Ω*

III. Machinery on Service Burning Fuel at Anchor

		PRIME MOVERS	AUXILIARY ENGINES	BOILERS	OTHER
Engine type					
Manufacturer					
Model					
Frequency	Hz				
Machine Power - Max	kW				
Machine Speed - Max	RPM				
Efficiency	%				
% of time on service at anchor	%				
Engine power at anchor	kW				
Speed at given power at anchor	RPM				
Sp. Fuel Consumption. [SCF] at anchor	gr./kW h				
Type of fuel used at anchor - ISO 8217					
Does it have a Common Rail system?					

If an option is marked '*Other*', please specify:

IV. Energy Efficiency and Abatement Capabilities

What CO_2 abatement technologies are installed onboard? — % of time on service at anchor — Average CO_2 savings/h

What renewable energy sources are installed onboard ? — % of time on service at anchor — Average kW savings/h

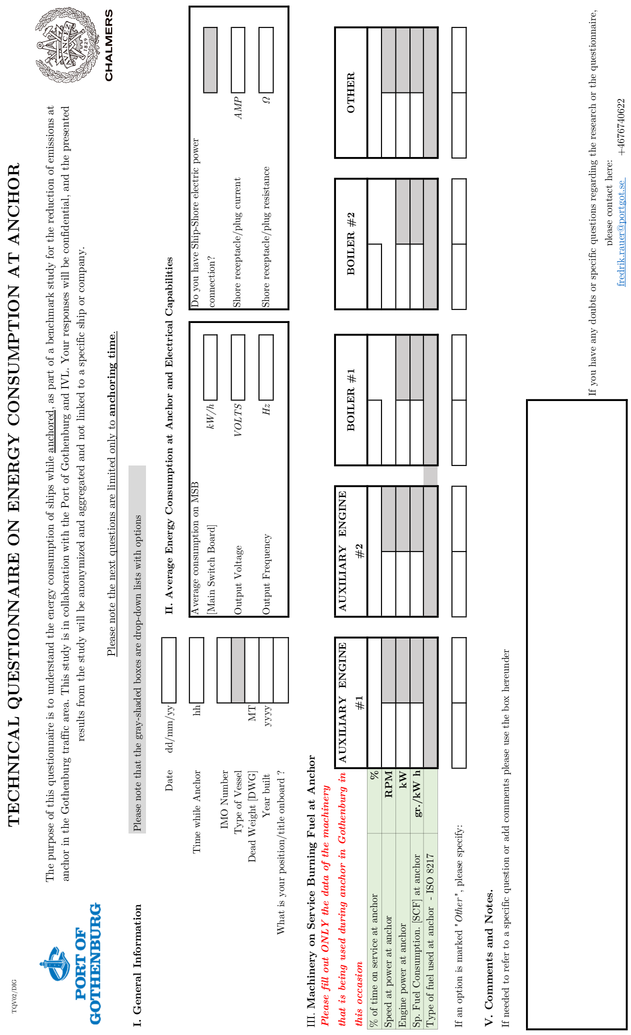
V. Comments and Notes.

If needed to refer to a specific question or add comments please use the box hereunder

Figure A.1: Technical questionnaire Version digTQV01

B

Appendix 2



TQV02/DIG

PORT OF GOTHENBURG

CHALMERS

TECHNICAL QUESTIONNAIRE ON ENERGY CONSUMPTION AT ANCHOR

The purpose of this questionnaire is to understand the energy consumption of ships while anchored, as part of a benchmark study for the reduction of emissions at anchor in the Gothenburg traffic area. This study is in collaboration with the Port of Gothenburg and IVL. Your responses will be confidential, and the presented results from the study will be anonymized and aggregated and not linked to a specific ship or company.

Please note the next questions are limited only to **anchoring time.**

I. General Information

Please note that the gray-shaded boxes are drop-down lists with options

Date dd/mm/yy

Time while Anchor hh

IMO Number

Type of Vessel

Dead Weight [DWG] MT

Year built yyyy

What is your position/title onboard ?

II. Average Energy Consumption at Anchor and Electrical Capabilities

Average consumption on MSB [Main Switch Board] *kW/h*

Output Voltage *VOLTS*

Output Frequency *Hz*

Do you have Ship-Shore electric power connection?

Shore receptacle/plug current *AMP*

Shore receptacle/plug resistance *Ω*

III. Machinery on Service Burning Fuel at Anchor

Please fill out ONLY the data of the machinery that is being used during anchor in Gothenburg in this occasion

		AUXILIARY ENGINE #1	AUXILIARY ENGINE #2	BOILER #1	BOILER #2	OTHER
% of time on service at anchor	%					
Speed at power at anchor	RPM					
Engine power at anchor	kW					
Sp. Fuel Consumption. [SCF] at anchor	gr./kW h					
Type of fuel used at anchor - ISO 8217						

If an option is marked "*Other*", please specify:

V. Comments and Notes.

If needed to refer to a specific question or add comments please use the box hereunder

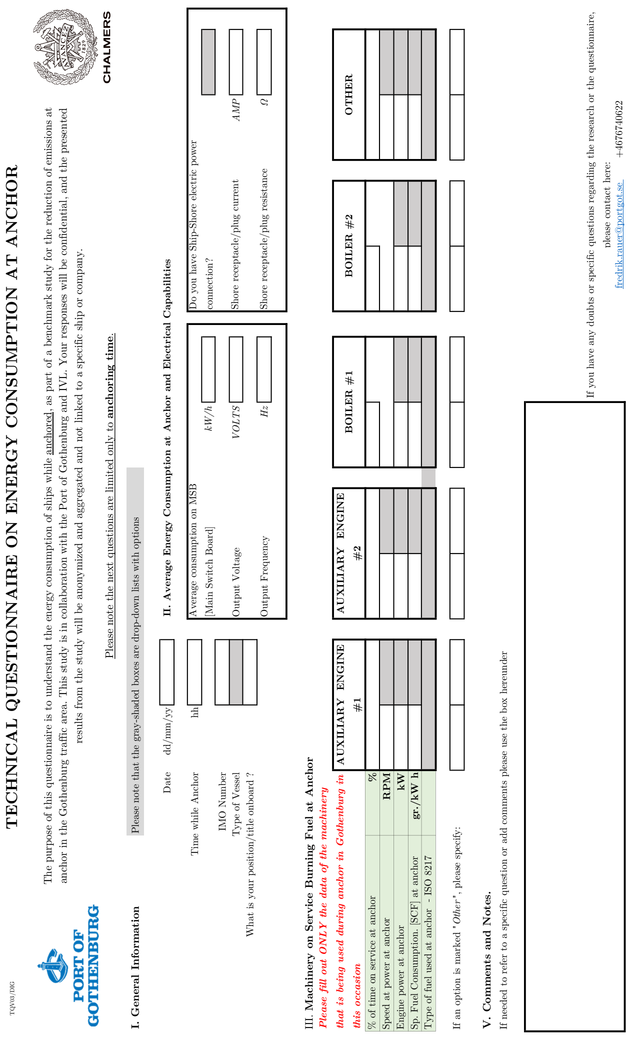
If you have any doubts or specific questions regarding the research or the questionnaire, please contact here:

fredrik.rauer@portgot.se +4676740622

Figure B.1: Technical questionnaire Version digTQV02

C

Appendix 3



TQV03/DIG

PORT OF GOTHENBURG

CHALMERS

TECHNICAL QUESTIONNAIRE ON ENERGY CONSUMPTION AT ANCHOR

The purpose of this questionnaire is to understand the energy consumption of ships while anchored, as part of a benchmark study for the reduction of emissions at anchor in the Gothenburg traffic area. This study is in collaboration with the Port of Gothenburg and IVL. Your responses will be confidential, and the presented results from the study will be anonymized and aggregated and not linked to a specific ship or company.

Please note the next questions are limited only to **anchoring time.**

Please note that the gray-shaded boxes are drop-down lists with options

I. General Information

Date	dd/mm/yy	
Time while Anchor	hh	
IMO Number		
Type of Vessel		
What is your position/title onboard ?		

II. Average Energy Consumption at Anchor and Electrical Capabilities

Average consumption on MSB [Main Switch Board]	kW/h	
Output Voltage	VOLTS	
Output Frequency	Hz	
Do you have Ship-Shore electric power connection?		
Shore receptacle/plug current	AMP	
Shore receptacle/plug resistance	Ω	

III. Machinery on Service Burning Fuel at Anchor

Please fill out ONLY the data of the machinery that is being used during anchor in Gothenburg in this occasion

		AUXILIARY ENGINE #1	AUXILIARY ENGINE #2	BOILER #1	BOILER #2	OTHER
% of time on service at anchor	%					
Speed at power at anchor	RPM					
Engine power at anchor	kW					
Sp. Fuel Consumption. [SCF] at anchor	gr./kW h					
Type of fuel used at anchor - ISO 8217						

If an option is marked "*Other*", please specify:

V. Comments and Notes.

If needed to refer to a specific question or add comments please use the box hereunder

If you have any doubts or specific questions regarding the research or the questionnaire, please contact here:

fredrik.cauer@portgot.se +46767740622

Figure C.1: Technical questionnaire Version digTQV03

D

Appendix 4

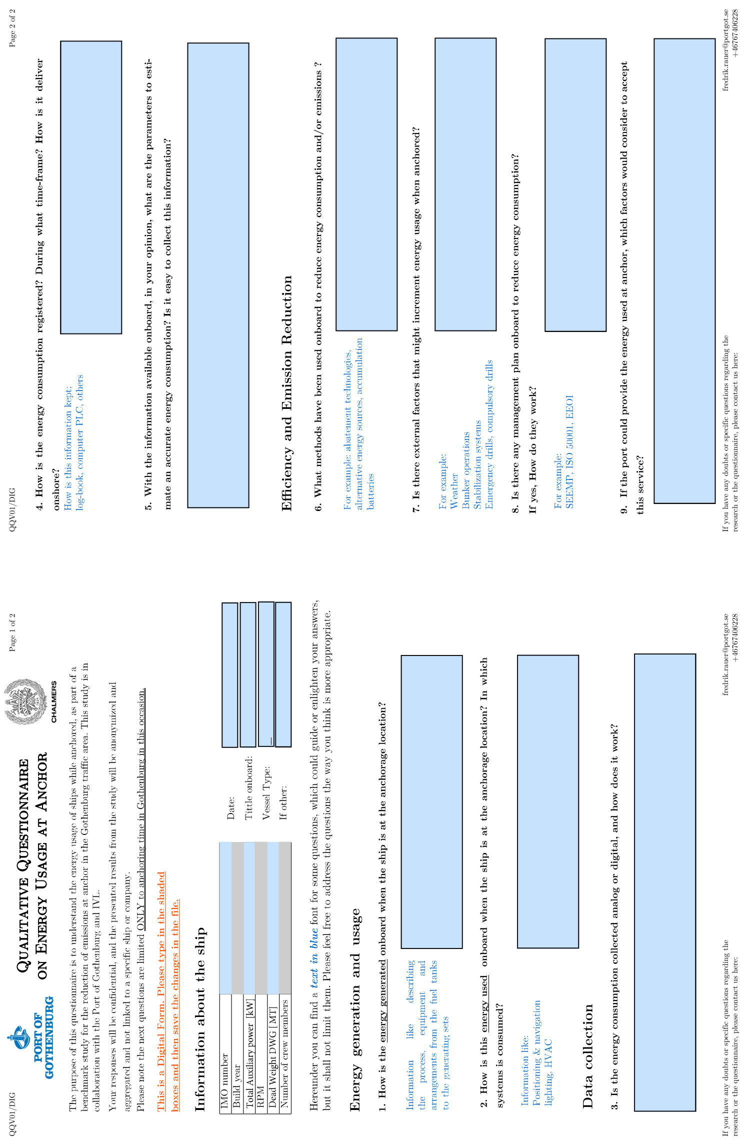


Figure D.1: Qualitative questionnaire Version digQQV01

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY