National Technical University of Athens

School of Naval Architecture and Marine Engineering

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Interactive Vessel and Shore Power Emissions Calculator

Diploma Graduation Thesis

of

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Athens, 2024

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Acknowledgments

I would firstly like to express my deepest gratitude to my thesis advisor and supervisor, Professor John M. Prousalidis, for his continuous and unwavering support and encouragement throughout this project. His invaluable guidance and assistance were significant in shaping the direction and outcome of this thesis.

I would also like to extend my heartfelt thanks to my family, especially my parents, Giorgo and Christiana, for their limitless support, patience, and encouragement through my whole life, which has brought me to this moment. Their love and understanding were a constant source of motivation for me.

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1. Introduction

1.1. Background of Study

As is the case with many tools and inventions of mankind, so has the shipping sector seen a rapid and explosive evolution and progress in the last centuries. Innovations in ship design, propulsion systems, and navigation technologies have significantly enhanced the efficiency and capacity of maritime transport.

Diesel engine, like other internal combustion engines, converts chemical energy contained in the fuel into mechanical power. Diesel fuel is a mixture of hydrocarbons which, during an ideal combustion process, would produce only CO_2 and water vapour (H_2O). Marine diesel engines, started replacing steam engines at the start of 20th century, and this has sparked an even greater progress.

However, this progress has come with substantial environmental costs. The shipping industry's emissions of air pollutants and greenhouse gases have grown dramatically in the previous two decades, contributing to global warming and adverse health effects. Despite being one of the least carbon-intensive and one of the most efficient modes of transport, shipping accounted for roughly 3% of the world's greenhouse gas emissions. And so, as we have been observing in recent years, the consequences of these emissions are becoming more and more apparent.

Recognizing the urgent need to address these issues, the International Maritime Organization (IMO) and other regulatory bodies have introduced measures to reduce the environmental footprint of the shipping industry.

The problem of unsustainable use of hydrocarbons as a fuel for energy production must be eliminated, or at least be minimized, in order to preserve environmental protection and sustainability. Solutions like electric propulsion for large vessels and Cold-Ironing (Onshore Power Supply) offer ways to reduce emissions.

1.2. Explanation of Objectives

This thesis focuses on the development of an emission calculator app to be used by ships and ports, aiming to address the pressing issue of emissions from maritime activities and provide an estimation of the associated costs of those emissions.

It should be noted that this work builds on the idea of future integration with two previous theses:

- «Θέματα ηλεκτρισμού σε πλοία και λιμένες», by Λευκίου Χριστόφορος [17].
- «Study for Power increase of local electrical grid in ports of European Economic Area (EEA) and United Kingdom (UK)», by Λευκίου Μιχάλης [16].

As in these previous projects, an interactive web application was developed. The interactive map within this application allows users to select ports (only European ports), and with that selection and other user inputs, several calculations are done. The results of those calculations provide an estimation of the costs of emissions from vessels using their engines at ports and compares them with the corresponding costs of those emissions if the vessels were using a Cold Ironing Infrastructure solution at each selected port.

2. Introduction to Marine Engines

2.1. A brief history of marine propulsion sources

The earliest instances of marine propulsion relied on natural phenomena instead of machines and engines. Sails were the predominant means of propelling maritime vessels with the help of oars, dating back to early civilizations such as the Greeks and Phoenicians. The transition to steam power propulsion marked a significant turning point during the end of 18th and start of the 19th century [1]. The first steam-powered vessel, *Pyroscaphe*, was built in 1783 by the French Claude de Jouffroy d' Abbans. Many years and attempts later, the *Savannah*, equipped with sails, a steam engine and fuel for 85 hours of operation, is considered the first steam powered ship to complete a transatlantic voyage in 1819 [5].

Steam engines gradually replaced sail, offering more reliable and controllable propulsion. The transition to internal combustion engines in maritime applications during the 20th century marked a profound shift in marine propulsion. The utilisation of diesel and gasoline engines brought enhanced efficiency, reliability, and manoeuvrability for various types of vessels. Diesel engines, in particular, gained popularity for their fuel efficiency and ability to generate substantial torque, making them well-suited for powering larger ships, including cargo vessels and naval ships.

Later came a surge in unconventional forms of propulsion, embracing technologies such as LNG (liquefied natural gas), hydrogen, electric, and nuclear engines. These innovations reflect a commitment to environmental sustainability, seeking cleaner and more efficient alternatives to traditional fossil fuels, and exploring diverse energy sources for propulsion in ships.

2.2. Operating Principles of Internal Combustion Engines

Internal combustion engines serve as the beating heart of countless vehicles and machinery, powering the modern world with efficiency and reliability. At its core, an internal combustion engine transforms chemical energy stored in fuel into mechanical energy to drive a vehicle or operate machinery.

There are many different types of internal combustion engines and they can be classified by: Application, Working cycle, Fuel, Method of ignition, Method of cooling and many more. Out of these, the main classification of internal combustion engines is the method of ignition of the fuel.

The two subcategories of this classification are:

a. Compression ignition
b. Spark ignition

The differentiation between spark ignition (SI) and compression ignition (CI) engines centers on the ignition mechanism and associated combustion processes. In SI engines, commonly found in gasoline-powered vehicles, combustion is initiated by a spark plug that ignites a pre-mixed air-fuel mixture. This method aligns with the Otto cycle, characterised by four-strokes: intake, compression, ignition, and exhaust (a stroke being the travel of the piston between its extreme points). On the other hand, CI engines, typical in diesel-powered vehicles, rely on spontaneous ignition due to the high compression and temperatures of air within the cylinder. As the piston compresses the air, the temperature and pressure rise to a point where fuel injected into the cylinder ignites without an external spark. This compression-ignition process follows the Diesel cycle, involving air intake, compression-fuel injection, combustion, and exhaust.

2.2.1. Ideal Air Standard Cycles

Internal combustion engines, whether they operate on a two-stroke or four-stroke cycle and whether they use spark ignition or compression ignition, follow a mechanical cycle rather than a thermodynamic cycle. However, their thermal efficiency is evaluated by comparing it to the thermal efficiency of air-standard cycles [4].

2.2.1.1. The Ideal Air Standard Otto Cycle

As previously stated, the Otto cycle is used as a comparison basis for spark ignition engines. The cycle consists of four non-flow processes, shown in the figure 2.i below, which are as follows:

1-2: Isentropic compression of air through a volume ratio of V_1 / V_2, called volumetric compression ratio r_v. In preparation for adding heat to the air, we next compress it by moving the piston up the cylinder. It is in this part of the cycle that we contribute work to the air. In the ideal Otto cycle, this compression is considered to be isentropic.

2-3: Addition of heat Q_{23} at constant volume. Heat is added to the air by fuel combustion when the piston is at its top dead centre position. Combustion is not initiated until a spark (from a spark plug, for instance) is generated in the cylinder. Because the piston is essentially immobile during this part of the cycle, we say that the heat addition is isochoric (no change in volume).

3-4: Isentropic expansion of air to the original volume V_1. In the Otto cycle, fuel is burned to heat compressed air and the hot gas expands forcing the piston to travel down in the cylinder. It is in this phase that the cycle contributes its useful work, rotating the crankshaft. Similar to the compression stage, this stage is also considered to be isentropic in the ideal Otto cycle.

4-1: Rejection of heat Q_{41} at constant volume to complete the cycle. Next, the expanded air is cooled down to ambient conditions. In an actual engine, this corresponds to exhausting the air from the engine to the environment and replacing it with fresh air. Since this happens when the piston is at the bottom dead centre position in the cycle and is not moving, we say this process is isochoric.

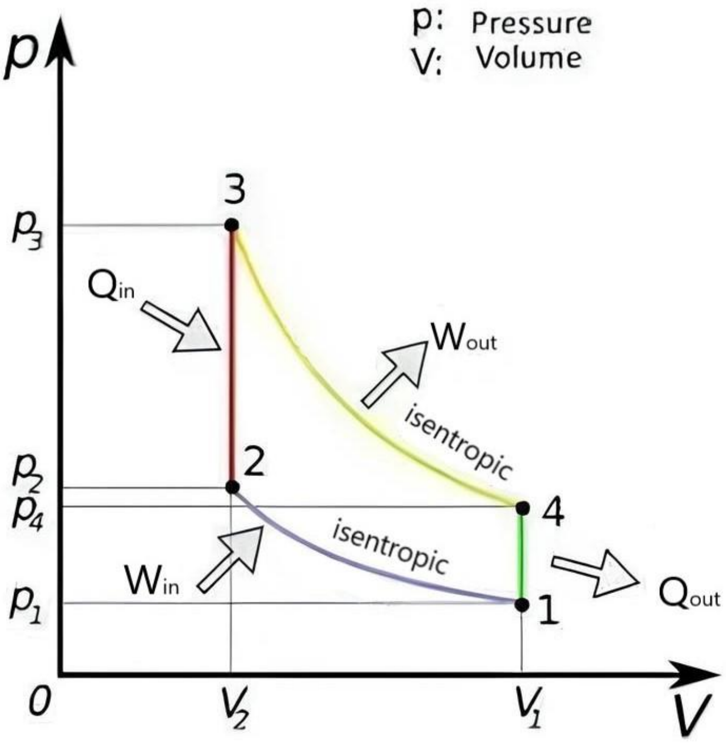


Figure 2.i Diagram of the Ideal Air Standard Otto Cycle

The efficiency of the Otto cycle, η_{Otto} is:

$$\eta_{Otto} = \frac{W}{Q_{23}} = \frac{Q_{23} - Q_{41}}{Q_{23}} = 1 - \frac{Q_{41}}{Q_{23}}$$

By considering air as a perfect gas, we have constant specific heat capacities, and for mass m of air the heat transfers are:

$Q_{23} = m\, c_v\, (T_3 - T_2)$ =and $Q_{41} = m\, c_v\, (T_4 - T_1)$

For the two isentropic processes 1-2 and 3-4, $T\, V^{\gamma-1}$ is a constant. Thus:

$T_2 / T_1 = T_3 / T_4 = r_v^{\gamma-1}$

Where γ is the ratio of gas specific heat capacities c_p, c_v. Substituting into the initial equation we have:

$\eta_{Otto} = 1 - 1 / r_v^{\gamma-1}$

And so, the efficiency of the Otto cycle is correlated to the compression ratio r_v and not the temperatures in the cycle.

2.2.1.2. The Ideal Air Standard Diesel Cycle

The Diesel cycle is very similar to the Otto cycle in that both are closed cycles commonly used to model internal combustion engines. The difference between them is that the Diesel cycle has heat addition at constant pressure, instead of heat addition at constant volume as in the Otto cycle. Also, the Diesel cycle is a *compression-ignition* cycle instead of a *spark-ignition* cycle like the Otto cycle. In large compression ignition engines, such as marine engines, fuel injection is arranged so that combustion occurs at approximately constant pressure in order to limit the peak pressures. The four non-flow processes constituting the cycle are shown in the state diagram (figure 2.ii) below, and are as follows:

1-2: Isentropic compression of air through a volume ratio of V_1 / V_2, called volumetric compression ratio r_v. In preparation for adding heat to the air, we compress it by moving the piston up the cylinder. It is in this part of the cycle that we contribute work to the air. In the ideal Diesel cycle, this compression is considered to be isentropic.

2-3: Addition of heat Q_{23} at constant pressure while the volume expands through a ratio V_3 / V_2, called load or cut off ratio α. Heat is added to the air by fuel combustion. This process begins just as the piston leaves its top dead centre position.

3-4: Isentropic expansion of air to the original volume V_1. In the Diesel cycle, fuel is burned to heat compressed air and the hot gas expands forcing the piston to travel down in the cylinder. It is in this phase that the cycle contributes its useful work, rotating the crankshaft. Similar to the compression stage, this stage is also considered to be isentropic in the ideal Diesel cycle.

4-1: Rejection of heat Q_{41} at constant volume to complete the cycle. Next, the expanded air is cooled down to ambient conditions. In an actual engine, this corresponds to exhausting the air from the engine to the environment and replacing it with fresh air. Since this happens when the piston is at the bottom dead centre position in the cycle and is not moving, we say this process is isochoric.

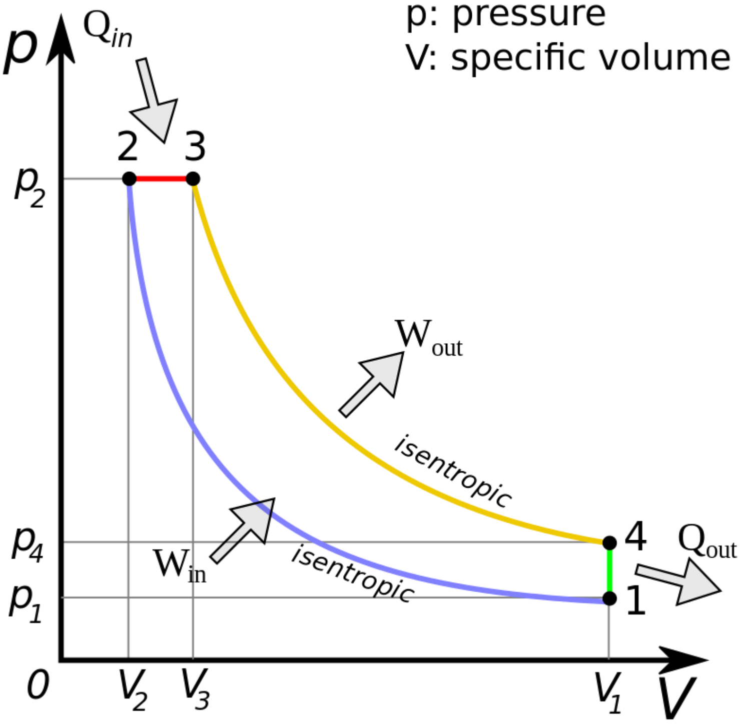


Figure 2.ii Diagram of the Ideal Air Standard Diesel Cycle

The efficiency of the Diesel cycle, η_{Diesel} is:

$$\eta_{Diesel} = \frac{W}{Q_{23}} = \frac{Q_{23} - Q_{34}}{Q_{23}} = 1 \frac{Q_{34}}{Q_{23}}$$

By considering air as a perfect gas, we have constant specific heat capacities, and for mass m of air the heat transfers are:

$Q_{23} = m\, c_p\, (T_3 - T_2)$ and $Q_{41} = m\, c_v\, (T_4 - T_1)$

For the isentropic process 1-2, $T\, V^{\gamma-1}$ is a constant. Thus:

$T_2 / T_1 = r_v^{\gamma-1}$

For the constant pressure process 3-4, $T\, V^{\gamma-1}$ is a constant. Thus:

$T_3 / T_2 = V_3 / V_2 = \alpha$

For the isentropic process 3-4, $T\, V^{\gamma-1}$ is a constant. Thus:

$T_4 / T_3 = (V_3 / V_4)^{\gamma-1} = (\alpha / r_v)^{\gamma-1}$

Where γ is the ratio of gas specific heat capacities c_p, c_v.

Substituting into the initial equation we have:

$$\eta_{Diesel} = 1 - \frac{1}{r_v^{\gamma - 1}} \cdot \left[\frac{\alpha^{\gamma} - 1}{\gamma(\alpha - 1)} \right]$$

2.2.2. Diesel Engines

According to D.A. Taylor, as he writes in his book: “Introduction to Marine Engineering” [6], the diesel engine is a type of internal combustion engine which ignites the fuel by injecting it into hot, high-pressure air in a combustion chamber. In common with all internal combustion engines the diesel engine operates with a fixed sequence of events, which may be achieved either in four strokes or two.

Each stroke is accomplished in half a revolution of the crankshaft. In a two-stroke engine, the power cycle is completed in just two-strokes of the piston: the compression and power strokes occur in a single revolution. This design simplifies the mechanical structure but often leads to higher emissions. On the other hand, the four-stroke engine, commonly employed in automotive applications, features four distinct strokes: intake, compression, power, and exhaust.

2.2.2.1. Two Stroke Engine Cycle

As stated before, the operation cycle of a two-stroke engine in a nutshell, consists of:

1. **Intake and Compression Stroke**: The piston moves toward the Top Centre (TC) and the compression starts when it has risen high enough to close the valves (intake and exhaust valves if any). A few degrees before the TC, the fuel is injected into the air of high temperature and pressure so that it sprinkles, evaporates and the combustion begins.
2. **Power and Exhaust Stroke**: The piston moves toward the Bottom Centre (BC) driven by the products of combustion factor work while as it approaches the BC it also reveals the valves in order to start the exchange of gases.

The piston and the ports are generally shaped to deflect the incoming charge from flowing directly into the exhaust ports and to achieve effective scavenging of the residual gases [3]. It should also be noted that in two-stroke engines, ports can be used instead of valves, which are revealed by the movement of the piston. For it to happen, the pressure at the intake port must necessarily be greater than the pressure at the exhaust port.

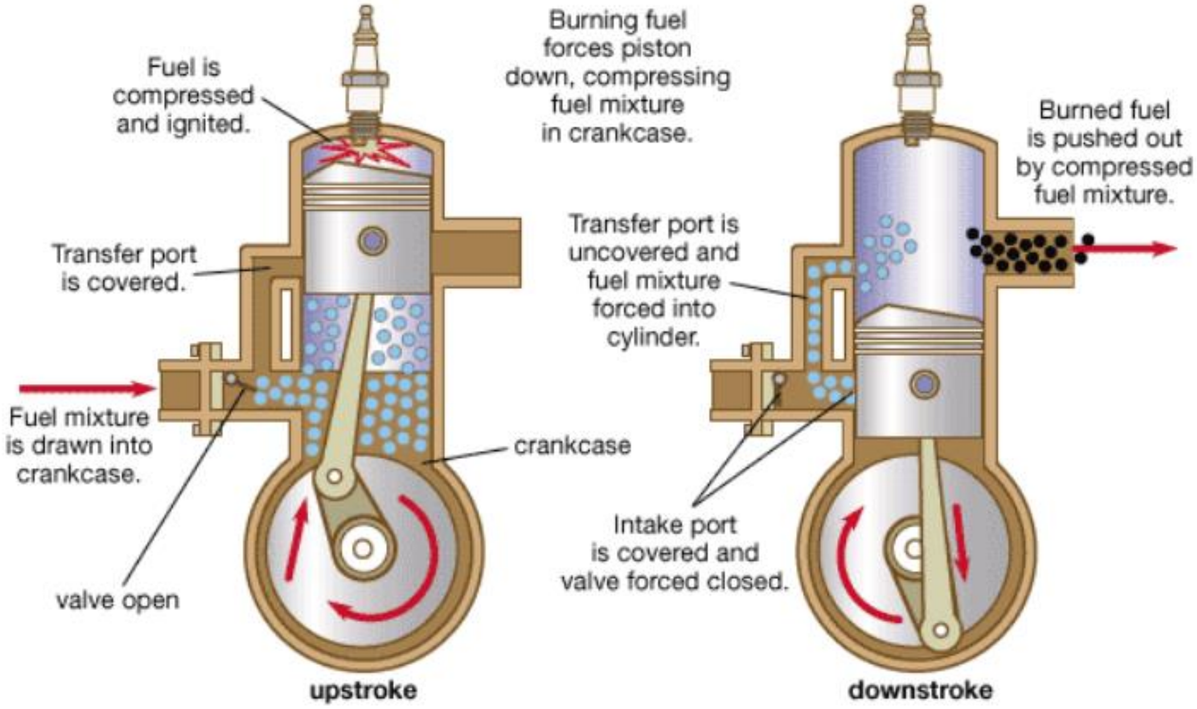


Figure 2.iii Two Stroke Engine Cycle diagram

2.2.2.2. Four Stroke Engine Cycle

In a four-stroke cycle engine, the cycle of operation is completed in four strokes of the piston or two revolutions of the crankshaft. The individual strokes are:

1. **Intake Stroke**: starts with the piston at TC and ends with the piston at BC, which draws fresh mixture into the cylinder. To increase the mass of the mixture inducted into the cylinder, the inlet valve opens shortly before the stroke starts and closes after it ends

2. **Compression Stroke:** where the piston moves from BC to TC and compresses the mixture inside the cylinder to a small fraction of its initial volume. Towards the end of the compression stroke, a combustion of the mixture is initiated and the cylinder pressure rises rapidly.
3. **Power or Expansion Stroke:** As the pressure and temperature of the gases rise, they push the piston from TC to BC position forcing the crank to rotate. As the piston approaches BC, the exhaust valve opens to initiate the exhaust process and drop the cylinder pressure close to the exhaust pressure.
4. **Exhaust Stroke:** As the piston moves from BC to TC again the remaining burned gases exit the cylinder due to the motion of the piston and the pressure inside the cylinder being higher than the exhaust pressure. As the piston approaches TC, the inlet valve opens and just after TC, the exhaust valve closes in order to start the cycle again.

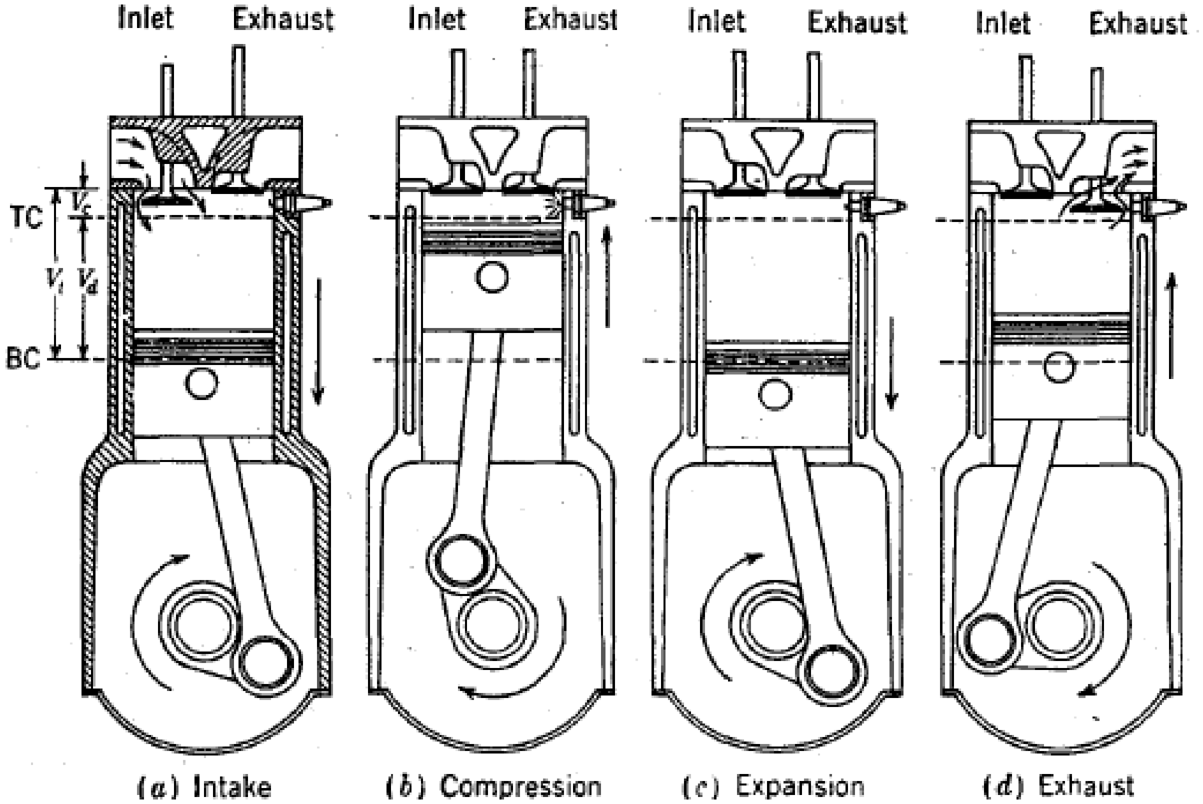


Figure 2.iv Four Stroke Engine Cycle diagram

2.2.2.3. Four Stroke and Two Stroke Cycle Engines Comparison

As explained previously, in four-stroke engines, one power stroke is obtained in every two revolutions of the crankshaft, as opposed to two-stroke engines where a power stroke is obtained in each revolution. This makes the turning movement of the shaft non-uniform and hence a heavier flywheel is needed in order to have a more uniform rotation, in the four-stroke engines. Additionally, for the same power output, the two-stroke engines are smaller in size, and due to the heavier weight and more complicated mechanism, the initial costs of four-stroke engines are usually higher. Generally, though, four-stroke engines have higher volumetric and thermal efficiency due to the positive scavenging and greater time of induction. Furthermore, as four-stroke engines are usually water cooled, the wear and tear is lower than the two-strokes. In conclusion, Four Stroke engines are used where high efficiency is important, and Two Stroke engines are used where low cost, low weight and compactness are required. For those reasons, ships are mostly fitted with two-stroke diesel engines, to minimise weight and size [7].

2.3. Marine Diesel Engines

In the construction of a ship, the selection of its main propulsion machinery is one of the critical decisions. The four-stroke and two-stroke engines are both widely used in the market; however, for large marine vessels, especially those heading out into the ocean, the two-stroke engine is more commonly installed. The four-stroke engine, while having a compact plant size and a higher revolution rate, is outshined by the two-stroke engine in several factors.

1. Fuel Usage:

Even though the two-stroke engine consumes fuel per one revolution, as opposed to the per two revolutions of the four-stroke engine, it also has the advantage of being able to burn low-grade fuel oil. This ability to use less expensive fuel makes two-stroke engines particularly advantageous and profitable for merchant ships.

2. Engine Efficiency

Comparing the two-stroke and four-stroke engines under a standard operating setting, the design of the two-stroke engine is more efficient as it reduces thermal and mechanical losses. In addition, energy is conserved more since the two-stroke engine has less heat transfer from the engine to the cooling system than that of the four-stroke.

3. Power-to-Weight Ratio

Since two-stroke engines are lighter and result in a higher power-to-weight ratio, ships that use this engine instead of the four-stroke can load more cargo with the same amount of power. This is crucial for marine applications where space and weight considerations are important. It should be noted, however, that the four-stroke engine has a greater manoeuvrability than that of a two-stroke.

There is also a great discrepancy between the installation cost of a two-stroke engine plant and the maintenance cost of a four-stroke engine. However, with all factors considered, the categorical recommendation for merchant and cargo ships is the two-stroke engine [2].

2.4. Auxiliary Engines

Marine auxiliary engines are secondary engines used on ships to generate power for various onboard systems and equipment. Unlike the main propulsion engines, which drive the ship forward, auxiliary engines provide the electrical power necessary for the operation of essential services such as lighting, heating, cooling, navigation systems, and communication equipment. They hold a vital place in a ship’s engine room, as they are responsible for its operational efficiency and safety8]. Marine auxiliary engines are manufactured keeping in mind the rigorous environment they will be installed and operated in, along with maintaining the continuity of operation to provide uninterrupted power supply to various ship systems. Some main key functions of marine auxiliary engines are:

1. **Electrical Power Generation**: They can be coupled with generators to produce electricity for the vessel. This power can then be used for operating various shipboard systems, including lighting, air conditioning, and electronic equipment.

2. **Mechanical Power Supply**: They can be used to provide mechanical power for other auxiliary machinery such as pumps (for ballast, bilge, and firefighting), compressors, and winches.
3. **Emergency Power**: In the event of a main engine failure, auxiliary engines can supply emergency power to critical systems, ensuring the safety and functionality of the ship.
4. **Operational Flexibility**: By distributing the load between multiple auxiliary engines, ships can operate more efficiently, optimising fuel consumption and reducing wear on individual engines.

2.4.1. Operating Principles of Auxiliary Engines

A ship functions much like a self-contained city, providing almost all the amenities and services available on land. Just like any city, the ship also requires the basic amenities to sustain and support life on board, the chief among them being power or electricity [12]. Power, lighting, and communications-navigation are the three core subsystems of a well-functioning ship. Because of the severe consequences an accident could have, the ship's electrical system not only must fulfil the requirements of the Classification Society that is registered to, but also the National Regulations and the SOLAS Regulations.

Power generation on ships usually comes from alternators (AC) or generators (AC or DC), and so what follows is a description of the types of auxiliary engines used in power generation in vessels and their operating principles.

Electric generators are used to convert mechanical energy into electric energy, and the ones described in this chapter operate on the principle of electromagnetic induction. All electric generators have two basic parts: a stator and a rotor. The significant difference between the rotor and the stator, as their names indicate, is that the rotor is the rotating part of the generator whereas the stator is the stationary part of the generator [15].

According to Faraday's laws of electromagnetic induction, whenever a conductor is placed in a varying magnetic field also called magnetic flux (OR a conductor is moved in a magnetic field), an emf (electromotive force) gets induced in the conductor [11].

That force will then be applied to its free electrons and thus creating electric current in the conductor. It must be noted that the conductor's movement should not be parallel to the outside electromagnetic field. Also, for the current to persist, the conductor must experience a change in the magnetic field.

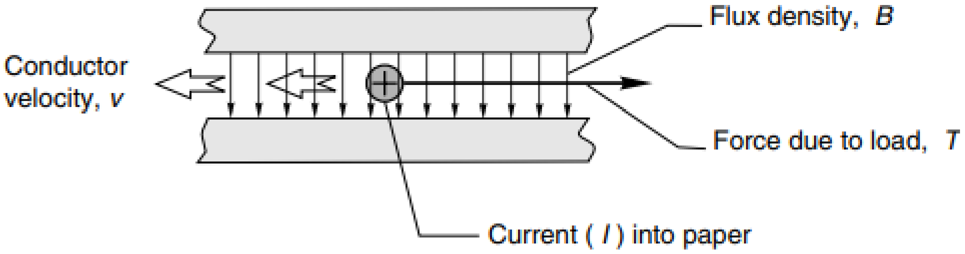


Figure 2.v Diagrammatic sketch of primitive linear DC motor / generator

Above figure 2.v shows the example that was previously described. As you can imagine it would be a difficult task to maintain electrical connections to a moving conductor, and so a different set up is used. One approach would be to use the rod as the moving magnetic field, and keep the coil stationary, like the figure 2.vi below shows.

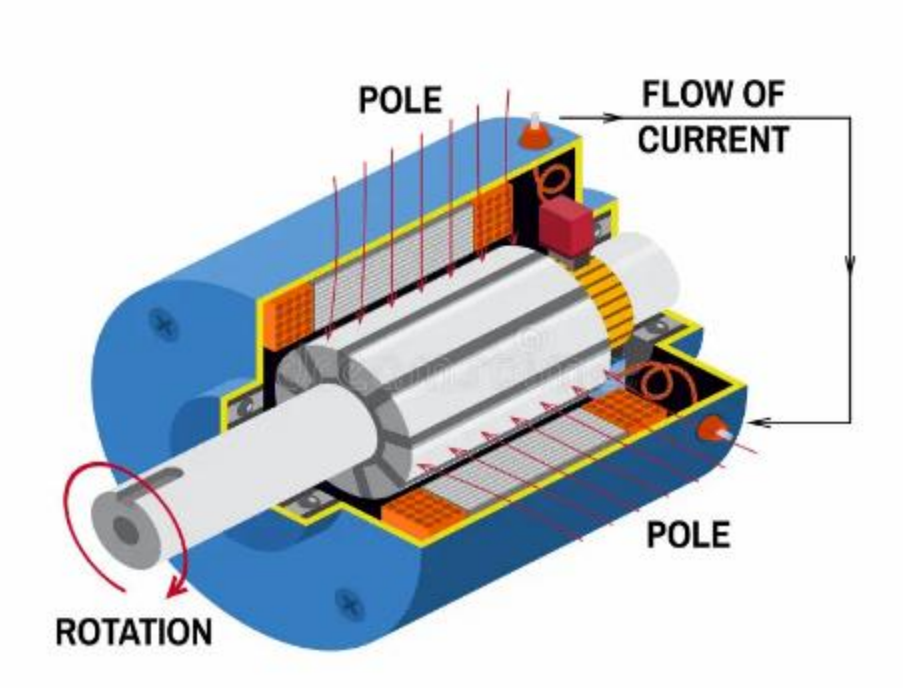


Figure 2.vi DC Generator cross section

2.4.2. DC / AC Auxiliary Engines

As it was previously mentioned, AC (Alternating Current) and DC (Direct Current) generators are the two primary types of generators. Both employ the same basic elements, but with minor differences that allow them to work with two distinct types of electrical power supplies. On board vessels, AC power generation is preferred over DC as it gives more power for the same size. Additionally, AC 3 phase is preferred over single phase as it draws more power and in the event of failure of one phase, other 2 can still work [13].

DC Generators:

DC generators can be classified in two main categories, separately excited and self-excited. In a separately excited type generator, field coils are energised from an independent external DC source and in a self-excited type dc generator, field coils are energised from the current produced by the generator itself. Initial emf generation is due to residual magnetism in field poles. An additional category is the generator using permanent magnets, but as the generated current is proportional to the magnitude of the magnetic flux, the permanent magnets cannot compete with electromagnets on large scale applications.

AC Generators:

AC machines typically fall into two categories: synchronous and induction. In synchronous machines, the rotor-winding currents are supplied directly from the stationary frame using a rotating contact. On the other hand, induction machines induce rotor currents through the time-variation of the stator currents combined with the relative motion of the rotor to the stator [10].

3. Types and Characteristics of Marine Fuels

As Monique B. Vermeire perfectly stated in her article *Everything you need to know about Marine Fuels*, "through thermal plants, marine engines and gas turbines, the energy obtained from fuel oil combustion is made available to fulfil our needs, be it for transport purposes or for electrical power applications" [18]. Since their introduction, marine diesel engines have experienced a significant rise in their applications in vessels across worldwide. As described in a previous chapter, a major factor contributing to their widespread adoption is their ability to efficiently burn low-grade fuels, making them extremely cost effective. In this chapter the different types of marine fuels, and their characteristics, will be discussed. Marine fuels can first be categorised by their type in *Conventional* and *Alternative* fuels. Conventional marine fuels refer to the traditional fuels derived from the refining process of crude oil that have been historically used to power marine vessels. On the other hand, alternative marine fuels include non-traditional fuels and energy sources that are being developed and utilised to minimise the impact of shipping on the environment. These fuels aim to provide cleaner, more sustainable options for marine propulsion, addressing issues such as greenhouse gas (GHG) emissions, sulfur oxides (SO_X), nitrogen oxides (NO_X), and particulate matter (PM). Each type of fuel has its advantages and challenges, and the choice of fuel often depends on the specific requirements of the vessel and the operating environment.

3.1. Conventional Marine Fuel

Before we begin analysing and describing the various types of conventional marine fuels oils used in the shipping industry today, it's crucial to first understand their origins and the refining processes involved in their production. All types of marine fuel oils originate from crude oil. Through varying degrees of refining and blending processes, crude oil is transformed into a diverse array of fuel oil types used in maritime applications [19].

Crude oil is a naturally occurring, unrefined mixture of many different hydrocarbons and small amounts of sulfur, nitrogen and oxygen. It is formed under great pressure and heat by the conversion of organic matter and occurs, for example, in sandstone and fractured limestone covered by impermeable layers. It is also found in oil shales and sands and in some cases may rise directly to the surface [20].

Marine fuel oils fall into two primary categories: residual oils and distillates. Distillates are refined petroleum products derived from crude oil. They are called distillates because distillation is a key step in upgrading these products; however, depending upon the refinery, there may be additional steps involved (such as vacuum distillation, catalytic cracking, and breaking). Distillate fuels include gasoline, naphtha, kerosene, and diesel (in this context, diesel refers to a specific distillation fraction of petroleum, not the engine type). On the other hand, residual oils consist of the heavier components left over after the distillation and upgrading processes. These residual marine fuels typically do not undergo further refining but can be blended with distillates to attain certain desired chemical or physical characteristics. This blending helps achieve specific performance criteria necessary for various maritime applications.

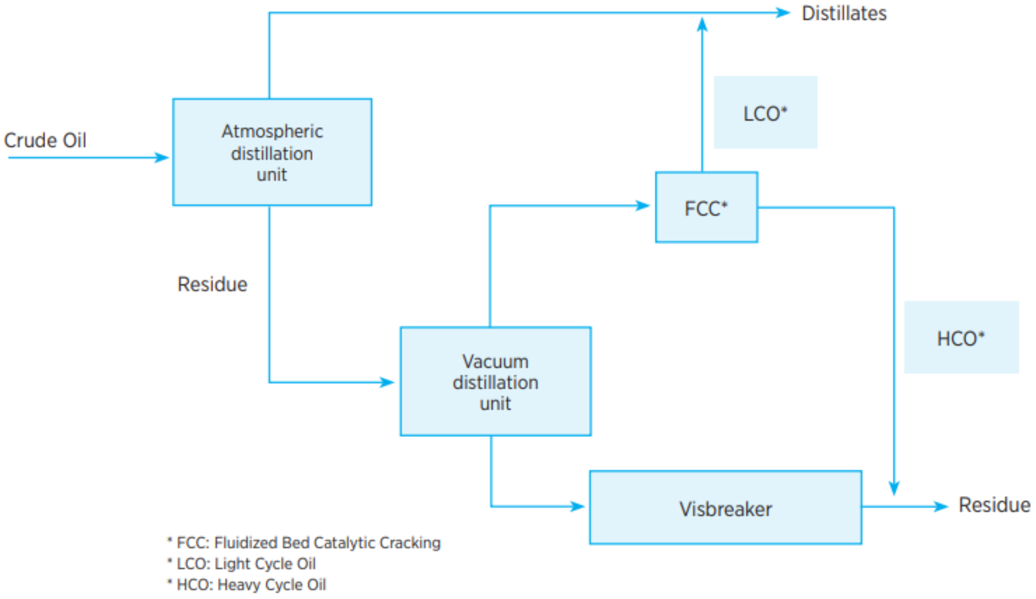


Figure 3.i Complex refinery with (fluid) catalytic cracking and visbreaking

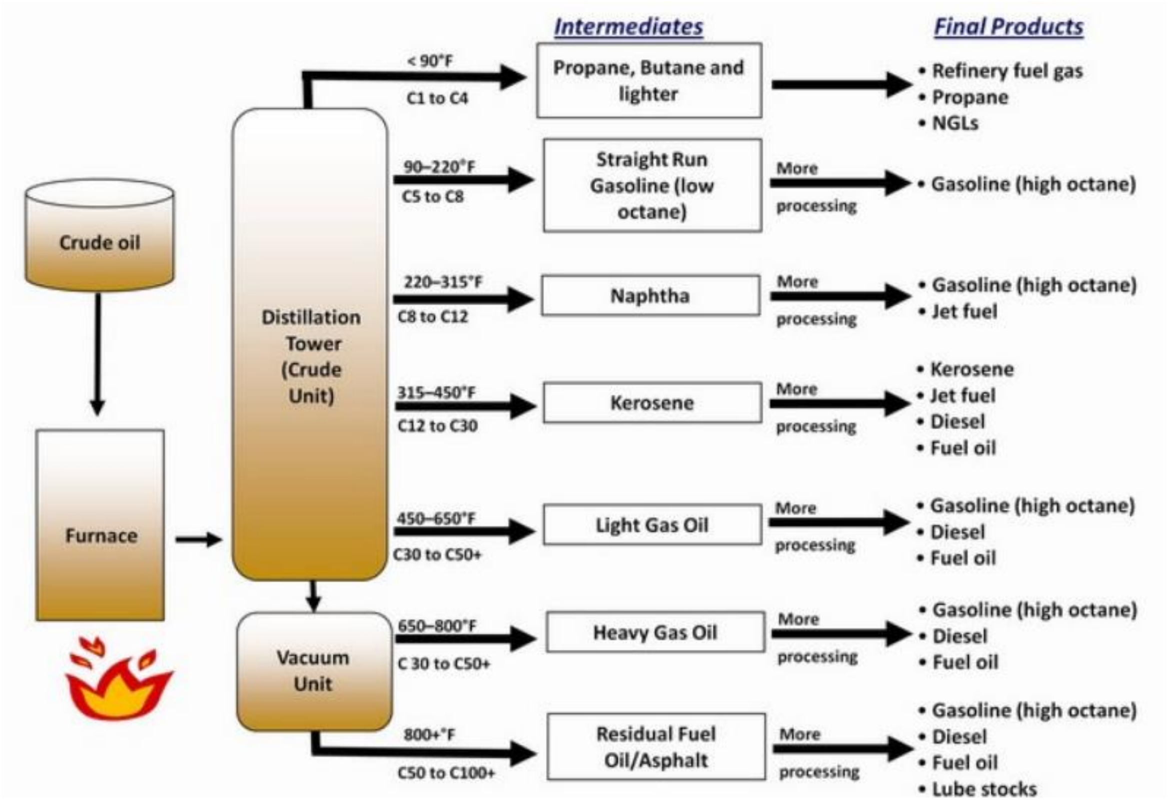


Figure 3.ii Refinement of crude oil with its products

3.1.1. Residual Oils and HFO

3.1.1.1. Heavy Fuel Oil (HFO)

The MARPOL Annex I Regulation 43A, defines HFO as a general category of marine fuels that have a density above 900 kg/m^3 at 15°C, or a viscosity of more than 180 mm^2 /s at 50°C [21]. Heavy fuel oils have large percentages of heavy molecules such as long-chain hydrocarbons and aromatics with long-branched side chains. HFOs are the cheapest fuel oils that refineries can produce, and its main consumers are the maritime industry and some developing countries. Due to its high viscosity at low temperatures, storage tanks for HFOs are usually heated to keep the viscosity low enough so that the fuel can be pumped. According to ISO 8217 [22], HFOs maximum sulfur content must not exceed 3.5%, and thus the following main categories based on sulfur emerge:

- High sulfur fuel oil (HSFO): 3.5%
- Low sulfur fuel oil (LSFO): 1.0%

- Ultra-low sulfur fuel oil (ULSFO): 0.1%

3.1.2. Distillate Fuels

3.1.2.1. Marine Diesel Oil (MDO)

Unlike the diesel fuels used for land vehicles, marine diesel oil (MDO) is not solely a distillate product. Marine diesel oil is sometimes also used synonymously with the term “intermediate fuel oil” (IFO), and it mainly refers to fuel oil blends with a very small proportion of HFO or other residual oils. Marine diesel oil is available with varying sulfur content levels. For instance, IFO 180 and IFO 380 can contain up to 3.5% sulfur as per ISO 8217 standards. Additionally, a low-sulfur variant of marine diesel oil is available, with sulfur content limited to less than 1%.

3.1.2.2. Marine Gas Oil (MGO)

On 1 January 2020, a new limit on the sulfur content in the fuel oil used on board ships came into force. The rule, known as “IMO 2020”, states that vessels, operating outside designated emission control areas, must now use fuel oils with sulfur 0.50% m/m (mass by mass) or less- a significant reduction from the previous limit of 3.5% [23]. This legislation made shipowners make the switch to marine gas oil (MGO) as it has a lower sulfur rate and meets the criteria of the regulations. Marine Gas Oil (MGO) refers to marine fuels that consist solely of distillates, the components of crude oil that evaporate in fractional distillation and are then condensed from the gas phase into liquid fractions. The main difference between MDO and MGO is that, MGO is made only from distilled fractions while MDO contains some part of the residual heavy fuel oil.

Marine Fuel Oil Name	**Composition**	**Type**
Bunker C/Fuel oil No. 6	Residual oil	HFO
Intermediate Fuel Oil (IFO) 380	Residual oil (~ 98%) blended with distillate	HFO
Intermediate Fuel Oil (IFO) 180	Residual oil (~ 88%) blended with distillate	HFO
Low sulfur marine fuel oils	Residual oil blended with distillate (higher ratio of distillate to residual)	HFO derivative
Marine diesel oil (MDO) / Fuel oil No. 2	Distillate fuel that may have traces of residual oil	Distillate
Marine gas oil (MGO)	100% distillate	Distillate

Table 3.i Composition and Types of Marine Fuel Oils

3.2. Alternative Marine Fuels

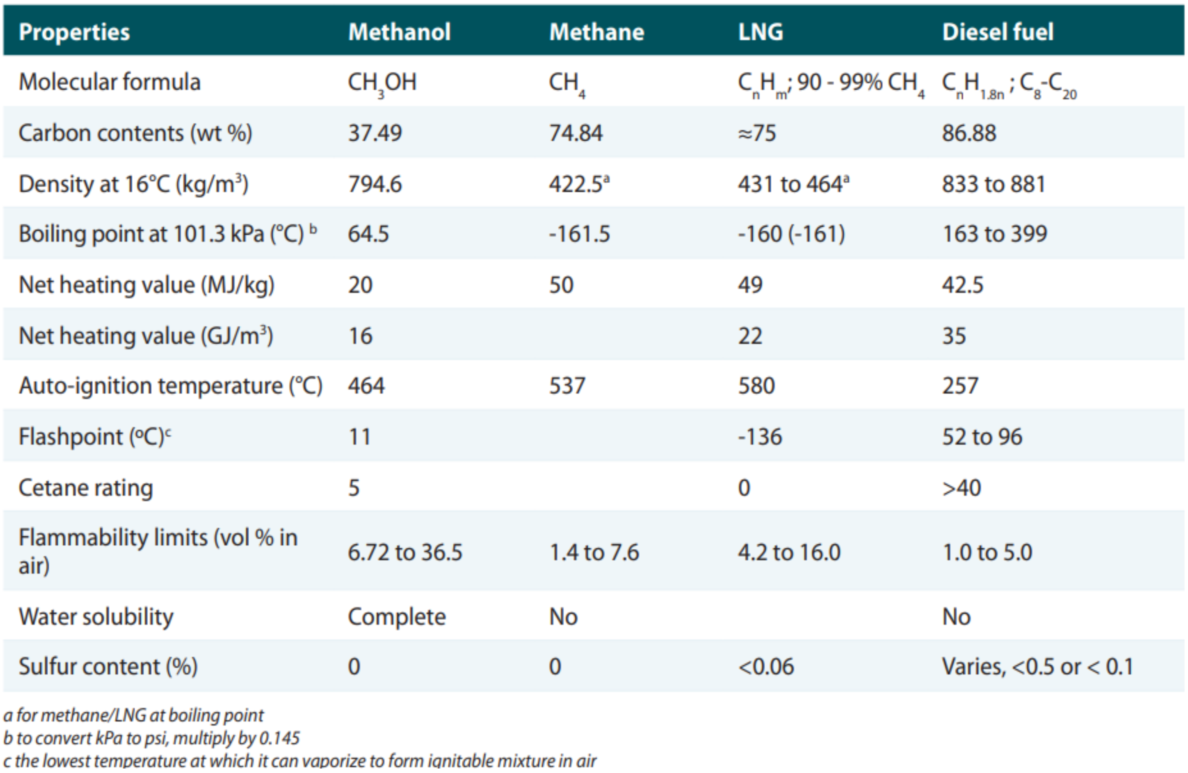
Alternative marine fuels come in different forms and, unlike conventional fuel oils, they don’t all come from a single source (crude oil). Even though conventional fuels have dominated the market due to their established infrastructure and lower costs, in recent years the shipping industry has been increasingly exploring alternative marine fuels to meet environmental regulations and reduce the industry's environmental impact.

3.2.1. LNG

Liquefied natural gas (LNG), as its name implies, is natural gas that has been converted to a liquid form for the ease and safety of natural gas transport. Natural gas is cooled to approximately -161 °C, creating a clear, colourless, and non-toxic liquid, taking approximately 1/600th of the space. It is a low-emission, clean-burning fossil fuel that emits significantly less SO_X, NO_X, and PM compared to conventional marine fuels. Use of LNG is claimed to reduce the direct combustion emissions of CO_2 with about 25% due to higher hydrogen-to-carbon ratio than diesel oils, but the effect on GHG emissions is counteracted by a possible methane (CH_4) slip [23-25]

3.2.2. Methanol

Methanol (CH_3OH) is a water-soluble, clean-burning and biodegradable fuel. It is mainly produced from natural gas, by steam-reforming natural gas to create a synthesis gas. Feeding this synthesis gas into a reactor with a catalyst produces methanol and water vapour. Various feedstocks can produce methanol, but natural gas is currently the most economical [26]. Marine methanol fuel produces no sulfur emissions and very low levels of nitrogen oxide emissions. This makes methanol compliant with current emissions reduction measures such as emission control areas (ECAs) and California’s Ocean-going Vessels Fuel Regulation [27]. A drawback of alcohol fuels like methanol is their lower energy content compared to traditional fuels. Methanol requires about twice the storage space of conventional diesel fuels for equivalent energy density (see table 3.ii below).



Properties	Methanol	Methane	LNG	Diesel fuel
Molecular formula	CH_3OH	CH_4	C_nH_m; 90 - 99% CH_4	$C_nH_{1.8n}$; C_8-C_{20}
Carbon contents (wt %)	37.49	74.84	≈75	86.88
Density at 16°C (kg/m^3)	794.6	422.5[a]	431 to 464[a]	833 to 881
Boiling point at 101.3 kPa (°C) [b]	64.5	-161.5	-160 (-161)	163 to 399
Net heating value (MJ/kg)	20	50	49	42.5
Net heating value (GJ/m^3)	16		22	35
Auto-ignition temperature (°C)	464	537	580	257
Flashpoint (ºC)[c]	11		-136	52 to 96
Cetane rating	5		0	>40
Flammability limits (vol % in air)	6.72 to 36.5	1.4 to 7.6	4.2 to 16.0	1.0 to 5.0
Water solubility	Complete	No		No
Sulfur content (%)	0	0	<0.06	Varies, <0.5 or < 0.1

a for methane/LNG at boiling point
b to convert kPa to psi, multiply by 0.145
c the lowest temperature at which it can vaporize to form ignitable mixture in air

Table 3.ii Properties of different marine fuels

3.2.3. Hydrogen

Hydrogen, with the molecular formula H_2, is still in its early stages as a maritime fuel. It is an invisible, clean fuel that, when consumed in a fuel cell, produces only water. Even though hydrogen is invisible, it is colour coded to differentiate between production means used. *Green Hydrogen* is made by using clean electricity from renewable energy sources, *Blue Hydrogen* is produced mainly from natural gas, *Grey Hydrogen* is created from natural gas or methane, and *Black/Brown Hydrogen* is produced from carbon such as coal or lignite. The most common methods today are natural gas reforming (a thermal process), and electrolysis [28-29].

3.2.4. Biodiesel

Biodiesel can theoretically be made from any animal or vegetable product which, after appropriate treatment, is capable of yielding fat or oil. However, certain criteria must be met for a product to be considered suitable for biodiesel production. These criteria include the availability of raw materials, their oil yield, cost, and quality [19]. Approximately 100 pounds of oil or fat are reacted with 10 pounds of a short-chain alcohol (usually methanol) in the presence of a catalyst (usually sodium hydroxide [NaOH] or potassium hydroxide [KOH]) to form 100 pounds of biodiesel and 10 pounds of glycerin (or glycerol). Biodiesel's physical properties are similar to those of petroleum diesel, but it is a cleaner-burning alternative. Using biodiesel in place of petroleum diesel significantly reduces emissions of toxic air pollutants [30-31].

Figure 3.iii Biofuel production technologies [32]

3.2.5. LPG

Liquefied Petroleum Gas or LPG, known to the wide public and commonly used as a domestic gas for cooking and also heating, is an alternative marine fuel that consists mainly of propane and butane. LPG has environmental performance close to that of LNG, both of them being fossil fuels, as it can contain close to zero sulfur and CO_2 and PM emissions are lowered significantly at the same time. One of the key advantages over LNG is that LPG is easier to store and can be stored almost indefinitely without any degradation, and because it is easily accessible in most ports of the world, it solves most of the logistics of LNG. Another benefit of LPG is that LPG carrier vessels can use their cargo as a bunker fuel. On the other hand, LPG is not a renewable fuel source as it is derived either as a by-product from crude oil refining or extracted from natural gas, but due to its emissions performance, its versatility in use and energy content per tonne, LPG is a great alternative fuel for ships trying to meet emission regulations [33-35].

3.2.6. Maritime electricity

The special case of electricity as an alternative fuel, known as “Onshore Power Supply – OPS” is discussed in detail in Chapter 5.

4. Maritime Emissions and Environmental Health

The Environmental and consequently Human health concerns are the leading drivers for the shipping industry's transition to greener and more sustainable power solutions. Understanding the environmental implications of maritime emissions is crucial for developing sustainable shipping practices and policies. This chapter aims to showcase and explain the types and sources of emissions from maritime activities, followed by an analysis of their environmental and health impacts. Furthermore, current international regulations and technological advancements designed to reduce emissions and promote cleaner maritime operations, will be examined.

It is essential to recognize that both natural and human-induced factors contribute to air pollution. Human air pollution can come from a variety of sources, like the life cycle of a product. A significant and crucial part of this product life cycle is the part of “shipping” the goods to their destination. In this context, shipping refers not only to the use of ships but to the entire process of delivering products from their origin to their final destination [41].

The implications and impact that air pollution has on human health cannot fully be comprehended, due to the complexity of the human organism and its interactions with the environment. But as the World Health Organisation has summarised in the “Ambient (outdoor) air pollution” [42] fact sheet, [air pollution] is the cause of millions of premature deaths and “99% of the world’s population was living in places where the WHO air quality guidelines levels were not met” in 2019.

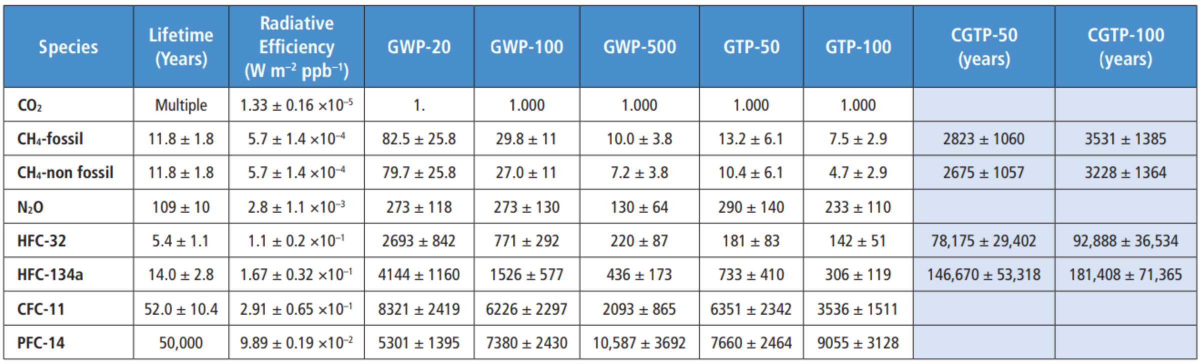
In the shipping industry, air pollution can be considered to have started with the first use of fossil fuels like coal. Of course there have been numerous examples of other types, except air, of pollution caused by the maritime industry like oil spills or noise pollution. But in this chapter, the main focus will be the implications of air pollution from the industry.

4.1. Greenhouse Effect

"Carbon footprint" is a term that refers to the total amount of Greenhouse Gases (GHGs) emitted directly or indirectly by human activities. In the context of the maritime industry, the carbon footprint encompasses emissions generated by the operation of ships, including the burning of fossil fuels for propulsion and auxiliary power, as well as emissions from the production and transportation of the fuels themselves [43].

Greenhouse gases (GHGs) are gases in the Earth's atmosphere, both natural and anthropogenic, that trap heat and contribute to the greenhouse effect. This effect is essential for maintaining the Earth's temperature at a level conducive to life. Some of the contributors to this effect are gases like: Water vapour (H_2O), Carbon Dioxide (CO_2), Nitrous Oxide (N_2O), Methane (CH_4), Ozone (O_3) and a variety of manmade gases such as Fluorinated Gases. These gases have varying degrees of heat-trapping capabilities, often measured in terms of their Global Warming Potential (GWP) or Global Temperature-change Potential (GTP), with CO_2 being used as the baseline with a GWP / GTP of 1. “Carbon Dioxide Equivalent” or “CO2eq”, is a metric used to compare the emissions of various greenhouse gases (GHGs) based on their global warming potential (GWP). It provides a standard measure that expresses the impact of different GHGs in terms of the amount of CO2 that would have the same warming effect over a specified period, usually 100 years. This allows for a simplified and unified way to account for the total greenhouse gas emissions from different sources and activities.

A list of these values is presented in the table 4.i below from the Sixth Assessment Report of the Intergovernmental Panel on Climate Change:



Species	Lifetime (Years)	Radiative Efficiency (W m^{-2} ppb^{-1})	GWP-20	GWP-100	GWP-500	GTP-50	GTP-100	CGTP-50 (years)	CGTP-100 (years)
CO_2	Multiple	$1.33 \pm 0.16 \times 10^{-5}$	1.	1.000	1.000	1.000	1.000		
CH_4-fossil	11.8 ± 1.8	$5.7 \pm 1.4 \times 10^{-4}$	82.5 ± 25.8	29.8 ± 11	10.0 ± 3.8	13.2 ± 6.1	7.5 ± 2.9	2823 ± 1060	3531 ± 1385
CH_4-non fossil	11.8 ± 1.8	$5.7 \pm 1.4 \times 10^{-4}$	79.7 ± 25.8	27.0 ± 11	7.2 ± 3.8	10.4 ± 6.1	4.7 ± 2.9	2675 ± 1057	3228 ± 1364
N_2O	109 ± 10	$2.8 \pm 1.1 \times 10^{-3}$	273 ± 118	273 ± 130	130 ± 64	290 ± 140	233 ± 110		
HFC-32	5.4 ± 1.1	$1.1 \pm 0.2 \times 10^{-1}$	2693 ± 842	771 ± 292	220 ± 87	181 ± 83	142 ± 51	78,175 ± 29,402	92,888 ± 36,534
HFC-134a	14.0 ± 2.8	$1.67 \pm 0.32 \times 10^{-1}$	4144 ± 1160	1526 ± 577	436 ± 173	733 ± 410	306 ± 119	146,670 ± 53,318	181,408 ± 71,365
CFC-11	52.0 ± 10.4	$2.91 \pm 0.65 \times 10^{-1}$	8321 ± 2419	6226 ± 2297	2093 ± 865	6351 ± 2342	3536 ± 1511		
PFC-14	50,000	$9.89 \pm 0.19 \times 10^{-2}$	5301 ± 1395	7380 ± 2430	10,587 ± 3692	7660 ± 2464	9055 ± 3128		

Table 4.i Emissions metrics for selected species: global warming potential (GWP), global temperature-change potential (GTP) [45]

However, an increase in the concentration of GHGs due to human activities has led to global warming and climate change and as a result higher and higher average global temperatures each year.

4.2. Air Pollutants

4.2.1. Carbon Dioxide [CO_2]

Carbon dioxide (CO_2) is a colourless, odourless gas that is a natural component of Earth's atmosphere. The shipping industry is responsible for a significant proportion of the global emissions with the industry contributing about 2.2% to global CO_2 emissions [51]. As Ellycia Harrould-Kolieb noted in her report, "If global shipping were a country, it would be the 6th largest producer of greenhouse gas emissions." [52]. In the maritime shipping industry, CO_2 emissions primarily originate from the combustion of fossil fuels from sources like: the ship's main engines, its auxiliary engines and boilers. While CO_2 is not toxic in low concentrations, higher levels can pose health risks, causing respiratory issues, headaches, fatigue and disturbance of acid-base balance [53].

The table 4.ii below shows the Conversion Factor (C_F) between fuel consumption and CO_2 emissions as presented in the ANNEX 9 - RESOLUTION MEPC.364(79) of the International Maritime Organization (IMO) [44].

Type of fuel	Reference	Lower calorific value (kJ/kg)	Carbon content	C_F (t-CO2/t-Fuel)
Diesel/Gas Oil	ISO 8217 Grades DMX through DMB	42,700	0.8744	3.206
Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	41,200	0.8594	3.151
Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	40,200	0.8493	3.114
Liquefied Petroleum Gas (LPG)	Propane	46,300	0.8182	3.000
	Butane	45,700	0.8264	3.030
Ethane		46,400	0.7989	2.927
Liquefied Natural Gas		48,000	0.7500	2.750

(LNG)				
Methanol		19,900	0.3750	1.375
Ethanol		26,800	0.5217	1.913

Table 4.ii CF; Conversion factor between fuel consumption and CO2 emission [44]

4.2.2. Carbon Monoxide [CO]

Carbon monoxide (CO) is one of the most toxic air pollutants, and it usually forms as a result of incomplete combustion of fossil or bio fuels, which can be caused by a lack of oxygen or low temperatures in certain areas of the combustion chamber. On its own, it has a chemical lifetime of 30-90 days; however, it reacts with oxygen to form O_3 and CO_2 which contribute further to air pollution [54]. In diesel engines, CO formation is influenced by the air/fuel mixture within the combustion chamber, and since diesel fuel typically maintains a consistently high fuel-air ratio and the efficient combustion process, formation of this toxic gas is minimal. However, incomplete combustion can still occur if the fuel droplets in a diesel engine are too large, the level of turbulence is insufficient, or if there is inadequate swirl in the combustion chamber [55]. The major health effects of CO include the binding of CO with haemoglobin in the blood, which affects oxygen supply to the body and can prove fatal [56].

4.2.3. Methane [CH_4]

Methane is the most prevalent hydrocarbon in the atmosphere, with a lifetime of about 10 years, and it can leak at every stage of extraction, processing, storage, transmission, maintenance, distribution, and use of natural gas [54-56]. In the shipping sector, methane emissions primarily come from the use of LNG as a fuel. Even though LNG is promoted for its significantly lower emissions of CO_2, SO_X, NO_X, and PM, it replaces them with methane (CH_4) emissions. A potent greenhouse gas (GHG), and within the first 20 years of its release, it’s 82.5 times more powerful than carbon dioxide (CO_2) at trapping heat [57].

4.2.4. Nitrous Oxide [N_2O]

Nitrous oxide (N_2O), is an important colourless atmospheric gas that is emitted mostly by natural sources, primarily by bacterial action in the soil and water. Even though by comparison to CO_2, N_2O has a far lower concentration, it is a very influential GHG due to its long lifetime (estimated at about 120 years) and its relatively large energy absorption capacity per molecule [56], with 273 times more GWP than CO_2 after 100 years. Wallington and Wiesen (2014) in their report, estimated that 0.022 Gg of N_2O–N per year was emitted by marine transportation in 2010, and is expected to rise by ~ 20% by 2030 [59]. Nitrous Oxide (N_2O), commonly known as “laughing gas” and commonly used as an anaesthetic, can pose a significant health hazard especially with prolonged or high-level exposure. It can damage the nerves, cause hypoxia, increase cardiovascular risks, induce nausea and vomiting, and is highly dangerous due to its addictive potential [60].

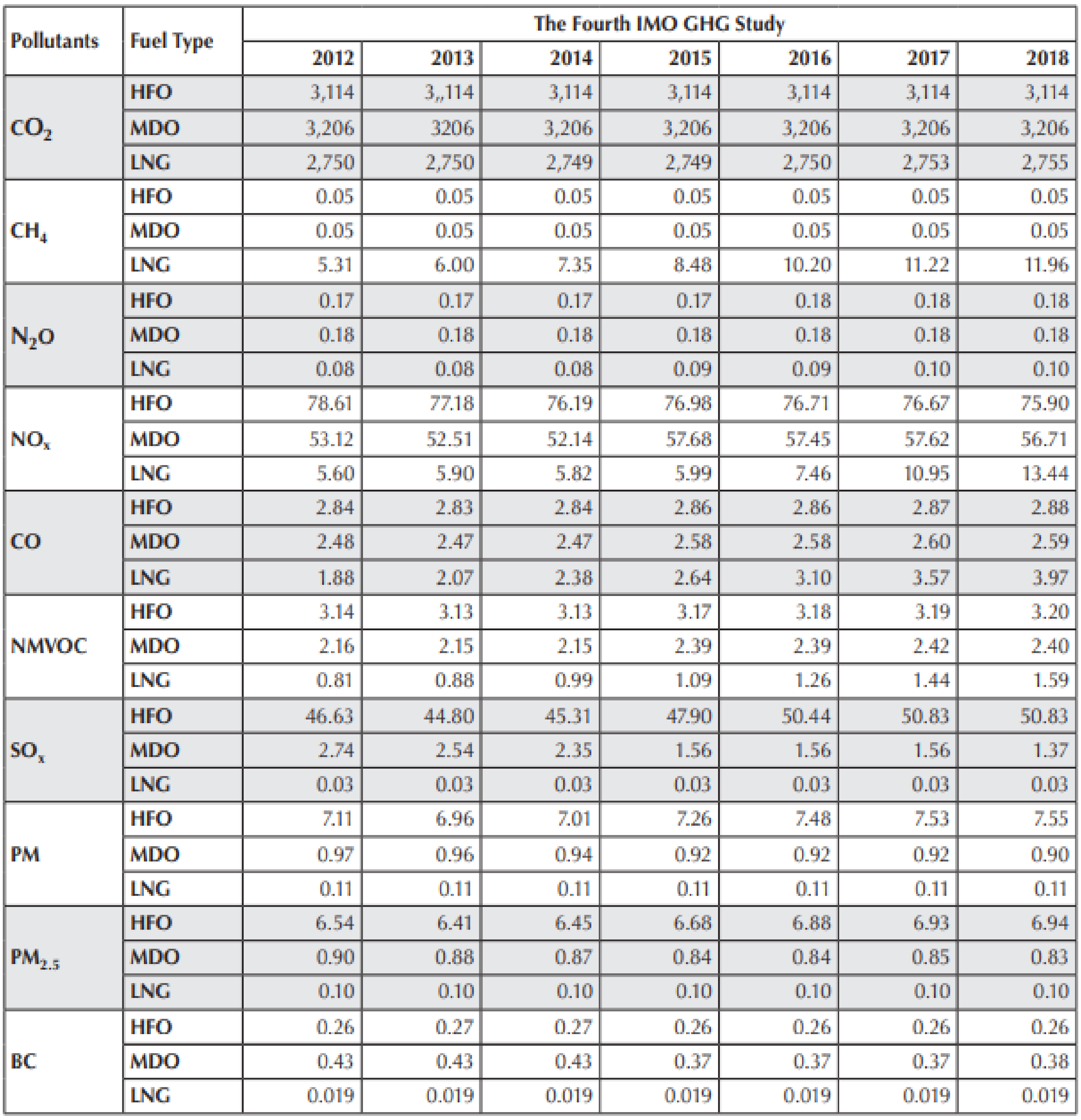
4.2.5. Particulate Matter [PM]

Particulate Matter, usually abbreviated as PM, is a mixture of liquid and solid particles suspended in the atmosphere for days or weeks depending on their size. Primary anthropogenic sources of PM are combustion of liquid or solid fuels, like petrol and coal, and other human activities like mining or the erosion of pavement due to traffic. Their small size poses a significant health risk, as they can easily penetrate the thoracic region of the respiratory system [48]. The health effects of these inhalable particles are well documented and show a great mortality risk factor for particles smaller than 2.5 μm ($PM_{2.5}$) [50] and no evidence of a safe level of exposure or a threshold below which no adverse health effects occur. And thus, improvements should be made to minimise the exposure to the PMs, like limiting emissions and having stricter air quality standards.

4.2.6. Non-Methane Volatile Organic Compounds [NMVOC]

Non-methane volatile organic compounds (NMVOCs) are a large group of organic compounds that exclude methane and can easily evaporate into the atmosphere. They are emitted from a wide variety of natural and anthropogenic sources such as trees and soil, fuel combustion, industrial processes, agriculture activities, landfill and waste. NMVOCs include organic compounds like benzene, ethanol, formaldehyde and other compounds that have different chemical compositions but behave similarly in the atmosphere [54]. In the atmosphere, NMVOCs play an important role in the formation of tropospheric ozone, and some (like benzene, toluene, ethylbenzene and xylene) react with hydroxyl radical and nitrates to degrade them into organic aerosols in the atmosphere. Even though they are not considered greenhouse gases, their role in the formation of ozone and particulate matter can indirectly influence climate. Most NMVOCs are hazardous to human health, including benzene and 1,3 butadiene, which are carcinogenic [61].

Below is a table 4.iii showing the emission factors estimated by the IMO and used in the Fourth IMO GHG Study 2020 [47].



Pollutants	Fuel Type	The Fourth IMO GHG Study						
		2012	2013	2014	2015	2016	2017	2018
CO_2	HFO	3,114	3,,114	3,114	3,114	3,114	3,114	3,114
	MDO	3,206	3206	3,206	3,206	3,206	3,206	3,206
	LNG	2,750	2,750	2,749	2,749	2,750	2,753	2,755
CH_4	HFO	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	MDO	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	LNG	5.31	6.00	7.35	8.48	10.20	11.22	11.96
N_2O	HFO	0.17	0.17	0.17	0.17	0.18	0.18	0.18
	MDO	0.18	0.18	0.18	0.18	0.18	0.18	0.18
	LNG	0.08	0.08	0.08	0.09	0.09	0.10	0.10
NO_x	HFO	78.61	77.18	76.19	76.98	76.71	76.67	75.90
	MDO	53.12	52.51	52.14	57.68	57.45	57.62	56.71
	LNG	5.60	5.90	5.82	5.99	7.46	10.95	13.44
CO	HFO	2.84	2.83	2.84	2.86	2.86	2.87	2.88
	MDO	2.48	2.47	2.47	2.58	2.58	2.60	2.59
	LNG	1.88	2.07	2.38	2.64	3.10	3.57	3.97
NMVOC	HFO	3.14	3.13	3.13	3.17	3.18	3.19	3.20
	MDO	2.16	2.15	2.15	2.39	2.39	2.42	2.40
	LNG	0.81	0.88	0.99	1.09	1.26	1.44	1.59
SO_x	HFO	46.63	44.80	45.31	47.90	50.44	50.83	50.83
	MDO	2.74	2.54	2.35	1.56	1.56	1.56	1.37
	LNG	0.03	0.03	0.03	0.03	0.03	0.03	0.03
PM	HFO	7.11	6.96	7.01	7.26	7.48	7.53	7.55
	MDO	0.97	0.96	0.94	0.92	0.92	0.92	0.90
	LNG	0.11	0.11	0.11	0.11	0.11	0.11	0.11
$PM_{2.5}$	HFO	6.54	6.41	6.45	6.68	6.88	6.93	6.94
	MDO	0.90	0.88	0.87	0.84	0.84	0.85	0.83
	LNG	0.10	0.10	0.10	0.10	0.10	0.10	0.10
BC	HFO	0.26	0.27	0.27	0.26	0.26	0.26	0.26
	MDO	0.43	0.43	0.43	0.37	0.37	0.37	0.38
	LNG	0.019	0.019	0.019	0.019	0.019	0.019	0.019

Table 4.iii Emission Factors from The Fourth IMO GHG Study of 2020 (unit: kg pollutant/tonne fuel) [47]

4.3. Regulations and Guidelines

In 2015, 196 countries adopted the Paris Agreement which took effect from 4 November 2016. The Paris Agreement is a legally binding international treaty on climate change to control greenhouse gas emissions to limit global warming to 2 degrees Celsius by 2100 from pre-industrial levels, aiming to keep warming at or below 1.5 degrees C [62]. Reducing the CO_2 and all GHGs pollution drastically implies the use of negative emission technologies and dramatic near-term societal transformations. These kinds of scenarios are usually met with resistance due to the difficulty of reconciling immediate, localised costs with global, long-term benefits. Other scenarios for 2^{o} C trajectory that are not relying on negative emissions, require elimination of most fossil fuel related emissions [58].

Additionally, on 14th of July, 2021, the European Commission published its “Fit for 55” package, which includes several important proposals to revise and update EU legislation and to put in place new initiatives with the aim of ensuring a 55% reduction on EU emissions by 2030. Among these is the inclusion of shipping in the EU Emissions Trading System (ETS), which establishes an annual absolute limit on certain GHG emissions and requires the purchase of emission permits, so setting a price on emissions [64]. Furthermore, in July 2023, the FuelEU Maritime initiative came into effect, a set of rules set by the EU Commission aiming to reduce the greenhouse gas intensity of the energy used on-board ships by up to 80% by 2050. The new regulations encourage the adoption of renewable and low-carbon fuels in the shipping industry [64].

4.3.1. International Maritime Organization (IMO)

The IMO, initially known as Inter-Governmental Maritime Consultative Organization (IMCO), was established in 1948 with the main purpose of effectively ensuring the safety, security, and environmental performance of international shipping [65]. It has many regulations and standards under its umbrella which are adopted and implemented by member states, making it a central authority in the maritime industry. Key regulations under the IMO's purview include:

- **International Convention for the Safety of Life at Sea (SOLAS):** Sets safety standards for the construction, equipment, and operation of ships.

- **International Convention for the Prevention of Pollution from Ships (MARPOL):** Addresses various forms of marine pollution caused by ships.
- **International Ship and Port Facility Security Code (ISPS Code):** Enhances the security of ships and port facilities.
- **International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW):** Establishes qualification standards for seafarers.

Out of these, the MARPOL standards are the critical regulations from IMO that deal with the pollution and emissions from the shipping industry. In September 1997, the international conference for the MARPOL (Marine Pollution) convention adopted a new protocol to update the convention (MARPOL Annex VI), which included Resolution 8 on carbon dioxide emissions from ships. This resolution invited the Marine Environment Protection Committee (MEPC) to investigate what strategies would be feasible for reducing carbon dioxide emissions. Following that, in 2000, the IMO published its first study on greenhouse gas (GHG) emissions, which estimated that international shipping contributed to 1.8% of total global carbon dioxide emissions [66].

Furthermore IMO, also implemented through amendments to MARPOL Annex VI, the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Existing Ship Index (EEXI) which are regulatory measures developed to improve the energy efficiency and reduce greenhouse gas emissions from ships.

The EEDI is a mathematical formula that expresses the relationship between the cost of operating a ship (i.e. CO2 emissions) and the profit made (i.e. ability to transport goods), and assesses the energy efficiency of new ships [67]. Similarly, the Energy Efficiency Existing Ship Index (EEXI) is also an index that evaluates the energy efficiency of ships, but it applies to existing ships rather than new builds [68].

5. On-shore Power Supply

As discussed in previous chapters, emissions from the shipping industry significantly impact both climate change and local air quality. Maritime traffic is continuously increasing, due to ships being the most fuel-efficient mode of transport in terms of ton-miles. Consequently, ports are experiencing higher volumes of traffic, which correlates with increased emissions, such as NOX, CO2, SOX and PM, and noise pollution in these areas. One process that shows great potential of reducing the unwanted environmental impact of ships at berth, is Cold Ironing.

Cold Ironing, is the process of meeting a ship's energy requirements while it is docked at berth with shoreside power. This process has the potential of being completely green, as it depends on the energy mix of the port's country, allowing the vessel's auxiliary engines to shut down. It is known also with the terms "Alternative Maritime Power (AMP)", "Shoreside Electricity" and "On-shore Power Supply".

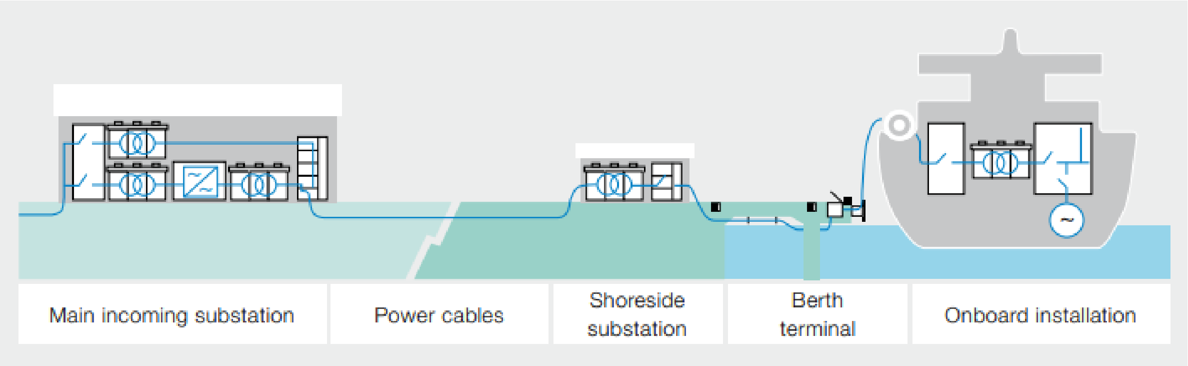


Figure 5.i Overview of SSE connection [83]

5.1. OPS drawbacks and barriers

Shore power, or Onshore Power Supply (OPS), as any other solution to the Greenhouse Gas problem, has a few drawbacks / barriers despite its potential environmental benefits. From a technical viewpoint, implementing OPS involves a relatively straightforward process of installing compatible hardware in both ports and vessels. Despite this, the adoption rate of OPS remains low. In the European Union (EU), only 31 ports provide high voltage OPS, and the adoption rate among the global vessel fleet varies between different categories, with the highest rate found among cruise ships (8.9%), followed by container ships (8.8%) and RO-PAX ferries (1.1%) [80].

Costs:

The costs and benefits of implementing Onshore Power Supply (OPS) systems are dependent on regional factors such as the grid factor, electricity prices, port size, grid conditions, and proximity to urban areas. Additionally, conditions differ between seaports and inland ports, which typically accommodate various types of ships with distinct sizes and cargo. Therefore, a region and port specific analysis is needed to comprehend how these different characteristics influence the effectiveness of OPS. Thus, a tailored approach considering the unique characteristics of each port is crucial to evaluate the practical benefits and feasibility of OPS. [69]

The high initial capital cost of installing OPS infrastructure, along with operational and maintenance costs is a significant barrier. The initial cost, of course, includes not only the installation of the shore-side equipment, including transformers, cables, and plug-in systems, but also retrofitting ships with compatible equipment. According to the International Council on Clean Transportation (ICCT) [77], the upfront costs for shore power infrastructure can range from several hundred thousand to millions of dollars per berth, depending on the size and complexity of the port and ships involved.

Compatibility of ships and shore-based systems:

The lack of standards in the production of a vessels power receiving system along with the inconsistencies in the land power production and distribution, create a barrier between shipowners and ports, making the move to OPS for ships rather tricky [79]. For example, the electric grid voltage frequency in Europe, Asia, and Africa is 50 $[Hz]$, but in North America it is 60 $[Hz]$. Also, according to Jagdesh et al [81], at the present time 75% of vessels have 60 $[Hz]$ power supply frequency, while the remaining 25% have 50 $[Hz]$ power supply frequency onboard globally. This poses a significant challenge, as the electrical frequency of power supply and equipment in many regions and countries is typically 50 $[Hz]$, which goes against the electrical frequency of most international ships that is 60 $[Hz]$.

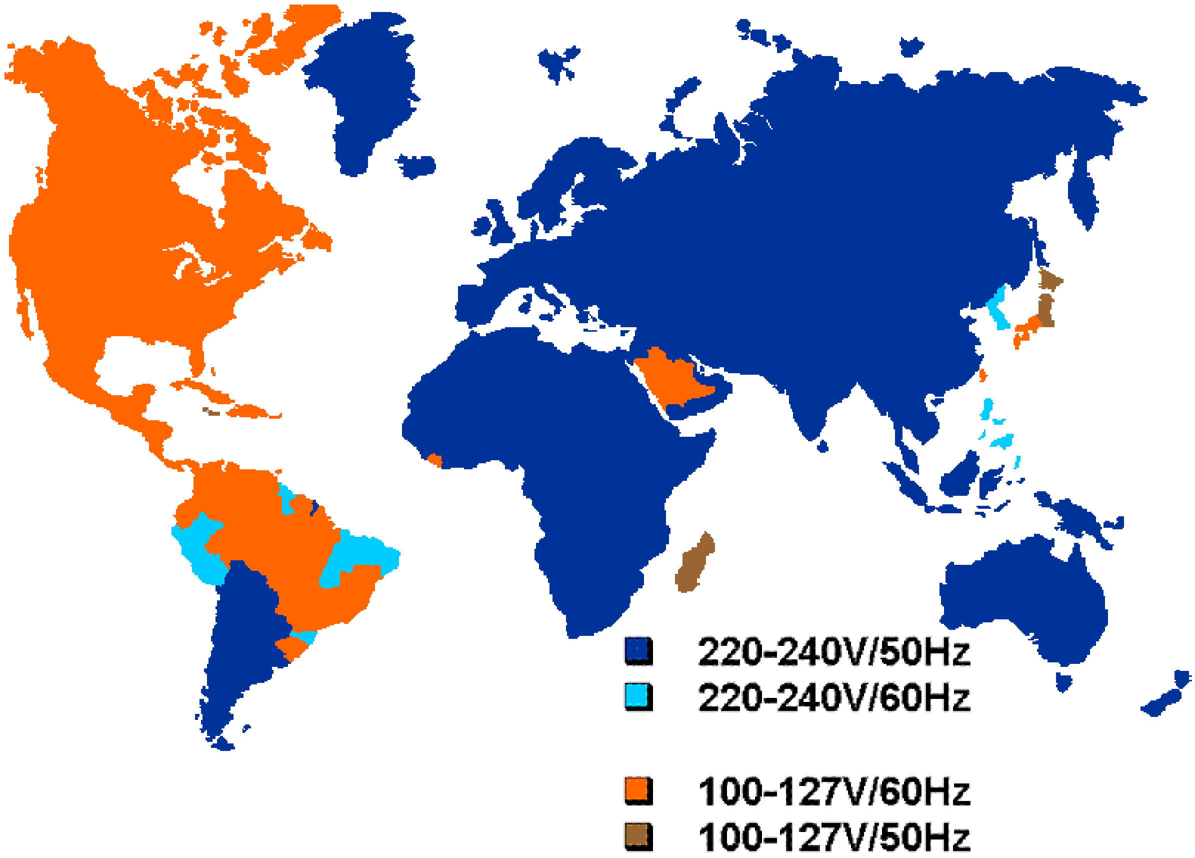


Figure 5.ii Map of the world coloured by voltage and frequency

Lack of Standards:

This aforementioned lack of standardisation in the testing and design of components further impedes the global adoption of OPS. The '*IEC/ISO/IEEE 80005-1:2019: Utility Connections in Port – Part 1: High Voltage Shore Connection (HVSC) Systems – General Requirements*' standard is commonly referred to internationally during the inspection of shore-based power supply systems. On the other hand, for shipboard power receiving systems, the ship and port side must refer to the specifications of the classification society in each county. This, of course means that due to differences in the inspection requirements of each class of each country, inconsistencies may exist that lead to unsuccessful operations between OPS systems of ports and the vessels.

5.2. Equipment breakdown of OPS

Based on already existing cases of installed OPS systems, the following equipment is commonly used and can serve as a foundational setup for ports to expand or adapt according to their specific requirements:

Transformers:

Power transformers are critical electrical devices used in the transmission and distribution of electrical energy. They are typically used to step up (increase) and step down (decrease) the source voltage levels to the specific output levels that are required. Size and capacity of a transformer are chosen based on application of course, but it is worth noting that nowadays there are Containerized Transformer Substation modules available that can be a great solution for many ports because of the modularity and scalability they offer.

Figure 5.iii Containerized Transformer Substation by Altgeld product

Frequency Converters:

Frequency converters are a crucial part of every Cold Ironing assembly as they are used for managing the difference in power supply frequencies, converting between 50 Hz and 60 Hz to match the vessel's requirements. Additionally, these devices can sometimes be used to regulate the voltage level to the desired output level. As previously mentioned, national grids may operate on different electrical frequency than that of the vessel, and thus frequency converters are must have devices for all ports that want to provide power to vessels.

Cables and Cable Management Systems:

Cables are used to transfer electricity for point A to point B, and their size correlates to their current-carrying capacity. Cables will connect the port substation with the national grid, as well as with the transformers and frequency converters which will then connect to the ship’s power receiving systems.

Cable Management Systems (CMS) include cable reels and handling equipment, like davit will, that facilitate the safe and efficient connection of power cables between the shore and the ship. CMS can be part of the ship or a part of the shore side installation.

6. Vessel and Shore Power Emissions Calculator

Ports serve as vital hubs of commerce and play a pivotal role in driving the economy. At the same time, they are places with significant concentrations of air pollution, including particulate matter (PM), nitrogen oxides (NOx), air toxics, and carbon dioxide (CO2), posing significant threats to both human health and the environment. These air pollutants in the ports come from marine vessels at berths who use combustion engines to power auxiliary systems such as lighting, air conditioning, refrigeration, and crew berths. To address these emissions, Onshore Power Supply (OPS) also known as Cold-Ironing, offers a promising solution by allowing vessels to turn off their engines, and use the local electricity grid while at berth [85].

The goal of this thesis was to design a “calculator” that allows users to calculate their vessel emissions and compare them to the emissions of the European Ports they are using. In this chapter, the process of developing this tool, an explanation of all its features and the challenges faced during the development process will be provided. Finally, recommendations for future improvements and potential extensions/merges of the tool with similar previous works, notably “Issues of Electricity in Ships and Ports” [17] and “Study for Power Increase of local electrical grid in ports of European Economic Area (EEA) and United Kingdom (UK)” [16], will be discussed in the next chapter.

It is worth noting that the idea came from an already existing “Emissions Calculator” tool from EPA (Environmental Protection Agency of United States of America) [85], which calculates vessel and port emissions for American ports. Inspiration for the methodology was drawn from that project but sources and formulas were changed and/or adapted to accommodate European Ports.

For the user’s convenience the tool was designed in Excel format as well as in an Interactive web application format, called VSPEC and IVSPEC respectively.

This chapter will explain the functionality of both but first …

6.1. A brief introduction to Programming

For the development of the Interactive Vessel and Shore Power Emissions Calculator application different programming languages were used along with the help of libraries. In order to better understand the explanation and description of the IVSPEC code that will follow, first a short introduction to programming will be given, as an appetiser.

Programming is one of the cornerstones of the modern world and the tool behind most of the technologies we use today. At its core, programming is the science of writing instructions, called programs (or code in the computer world), that a machine will follow in order to perform a task. Programmable apparatuses have existed for many centuries in various forms, starting with different versions of programmable music devices.

The first computer program is dated to 1843 when Ada Lovelace, an English mathematician and writer widely regarded as the first programmer, published an algorithm to calculate a sequence of Bernoulli numbers, intended to be carried out by Charles Babbage's mechanical general-purpose computer, the Analytical Engine [86].

Programming languages are the bridge between humans and machines. By translating human logic into machine-readable instructions, programmers can automate tasks, analyse data, and develop innovative solutions to real-world challenges. Whether optimising supply chains, predicting stock market trends, or simulating complex systems, programming enables individuals to leverage the computational power of computers to tackle problems efficiently and effectively.

With creativity and a problem-solving mindset, programming can be a helpful tool to anyone and everyone that wishes to automate simple or complex tasks.

6.2. Programming Languages used

6.2.1. Python and Python Libraries

Launched in 1991 by Guido van Rossum, Python is a versatile and dynamic high-level programming language. In addition to its simple language structure and an interactive shell with which to experiment, Python runs on an interpreter system, meaning that code can be executed as soon as it is written. This means that prototyping can be very quick [87].

Programming libraries are collections of code modules that extend the functionality of the language. They are reusable bits of code that developers can integrate into their own scripts using the import statement [88]. By leveraging them, developers can save time and effort by using existing solutions to common programming challenges, allowing them to focus on solving higher-level problems and building innovative applications. While it's admirable to seek a deep understanding of how everything works, in many cases, using libraries is faster, easier and more efficient than developing functions from scratch. This is because libraries are specifically designed with reliability and efficiency in mind, allowing developers to leverage years of tried-and-tested solutions for common tasks. That being said, understanding what you are using is the best way to make sure you are leveraging it the correct way and to the fullest amount. For those reasons python libraries were used to help this project come to life faster and with cleaner code.

Some of the Libraries that were used for this project and will be analysed later on are: Folium [89], pandas [89], http [91], socketserver [92], webserver [93].

6.2.2. HTML , JavaScript, CSS

Another Programming Language that was used in this project was JavaScript, along with HTML and CSS of course. As Douglas Crockford said in his *JavaScript: The Good Parts* book, “JavaScript is an important language because it is the language of the web browser. Its association with the browser makes it one of the most popular programming languages in the world”. JavaScript is essential for building modern web applications, providing functionality such as form validation, animations, and asynchronous communication with web servers.

HTML (Hypertext Markup Language) is the standard markup language used by developers for creating web pages and web applications. It is used to define the content and the structure of a webpage, allowing developers to organise and display anything they desire, from text to images, links, videos and everything else. HTML is essential for building the foundation of a website, providing the structure that CSS then styles and formats [94].

CSS (Cascading Style Sheets) is a style sheet language, it's a powerful tool used for transforming the presentation of a document. It enables the control of appearance, layout and visual design of web pages and all their elements [95]. By applying CSS rules to HTML elements, developers have access to different aspect attributes such as colours, fonts, spacing, and positioning. With the help of CSS visually appealing and responsive web designs can be created that enhance the user experience.

6.3. Project Structure Overview and Explanation

6.3.1. Installation

As stated before, the Project consists of two main files: The Excel and the Interactive Web Application (aka Interactive Vessel and Shore Power Emissions Calculator or IVSPEC for short) versions of the Calculator.

For the main functionality of the Calculator, simply extracting all the contents in a single folder should work. If the user wishes to use the Excel version, Microsoft Excel or a compatible alternative is required. For those who wish to make changes to the .py files, a simple text editor like Notepad can suffice. If the intention is to execute these files, Python (version 3.7 and above) and several Python libraries (Folium, pandas, http, socketserver, os, webbrowser) are required. Please note that making changes to the python files doesn’t change the functionality of the executables. For that, PyInstaller is needed to recreate them by running a command like *“python -m PyInstaller --onefile filename.py”* in Command Prompt.

6.3.2. Usage and Features

Excel (Vessel and Shore Power Emissions Calculator | VSPEC):

Using the Excel calculator is pretty straight forward. User input is required in the blue cells of the "Calculator" Sheet, with the output calculations (Vessel and Shore Emissions and Costs) following them. User firstly selects a country and the corresponding port used by the ships. Following that selection, the user needs to specify the type of ship, its engine type during hotelling hours, and the engine’s fuel type. The ***Number of Ships*** input field is numeric and shows how many ships exist with the same configuration. The ***Average Hotel Hours per Vessel per Month*** input field is also numeric and corresponds to the average hours per month a single vessel is spending in the selected port.

Web App (Interactive Vessel and Shore Power Emissions Calculator | IVSPEC):

To run the Interactive Web version of the Calculator, the user needs to ensure that 7 files are present in the same folder: *Ships.csv, Ports.csv, InputData.csv, IVSPEC.html, IVSPEC.js, IVSPEC.css, IVSPEC.exe*. If the *Ships.csv, Ports.csv, InputData.csv* files are not present or require updating, running the *createInputCSVs.exe* should recreate them using the data from the Excel Calculator. Once the necessary files are in place, running *IVSPEC.exe* is sufficient. Shortly after, a command prompt window should open, indicating that a local server is running. Then, a new tab will open in your browser, presenting the IVSPEC.

Below the main features of the IVSPEC and their functionality are explained:

Features:

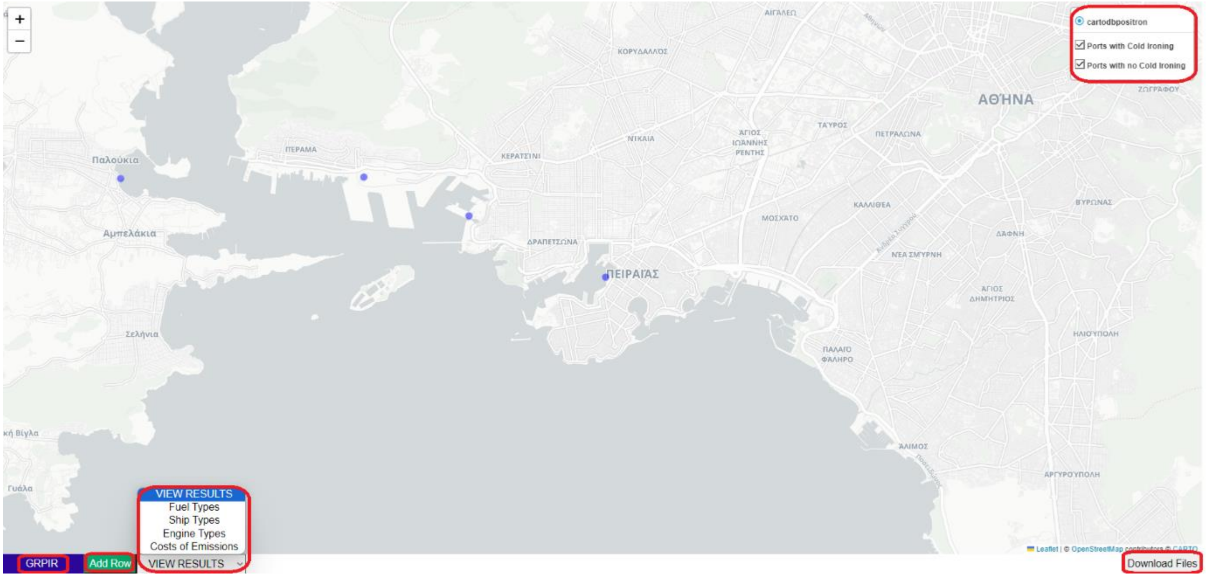


Figure 6.i Screenshot of the Interactive Map portion of the web application

1. Interactive Map
    - ○ The layer selection at the top right allows users to toggle between viewing ports with or without Cold Ironing / OPS
    - ○ Ports indicated with green circles already have Cold Ironing / OPS installed, while the rest (blue circles) do not.

   - Selecting a port (clicking on it) will zoom on it and display a popup with additional information about that port. It will also update the “Input Port Code” field below the map with the code of the selected port

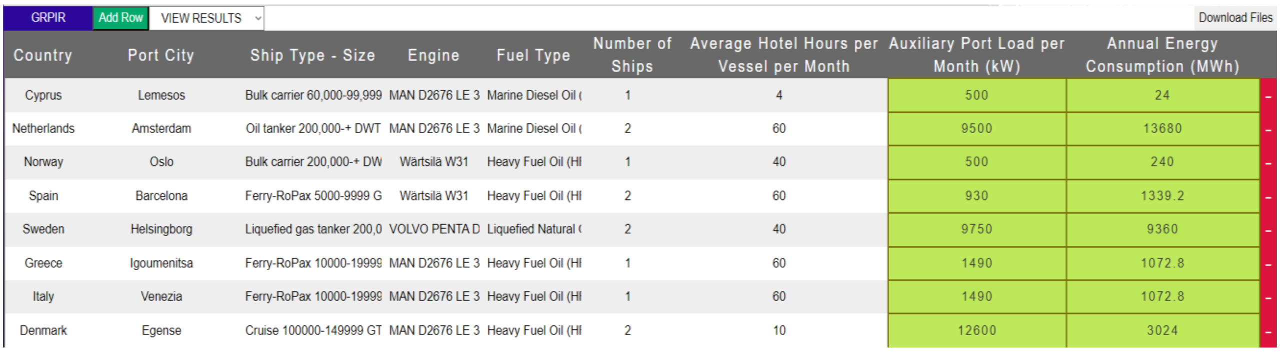
2. Input Port Code field
   - Entering a correct port code and pressing “Enter” will centre the port on the map

3. Table View dropdown selection
   - The dropdown list provides a selection of available tables that the user can view and modify. By default, the value should be the “VIEW RESULTS” table. Selecting any other table will update the screen and present the selected table to the user. Switching back to “VIEW RESULTS” option will save and update all the tables and options associated with them

4. Add Row button
   - Pressing it will add a row to the current viewing table

5. Download Files button
   - The button allows the user to download updated Ships2.csv and InputData2.csv files reflecting any changes made to the tables. If the user intends to use these updated files, they must move them to the same folder as IVSPEC.exe and rename them to Ships.csv and InputData.csv, replacing the previous files

6. Ships Input Table

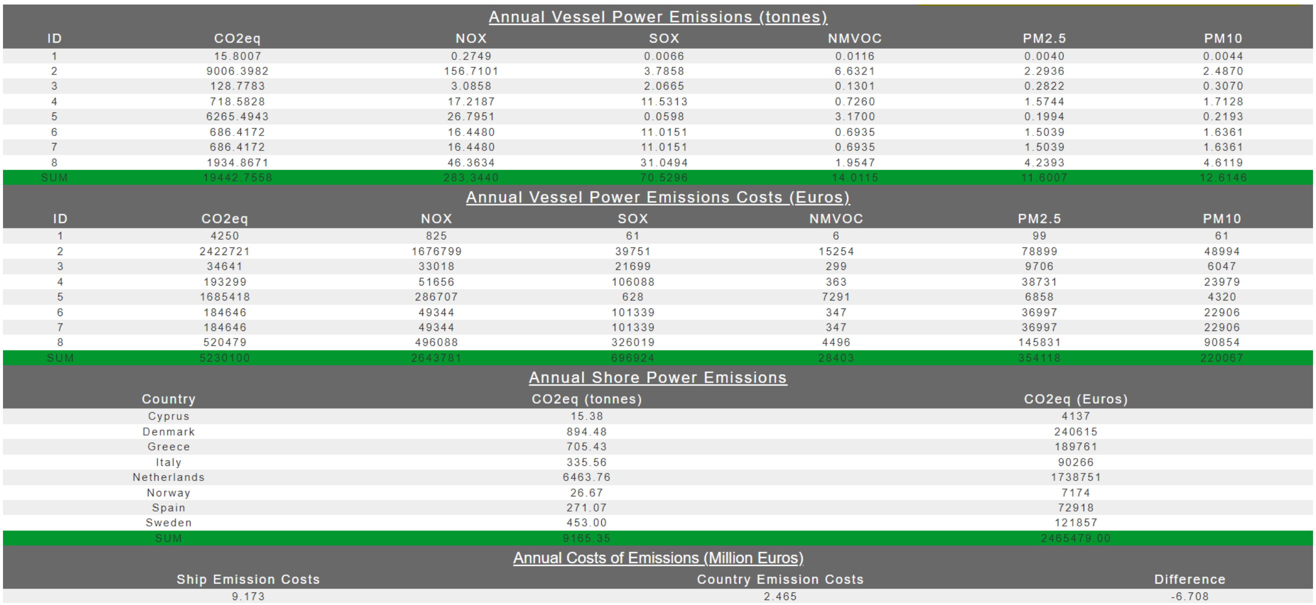


Country	Port City	Ship Type - Size	Engine	Fuel Type	Number of Ships	Average Hotel Hours per Vessel per Month	Auxiliary Port Load per Month (kW)	Annual Energy Consumption (MWh)	
Cyprus	Lemesos	Bulk carrier 60,000-99,999	MAN D2676 LE 3	Marine Diesel Oil (	1	4	500	24	-
Netherlands	Amsterdam	Oil tanker 200,000-+ DWT	MAN D2676 LE 3	Marine Diesel Oil (	2	60	9500	13680	-
Norway	Oslo	Bulk carrier 200,000-+ DW	Wärtsilä W31	Heavy Fuel Oil (HI	1	40	500	240	-
Spain	Barcelona	Ferry-RoPax 5000-9999 G	Wärtsilä W31	Heavy Fuel Oil (HI	2	60	930	1339.2	-
Sweden	Helsingborg	Liquefied gas tanker 200,0	VOLVO PENTA D	Liquefied Natural (	2	40	9750	9360	-
Greece	Igoumenitsa	Ferry-RoPax 10000-19999	MAN D2676 LE 3	Heavy Fuel Oil (HI	1	60	1490	1072.8	-
Italy	Venezia	Ferry-RoPax 10000-19999	MAN D2676 LE 3	Heavy Fuel Oil (HI	1	60	1490	1072.8	-
Denmark	Egense	Cruise 100000-149999 GT	MAN D2676 LE 3	Heavy Fuel Oil (HI	2	10	12600	3024	-

Figure 6.ii Screenshot of the Ships Input table from the web application

    - The Input table has the same inputs as the Excel version
    - If “Input Port Code” field is populated with a correct Port Code and user pressed the “Add Row” button, then the “Country” and “Port City” are automatically populated

7. At the last column of every row of an input table, there is a “-” button that lets the user remove the row
8. Output – Results Tables:



Annual Vessel Power Emissions (tonnes)

ID	CO2eq	NOX	SOX	NMVOC	PM2.5	PM10
1	15.8007	0.2749	0.0066	0.0116	0.0040	0.0044
2	9006.3982	156.7101	3.7858	6.6321	2.2936	2.4870
3	128.7783	3.0858	2.0665	0.1301	0.2822	0.3070
4	718.5828	17.2187	11.5313	0.7260	1.5744	1.7128
5	6265.4943	26.7951	0.0598	3.1700	0.1994	0.2193
6	686.4172	16.4480	11.0151	0.6935	1.5039	1.6361
7	686.4172	16.4480	11.0151	0.6935	1.5039	1.6361
8	1934.8671	46.3634	31.0494	1.9547	4.2393	4.6119
SUM	19442.7558	283.3440	70.5296	14.0115	11.6007	12.6146

Annual Vessel Power Emissions Costs (Euros)

ID	CO2eq	NOX	SOX	NMVOC	PM2.5	PM10
1	4250	825	61	6	99	61
2	2422721	1676799	39751	15254	78899	48994
3	34641	33018	21699	299	9706	6047
4	193299	51656	106088	363	38731	23979
5	1685418	286707	628	7291	6858	4320
6	184646	49344	101339	347	36997	22906
7	184646	49344	101339	347	36997	22906
8	520479	496088	326019	4496	145831	90854
SUM	5230100	2643781	696924	28403	354118	220067

Annual Shore Power Emissions

Country	CO2eq (tonnes)	CO2eq (Euros)
Cyprus	15.38	4137
Denmark	894.48	240615
Greece	705.43	189761
Italy	335.56	90266
Netherlands	6463.76	1738751
Norway	26.67	7174
Spain	271.07	72918
Sweden	453.00	121857
SUM	9165.35	2465479.00

Annual Costs of Emissions (Million Euros)

Ship Emission Costs	Country Emission Costs	Difference
9.173	2.465	-6.708

Figure 6.iii Screenshot of the Results tables from the web application

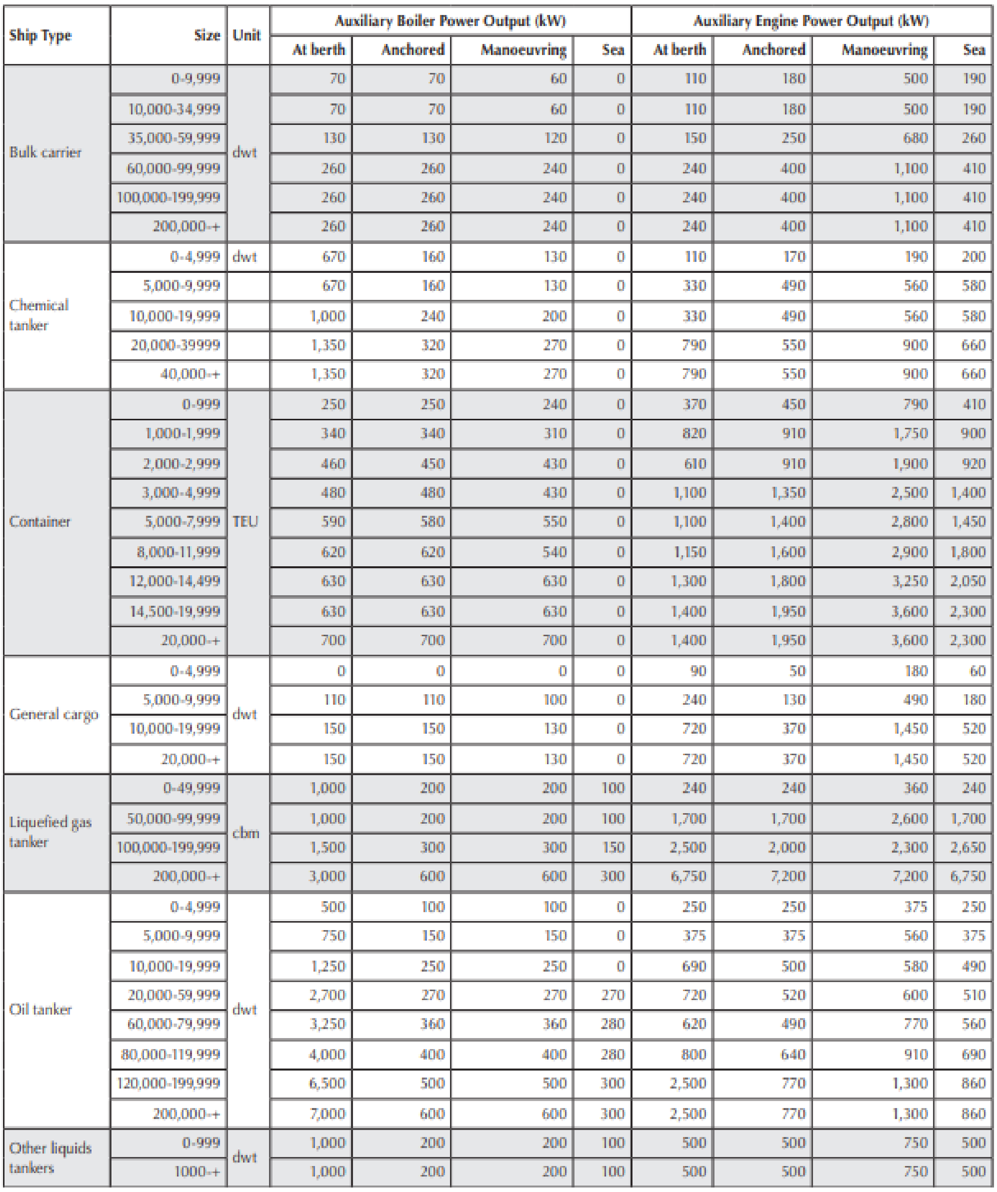
    - First output table are the results of the calculation of the vessels emissions in the same order as they appear in the input table. The results are in tonnes of pollutants per year.
    - The second output table contains the results of the costs of the previously calculated emissions, again in the same order as they appear in the input table. The results are in euros per year.
    - The third table is populated with the results of the calculation of the emissions per country based on the power needs of the vessels selected.
    - The fourth and final table is the sum of the costs from the 2nd and 3rd table, and their difference.

6.3.3. Predefined Input Data

For the application to calculate the ships and shore power emissions, several predefined input data are required along. Of course, to avoid unnecessary complexity and therefore making it impractical, some assumptions have been made.

For the users of the Calculator applications the initial input involves the selection of the Port used by their vessels, by choosing ***Country*** and ***Port City***. All the information about Ports (PortID, Port City, Country, Geographic location, Sea) were taken from the European Maritime Observation and Data Network EMDONet [97] established by the European Commission. Whether or not a port has Cold Ironing Infrastructure installed was found with the help of the European Alternative Fuel Observatory's Port Infrastructure dataset [98], also established by the European Commission.

Following that, come three input fields regarding the ship's configurations. ***Ship Type - Size - Unit*** field includes vessel types categorised by Type and Size according to the "Fourth IMO Greenhouse Gas Study" (2020) [99]. This categorisation table (table 6.i below) by the "Fourth IMO GHG Study", provides us with estimates of Auxiliary Engine Loads across various operating modes by vessel type. For the purpose of this project only the power requirements "**At Berth"** were taken into consideration.



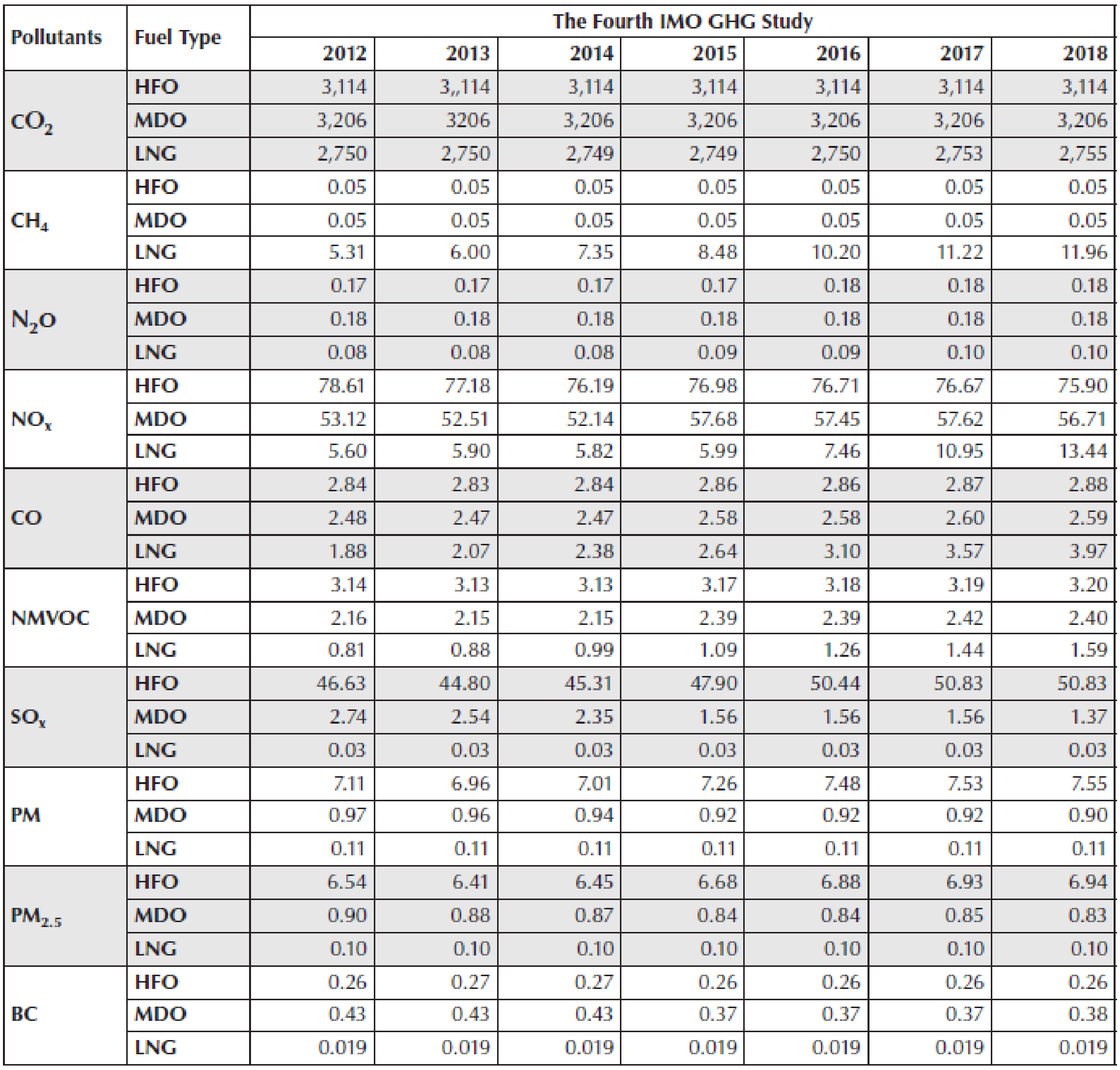
Ship Type	Size	Unit	Auxiliary Boiler Power Output (kW)				Auxiliary Engine Power Output (kW)			
			At berth	Anchored	Manoeuvring	Sea	At berth	Anchored	Manoeuvring	Sea
Bulk carrier	0-9,999	dwt	70	70	60	0	110	180	500	190
	10,000-34,999		70	70	60	0	110	180	500	190
	35,000-59,999		130	130	120	0	150	250	680	260
	60,000-99,999		260	260	240	0	240	400	1,100	410
	100,000-199,999		260	260	240	0	240	400	1,100	410
	200,000-+		260	260	240	0	240	400	1,100	410
Chemical tanker	0-4,999	dwt	670	160	130	0	110	170	190	200
	5,000-9,999		670	160	130	0	330	490	560	580
	10,000-19,999		1,000	240	200	0	330	490	560	580
	20,000-39999		1,350	320	270	0	790	550	900	660
	40,000-+		1,350	320	270	0	790	550	900	660
Container	0-999	TEU	250	250	240	0	370	450	790	410
	1,000-1,999		340	340	310	0	820	910	1,750	900
	2,000-2,999		460	450	430	0	610	910	1,900	920
	3,000-4,999		480	480	430	0	1,100	1,350	2,500	1,400
	5,000-7,999		590	580	550	0	1,100	1,400	2,800	1,450
	8,000-11,999		620	620	540	0	1,150	1,600	2,900	1,800
	12,000-14,499		630	630	630	0	1,300	1,800	3,250	2,050
	14,500-19,999		630	630	630	0	1,400	1,950	3,600	2,300
	20,000-+		700	700	700	0	1,400	1,950	3,600	2,300
General cargo	0-4,999	dwt	0	0	0	0	90	50	180	60
	5,000-9,999		110	110	100	0	240	130	490	180
	10,000-19,999		150	150	130	0	720	370	1,450	520
	20,000-+		150	150	130	0	720	370	1,450	520
Liquefied gas tanker	0-49,999	cbm	1,000	200	200	100	240	240	360	240
	50,000-99,999		1,000	200	200	100	1,700	1,700	2,600	1,700
	100,000-199,999		1,500	300	300	150	2,500	2,000	2,300	2,650
	200,000-+		3,000	600	600	300	6,750	7,200	7,200	6,750
Oil tanker	0-4,999	dwt	500	100	100	0	250	250	375	250
	5,000-9,999		750	150	150	0	375	375	560	375
	10,000-19,999		1,250	250	250	0	690	500	580	490
	20,000-59,999		2,700	270	270	270	720	520	600	510
	60,000-79,999		3,250	360	360	280	620	490	770	560
	80,000-119,999		4,000	400	400	280	800	640	910	690
	120,000-199,999		6,500	500	500	300	2,500	770	1,300	860
	200,000-+		7,000	600	600	300	2,500	770	1,300	860
Other liquids tankers	0-999	dwt	1,000	200	200	100	500	500	750	500
	1000-+		1,000	200	200	100	500	500	750	500

Table 6.i Auxiliary Engine Power Output by ship type, size and mode of operation [99]

Then come ***Engine*** and ***Fuel Type*** fields. For the engine options some auxiliary engines, from MAN [100], Wartsila [101] and Volvo [102], are provided by default with their Specific Fuel Oil or Gas Consumptions. As for the Fuel Type selection, Emission Factors by Fuel were also extracted from the “Fourth IMO GHG Study 2020” table 27 [99] (table 6.ii below). Of those fuel emissions Carbon Dioxide (CO_2), Carbon Monoxide (CO), Methane (CH_4) and Nitrous Oxide (N_2O) were combined into $CO_{2equivalent}$ using the Global Warming Potential values for 100-year time horizon from the Sixth Assessment Report 2021 written by the Intergovernmental Panel on Climate Change aka IPCC [103]. Out of the remaining emissions factors given by the IMO, Nitrogen Oxides (NO_X), Sulphur Oxides (SO_X), Non-Methane Volatile Organic

Compounds (NMVOC) and Particulate Matter of diameter 10 and 2.5 micrometres (PM_{10}, $PM_{2.5}$), are selected and presented.

And so, the calculations for the ***Annual Vessel Power Emissions*** are made. A multiplication of ***Annual Energy Consumption (MWh) * Fuel Type Emission Factor (g Pollutant / kg Fuel) * Specific Fuel Oil Consumption (kg Fuel / MWh) * 10^{-6}*** resulting in tonnes per year of pollutant.



Pollutants	Fuel Type	The Fourth IMO GHG Study						
		2012	2013	2014	2015	2016	2017	2018
CO_2	HFO	3,114	3,,114	3,114	3,114	3,114	3,114	3,114
	MDO	3,206	3206	3,206	3,206	3,206	3,206	3,206
	LNG	2,750	2,750	2,749	2,749	2,750	2,753	2,755
CH_4	HFO	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	MDO	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	LNG	5.31	6.00	7.35	8.48	10.20	11.22	11.96
N_2O	HFO	0.17	0.17	0.17	0.17	0.18	0.18	0.18
	MDO	0.18	0.18	0.18	0.18	0.18	0.18	0.18
	LNG	0.08	0.08	0.08	0.09	0.09	0.10	0.10
NO_x	HFO	78.61	77.18	76.19	76.98	76.71	76.67	75.90
	MDO	53.12	52.51	52.14	57.68	57.45	57.62	56.71
	LNG	5.60	5.90	5.82	5.99	7.46	10.95	13.44
CO	HFO	2.84	2.83	2.84	2.86	2.86	2.87	2.88
	MDO	2.48	2.47	2.47	2.58	2.58	2.60	2.59
	LNG	1.88	2.07	2.38	2.64	3.10	3.57	3.97
NMVOC	HFO	3.14	3.13	3.13	3.17	3.18	3.19	3.20
	MDO	2.16	2.15	2.15	2.39	2.39	2.42	2.40
	LNG	0.81	0.88	0.99	1.09	1.26	1.44	1.59
SO_x	HFO	46.63	44.80	45.31	47.90	50.44	50.83	50.83
	MDO	2.74	2.54	2.35	1.56	1.56	1.56	1.37
	LNG	0.03	0.03	0.03	0.03	0.03	0.03	0.03
PM	HFO	7.11	6.96	7.01	7.26	7.48	7.53	7.55
	MDO	0.97	0.96	0.94	0.92	0.92	0.92	0.90
	LNG	0.11	0.11	0.11	0.11	0.11	0.11	0.11
$PM_{2.5}$	HFO	6.54	6.41	6.45	6.68	6.88	6.93	6.94
	MDO	0.90	0.88	0.87	0.84	0.84	0.85	0.83
	LNG	0.10	0.10	0.10	0.10	0.10	0.10	0.10
BC	HFO	0.26	0.27	0.27	0.26	0.26	0.26	0.26
	MDO	0.43	0.43	0.43	0.37	0.37	0.37	0.38
	LNG	0.019	0.019	0.019	0.019	0.019	0.019	0.019

Table 6.ii Emission Factors by type of fuel (unit: kg pollutant / tonne fuel) [99]

In order to calculate the ***Shore Power Emissions,*** the energy mix of each country is required. Greenhouse Gas Emissions by Country were sourced from the "Greenhouse gas emissions by source sector" [104] dataset for the year 2019 from Eurostat, and then accumulated into one CO_{2eq} value per country. Dividing that with Gross Electricity Production of each country, this was taken from the “Production of electricity and derived heat by type of fuel” [105] dataset for the year 2019 from Eurostat, resulting in tonnes of CO_{2eq} per MWh of energy produced by each country.

In addition to the vessels and shore power emissions calculations, a final estimation of the costs associated with each pollutant is carried out based on the previous emissions results. The costs per kg of pollutant was sourced from the “Handbook on the external costs of transport” [106] report created by the European Commission in 2019. In the report a table exists describing the costs in Euros per kg of pollutant based on the Sea. An exception is CO_2 where the values were taken from a different table in that report, which presents the costs of CO_2 in different time periods. For this project the **Central** value of **Long run (from 2040 to 2060)** was taken with a value of 269 € per tonne of CO_2 emitted.

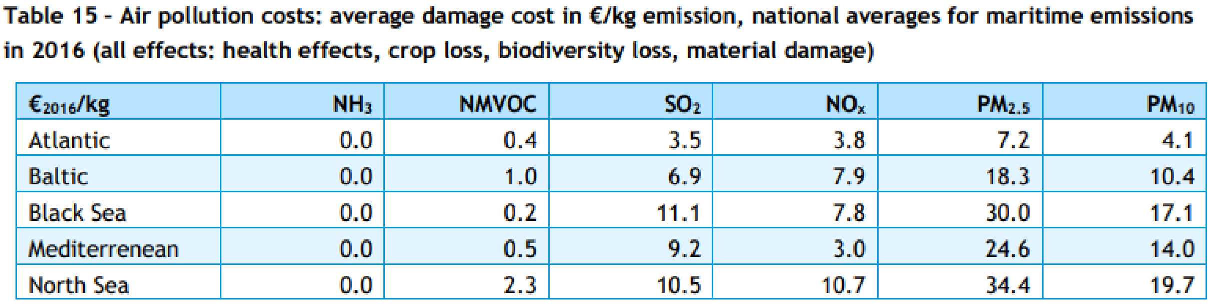


Table 15 - Air pollution costs: average damage cost in €/kg emission, national averages for maritime emissions in 2016 (all effects: health effects, crop loss, biodiversity loss, material damage)

$€_{2016}$/kg	NH_3	NMVOC	SO_2	NO_x	$PM_{2.5}$	PM_{10}
Atlantic	0.0	0.4	3.5	3.8	7.2	4.1
Baltic	0.0	1.0	6.9	7.9	18.3	10.4
Black Sea	0.0	0.2	11.1	7.8	30.0	17.1
Mediterrenean	0.0	0.5	9.2	3.0	24.6	14.0
North Sea	0.0	2.3	10.5	10.7	34.4	19.7

Table 6.iv Costs of kilogram of different pollutant emissions [106]

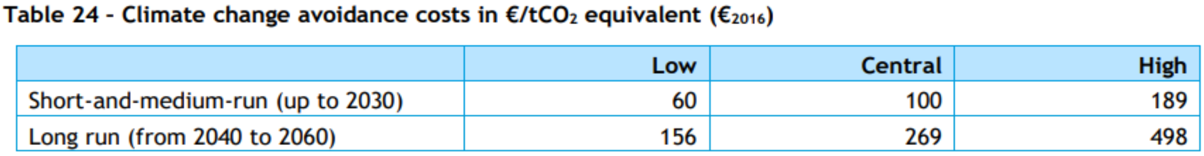


Table 24 - Climate change avoidance costs in €/tCO_2 equivalent ($€_{2016}$)

	Low	Central	High
Short-and-medium-run (up to 2030)	60	100	189
Long run (from 2040 to 2060)	156	269	498

Table 6.iii Costs of a ton of CO2 emission [106]

It goes without saying that the users can add / remove or change any row of any table mentioned above in both versions of the calculator. Meaning, the users have full access to the:

- Ship Types table, allowing them to add any of their ship types they might have, with specific auxiliary engine loads

- Fuel Types table, allowing them to add any specific fuel type with its associated fuel emissions
- Engine Types table, allowing them to add any type of engine they use to power their auxiliary systems
- Costs of Emissions by Sea table, allows users to update the costs of a tonne of pollutant in each Sea

After calculating the emissions from both the Vessels and the Shore power plants, the associated costs are also displayed at the end. This presentation provides the users complete understanding of the cost benefits associated with utilising the OPS infrastructure of the ports.

6.3.4. Additional Files and Information

In order for the user experience to be as easy as possible *createInputCSVs.exe* was created. Executing it will transform the input from the Excel Version of the Calculator into the three input CSVs that the web version needs.

- **Ships.csv** is created using the input data from the "*Calculator*" sheet
- **Ports.csv** is created using the data from the "*Ports*" sheet
- **InputData.csv** is created using the data from "Engines", "*Fuel Emissions*", "*SEC by vessel type*" and "*GGE per GEP by sector*" sheets

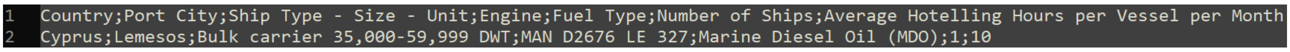
If the user has modified the three CSV files and wishes to update the tables in Excel with those values, a simple process of copying and pasting them to the correct sheet should suffice.

Additionally, as previously stated, if the user wishes to modify the executables (*IVSPEC.exe* and *createInputCSVs.exe*) by changing the corresponding python files, then Python along with the libraries that were mentioned above are needed in order to run a command like *"python -m PyInstaller --onefile filename.py"* in Command Prompt.

Input File Templates:

It is recommended to use the **VSPEC** or **IVSPEC** along with the **creatInputCSVs.exe,** in order to create the input files.

- **Ships.csv:**



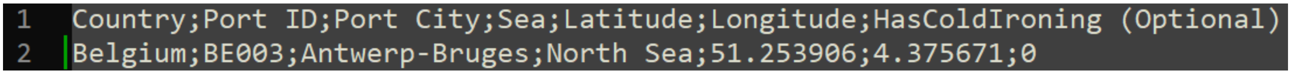
```
Country;Port City;Ship Type - Size - Unit;Engine;Fuel Type;Number of Ships;Average Hotelling Hours per Vessel per Month
Cyprus;Lemesos;Bulk carrier 35,000-59,999 DWT;MAN D2676 LE 327;Marine Diesel Oil (MDO);1;10
```

Figure 6.iv Overview of the structure of Ships.csv file

The 1st row of the file is the header titles of all the user input columns, and it's the only mandatory row of the file. After that User can populate the rest of the rows with his data manually according to the column headers

- **Ports.csv:**

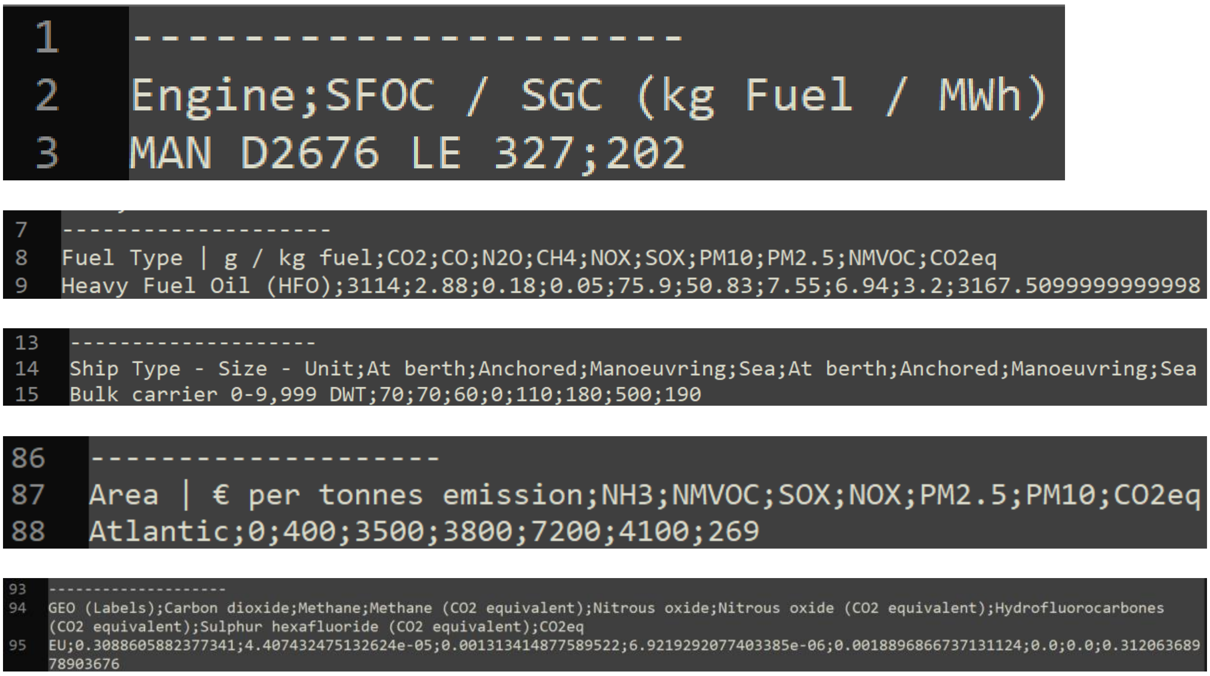
Again the 1st row of the file is the header titles of all the user input columns, and it's the only mandatory row of the file. Then comes the Ports data following the same rules as the **Ships.csv**, with the last column being the only exception as it is the only column that is optional to fill. Not filling a “1” or “0” in the *HasColdIroning (Optional)* column will be by default translated to “**0**”.



```
Country;Port ID;Port City;Sea;Latitude;Longitude;HasColdIroning (Optional)
Belgium;BE003;Antwerp-Bruges;North Sea;51.253906;4.375671;0
```

Figure 6.v Overview of the structure of Ports.csv file

- **InputData.csv:**



```
--------------------
Engine;SFOC / SGC (kg Fuel / MWh)
MAN D2676 LE 327;202
```

```
--------------------
Fuel Type | g / kg fuel;CO2;CO;N2O;CH4;NOX;SOX;PM10;PM2.5;NMVOC;CO2eq
Heavy Fuel Oil (HFO);3114;2.88;0.18;0.05;75.9;50.83;7.55;6.94;3.2;3167.5099999999998
```

```
--------------------
Ship Type - Size - Unit;At berth;Anchored;Manoeuvring;Sea;At berth;Anchored;Manoeuvring;Sea
Bulk carrier 0-9,999 DWT;70;70;60;0;110;180;500;190
```

```
--------------------
Area | € per tonnes emission;NH3;NMVOC;SOX;NOX;PM2.5;PM10;CO2eq
Atlantic;0;400;3500;3800;7200;4100;269
```

```
--------------------
GEO (Labels);Carbon dioxide;Methane;Methane (CO2 equivalent);Nitrous oxide;Nitrous oxide (CO2 equivalent);Hydrofluorocarbones
(CO2 equivalent);Sulphur hexafluoride (CO2 equivalent);CO2eq
EU;0.3088605882377341;4.407432475132624e-05;0.001313414877589522;6.9219292077403385e-06;0.0018896866737131124;0.0;0.0;0.312063689
78903676
```

Figure 6.vi Overview of the structure of InputData.csv file

This input file has a bit different structure than the previous two. In this file *Engine Types*, *Fuel Types*, *Ship Types*, *Costs of Emissions* and *Energy Mixes by Country* data are presented in this order. For each of these it’s first required to have a line of 20 dashed lines “--------------------” and then the headers of that section.

6.3.5. Troubleshooting

A common issue when starting the IVSPEC is that sometimes it fails to load the Input Files. A simple reload of the browser tab should fix this problem

6.3.6. Differences and Similarities with EPA’s Emissions Calculator

As was mentioned before, the inspiration for this Thesis was EPA’s Shore Power Emissions Calculator. One of the biggest differences is that in this Thesis, the scope was extended to also calculating an estimation of the costs for the pollutants for both the vessels and the ports emissions. For that reason, an additional input field needed to be added to specify the port where the vessels were docked and subsequently the sea in which they were stationed. After that, of course, the ship type, fuel type and engine type categories are different as the data for those is taken from other sources. Another differentiation between the two projects, is that the last two input fields from EPA’s Calculator, *Number of Annual Vessel Calls* and *Average Hotel Hours per Vessel Call*, were changed to *Number of Ships* and *Average Hotel Hours per Vessel per Month*, this was done to allow the users to bundle ships with the same configuration together.

7. Conclusions

In conclusion, this thesis has showed the critical issue of emissions that come from the maritime industry especially in ports, with the development of an emission calculator app for ships and ports.

Even the simple act of measuring and keeping track of data, is a step in the right direction. Because you cannot improve something for which you have no data to compare to. The interactive map application, which allows users to compare the costs of traditional engine use with the use of Cold Ironing Infrastructure solutions, offers valuable insights on ships emissions and serves as great promoter of more sustainable practices in the shipping industry.

As the shipping industry continues to evolve, the adoption of such solutions will help us into creating a new more sustainable path with efforts to mitigate the environmental impact of this industry.

Of course, OPS systems are not the only solutions and certainly not a “one size fits all” kind of solution to the ships emissions in ports. Further technologies, better standards and many other issues need to improve in order to make them a more reliable and available solution. Additionally, even with neglecting the resources issue that many ports have, some ports only have seasonal needs so OPS systems seem as a bad or as a not-worth- the-time solution. With those points in mind Cold Ironing as an idea should work on every port with the only main problems being limitation on resources and maintenance costs.

Some remarks on the Interactive Vessel and Shore Power Emissions Calculator:

- As previously noted, this project was designed with the prospect of merging with the previous works of Christoforos Lefkiou and Michalis Lefkiou. A merge with those works, would create a powerful and helpful set of tools that are able to give much more information on ports, ships and emissions.

- This Interactive Emissions Calculator can be used by shipowners and ports alike, to keep track of their emissions and to showcase the cost effectiveness of implementing Cold Ironing Infrastructure
- With future developments the estimation of the costs can be increased by adding for example the costs associated with implementing and maintaining OPS solutions.
- As it was explained in previous chapters, this calculator was designed with adaptability in mind. Many of the variables such as ship types/sizes, fuels and engines are all adjustable, and so the user can customize the calculator to their needs.

I would like to close with a Native American proverb which goes like: "We do not inherit the Earth from our ancestors; we borrow it from our children", which stresses the importance of adopting sustainable practices in every area of our lives in order to ensure and secure a better world for our children to live in. This is a continuous and daunting task, but as Lao Tzu once said “The journey of a thousand steps begins with a single step”, and so we as whole should collectively work to improve our world day by day.

8. Bibliography

[1] J. H. Morrison, *History of American Steam Navigation*. New York, W. F. Sametz & Company, Incorporated, 1908.

[2] Eng. W. Alturki, “Four-Stroke and Two-Stroke Marine Engines Comparison and Application,” *International Journal of Engineering Research and Applications*, vol. 07, no. 04, pp. 49–56, Apr. 2017, doi: https://doi.org/10.9790/9622-0704034956.

[3] J. B. Heywood, *Internal Combustion Engine Fundamentals*, 2nd ed. New York: Mcgraw-Hill Education, 2018. Available: https://archive.org/details/john-heywood-internal-combustion-engine-fundamentals-mc-graw-hill-science-engineering-math-1988/page/n5/mode/2up

[4] R. Stone, *Introduction to Internal Combustion Engines*. Basingstoke: Palgrave Macmillan, 2012.

[5] Γ. Ζαραφωνίτης, *Εισαγωγή στη Ναυπηγική και Θαλάσσια Τεχνολογία*. Athens: National Technical University of Athens, 2015. Available: https://mycourses.ntua.gr/courses/NAVAL1063/document/%C5%E9%F3%E1%E3%F9%E3%DE_%F3%F4%E7_%CD%E1%F5%F0%E7%E3%E9%EA%DE_2015-09-10_1%EF_%CC%DD%F1%EF%F2.pdf

[6] D. A. Taylor, *Introduction to Marine Engineering*. Elsevier, 2014.

[7] H. N. Gupta, *Fundamentals of Internal Combustion Engines*. Delhi: Phi Learning Private Limited, 2015.

[8] H. D. Mcgeorge, *Marine Auxiliary Machinery*. Oxford: Elsevier Butterworth Heinemann, 2008.

[9] Χ. Φραγκόπουλος and Ι. Προυσαλίδης, *Ενεργειακά Συστήματα Πλοίου*. Athens: DaVinci, 2019.

[10] S. Umans, A. Fitzgerald, and C. Kingsley, *Electric Machinery*. McGraw-Hill Higher Education, 2013.

[11] B. Pal, S. Rana, and B. Kundu, “An Introduction to DC Generator,” *International Journal of Research and Discovery (IJRD)*, vol. 1, no. 3, 2016.

[12] R. Kantharia, *A Guide to Ship’s Electro-Technology*. Marine Insight, 2023.

[13] R. Kantharia, *A Brief Overview of Ship’s Auxiliary Engine*. Marine Insight, 2016.

[14] A. Hughes, *Electric Motors and Drives : Fundamentals, Types, and Applications*. Amsterdam ; Boston: Elsevier/Newnes, 2006.

[15] Ι. Προυσαλίδης, *Ηλεκτροτεχνικές Εφαρμογές Σε Πλοία Και Πλωτές Κατασκευές*. Athens: Simmertria, 2012.

[16] M. Λευκίου, “Study for Power Increase of local electrical grid in ports of European Economic Area (EEA) and United Kingdom (UK),” Digital Library of NTUA, Athens, 2022. Available: https://dspace.lib.ntua.gr/xmlui/handle/123456789/56453

[17] Χ. Λευκίου, “Θέματα Ηλεκτρισμού σε Πλοία και Λιμένες,” Digital Library of NTUA, Athens, 2021. Available: https://dspace.lib.ntua.gr/xmlui/handle/123456789/54435

[18] M. B. Vermeire, “Everything You Need to Know about Marine Fuels,” Chevron Marine Products, Aug. 2021. Available: https://www.chevronmarineproducts.com/content/dam/chevron-marine/fuels-brochure/Everything%20You%20Need%20To%20Know%20About%20Marine%20Fuels.pdf

[19] E. DeCola, T. Robertson, M. Fischer, and L. Blair, “Phasing out the Use and Carriage for Use of Heavy Fuel Oil in the Canadian Arctic: Impacts to Northern Communities,” Nuka Research and Planning Group LLC, Jul. 2018. Available: https://wwf.ca/wp-content/uploads/2020/03/Phasing-Out-the-Use-and-Carriage_July-2018.pdf

[20] “Important Terms from A to Z: Marine Fuels,” Bomin Group, 2015.

[21] “Annex I - Regulations for the Prevention of Pollution by Oil,” MAPROL.

[22] “ISO 8217:2017 - Petroleum Products - Fuels (class F) - Specifications of Marine Fuels,” ISO, 2017.

[23] “IMO 2020 - Cutting Sulphur Oxide Emissions,” IMO, 2020.

[24] A. A. Banawan, M. M. El Gohary, and I. S. Sadek, “Environmental and Economical Benefits of Changing from Marine Diesel Oil to natural-gas Fuel for short-voyage high-power Passenger Ships,” *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, vol. 224, no. 2, pp. 103–113, Dec. 2009, doi: https://doi.org/10.1243/14750902jeme181.

[25] S. Bengtsson, K. Andersson, and E. Fridell, “A Comparative Life Cycle Assessment of Marine Fuels,” *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, vol. 225, no. 2, pp. 97–110, May 2011, doi: https://doi.org/10.1177/1475090211402136.

[26] K. Andersson and C. Márquez Salazar, “Methanol as a Marine Fuel Report,” Methanol Institute, 2015.

[27] U.S. Department of Energy, “Alternative Fuels Data Center: Methanol,” *Energy.gov*, 2020. https://afdc.energy.gov/fuels/emerging-methanol#:~:text=This%20fuel%20is%20generally%20produced,is%20currently%20the%20most%20economical.

[28] National Grid Group, “The Hydrogen Colour Spectrum,” *Nationalgrid.com*, 2023. https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum

[29] Κ. Αθανάσιος, “Διερεύνηση της Επίδρασης Εναλλακτικών Καυσίμων στην Επίδοση Πλοίων,” Digital Library of NTUA, Athens, 2022. Available: https://dspace.lib.ntua.gr/xmlui/handle/123456789/56164

[30] U.S. Department of Energy, “Alternative Fuels Data Center: Biodiesel Production and Distribution,” *Energy.gov*, 2024. https://afdc.energy.gov/fuels/biodiesel-production#:~:text=Biodiesel%20is%20produced%20from%20vegetable,and%20glycerin%20(a%20coproduct).

[31] J. Sheehan *et al.*, *An Overview of Biodiesel and Petroleum Diesel Life Cycles*. Golden, Co: National Renewable Energy Laboratory, May, 1998.

[32] European Technology and Innovation Platform, “Bioenergy Factsheet: Marine Biofuels,” ETIP, 2017. Available: https://www.etipbioenergy.eu/images/ETIP_Bioenergy_Factsheet_Marine_Biofuels.pdf

[33] S. Brynolf, “Environmental Assessment of Present and Future Marine Fuels,” CHALMERS UNIVERSITY OF TECHNOLOGY, 2014.

[34] T. Morgan, “LPG and the Global Energy Transition : A study on behalf of the World LPG Association,” World LP Gas Association, 2015. Available: https://www.worldliquidgas.org/wp-content/uploads/2015/05/LPG-and-the-Global-Energy-Transition.pdf

[35] “LPG I Future fuels,” *MAN Energy Solutions*, 2024. https://www.man-es.com/marine/strategic-expertise/future-fuels/lpg

[36] M. R. Saxena, R. K. Maurya, and P. Mishra, “Assessment of performance, combustion and emissions characteristics of methanol-diesel dual-fuel compression ignition engine: A review,” *Journal of Traffic and Transportation Engineering (English Edition)*, vol. 8, no. 5, pp. 638–680, Oct. 2021, doi: https://doi.org/10.1016/j.jtte.2021.02.003.

[37] Massachusetts Institute Of Technology, *The Future of Natural Gas : an Interdisciplinary MIT study.* Cambridge, Mass.: Massachusetts Institute of Technology, 2011.

[38] Δ. Φιλήμων, “Συσχέτιση Ποιότητας Ανάφλεξης και Σύστασης Ναυτιλιακών Gasoil,” Digital Library of NTUA, Athens, 2015. Available: https://dspace.lib.ntua.gr/xmlui/handle/123456789/40716

[39] Κ. Βολογιάννης, “Ναυτικοί Κινητήρες και Ναυτιλιακά Καύσιμα,” Dioni, University of Pireaus, Athens, 2017. Available: https://dione.lib.unipi.gr/xmlui/handle/unipi/10905

[40] American Bureau of Shipping, “Sustainability Whitepaper: Biofuels as Marine Fuel,” ABS, May 2021. Available: https://ww2.eagle.org/content/dam/eagle/publications/whitepapers/biofuels-as-marine-fuel-whitepaper-21089.pdf

[41] B. R. Gurjar, L. Molina, and C. Ojha, *Air Pollution Health and Environmental Impacts*. Crc Press, 2010.

[42] World Health Organization, “Ambient (outdoor) air pollution,” *Who.int*, Dec. 19, 2022. https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

[43] The Climate Change Secretariat Ministry of Mahaweli Development and Environment, *A Guide for Carbon Footprint Assessment*. The Climate Change Secretariat Ministry of Mahaweli Development and Environment, 2016.

[44] Marine Environment Protection Committee, “ANNEX 9 - RESOLUTION MEPC.364(79) - 2022 GUIDELINES ON THE METHOD OF CALCULATION OF THE ATTAINED ENERGY EFFICIENCY DESIGN INDEX (EEDI) FOR NEW SHIPS,” IMO, 2022.

[45] V. Masson-Delmotte *et al.*, “The Physical Science Basis Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change Edited by,” *Climate Change 2021 The Physical Science Basis*, vol. 2, 2021, doi: https://doi.org/10.1017/9781009157896.

[46] Directorate-General for Mobility and Transport; European Commission, “Handbook on the External Costs of Transport,” European Union, 2019.

[47] IMO, “Fourth IMO GHG Study 2020 - Full Report and Annexes,” International Maritime Organization, 2021.

[48] World Health Organization, “Health Effects of Particulate Matter,” WHO, 2013.

[49] World Health Organization, “WHO Global Air Quality Guidelines,” *Who.int*, 2021. https://www.who.int/news-room/questions-and-answers/item/who-global-air-quality-guidelines

[50] E. Samoli *et al.*, “Acute Effects of Ambient Particulate Matter on Mortality in Europe and North America: Results from the APHENA Study,” *Environmental Health Perspectives*, vol. 116, no. 11, pp. 1480–1486, Nov. 2008, doi: https://doi.org/10.1289/ehp.11345.

[51] S. Wang *et al.*, “Decarbonizing in Maritime Transportation: Challenges and Opportunities,” *Journal of Transportation Technologies*, vol. 13, no. 2, pp. 301–325, Feb. 2023, doi: https://doi.org/10.4236/jtts.2023.132015.

[52] E. Harrould-Kolieb, “Shipping Impacts on Climate: A Source with Solutions,” Oceana, Oceana.org, 2008.

[53] S. N. Assadi, “Carbon Dioxide and Health,” *East African Scholars Journal of Medical Sciences*, vol. 5, no. 4, pp. 117–121, Apr. 2022, doi: https://doi.org/10.36349/easms.2022.v05i04.005.

[54] EMEP/EEA, “Air Pollutant Emission Inventory Guidebook 2023,” European Environment Agency, 2023. doi: https://doi.org/10.2800/795737.

[55] I. Komar and B. Lalić, “Sea Transport Air Pollution,” *Current Air Quality Issues*, Oct. 2015, doi: https://doi.org/10.5772/59720.

[56] J. H. Seinfeld and S. N. Pandis, *Atmospheric Chemistry and Physics : from Air Pollution to Climate Change*. New York: Wiley, 2012.

[57] E. D. O. Menezes and M. Lem, “Liquefied Natural Gas: the 21st Century Myth of Green Fossil Fuel for the Shipping Industry,” *The Magazine for Environmental Managers, A&WMA*, Dec. 2022.

[58] D. Shindell, G. Faluvegi, K. Seltzer, and C. Shindell, “Quantified, Localized Health Benefits of Accelerated Carbon Dioxide Emissions Reductions,” *Nature Climate Change*, vol. 8, no. 4, pp. 291–295, Mar. 2018, doi: https://doi.org/10.1038/s41558-018-0108-y.

[59] T. J. Wallington and P. Wiesen, “N2O Emissions from Global Transportation,” *Atmospheric Environment*, vol. 94, pp. 258–263, Sep. 2014, doi: https://doi.org/10.1016/j.atmosenv.2014.05.018.

[60] Y. Ja, “Health Hazards and Nitrous oxide: A Time for Reappraisal,” *Anesthesia Progress*, vol. 38, no. 1, pp. 1–11, Jan. 1991.

[61] B. J. Finlayson-Pitts and J. N. Pitts, *Chemistry of the Upper and Lower Atmosphere*. Elsevier, 1999, pp. 547–656, ch. 11.

[62] UNFCCC, “The Paris Agreement,” *Unfccc.int*, 2020. https://unfccc.int/process-and-meetings/the-paris-agreement

[63] S. Aseel, H. Al-Yafei, M. Kucukvar, and N. C. Onat, “Life Cycle Air Emissions and Social Human Health Impact Assessment of Liquified Natural Gas Maritime Transport,” *Energies*, vol. 14, no. 19, p. 6208, Sep. 2021, doi: https://doi.org/10.3390/en14196208.

[64] “Fit for 55 - the EU’s Plan for a Green Transition,” *Consilium*, 2024. https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55/

[65] “Brief History of IMO,” *Imo.org*, 2016. https://www.imo.org/en/About/HistoryOfIMO/Pages/Default.aspx

[66] Χ. Κ. Τσούμαρης, “Δείκτης EEDI, Περιβάλλον Και Ζητήματα Εφαρμογής Του,” Digital Library of NTUA, Athens, 2015. Available: https://dspace.lib.ntua.gr/xmlui/handle/123456789/40598

[67] Α. Μ. Κοτρίκλα, *Ναυτιλία και Περιβάλλον*. Athens: ΣΥΝΔΕΣΜΟΣ ΕΛΛΗΝΙΚΩΝ ΑΚΑΔΗΜΑΪΚΩΝ ΒΙΒΛΙΟΘΗΚΩΝ, 2015.

[68] ABS, “Energy Efficiency Existing Ship Index(EEXI),” American Bureau of Shipping, Dec. 2020. Available: https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/regulatory-debrief-energy-efficiency-existing-ship-index.pdf

[69] R. Winkel, U. Weddige, D. Johnsen, V. Hoen, and G. Papaefthymiou, “Potential for Shore Side Electricity in Europe,” Ecofys & Technical University of Crete, 2015.

[70] P. Ericsson and I. Fazlagic´, “Shore-side Power Supply,” Master of Science Thesis, CHALMERS UNIVERSITY OF TECHNOLOGY, 2008.

[71] A. Innes and J. Monios, “Identifying the unique challenges of installing cold ironing at small and medium ports – The case of aberdeen,” *Transportation Research Part D: Transport and Environment*, vol. 62, pp. 298–313, Jul. 2018, doi: https://doi.org/10.1016/j.trd.2018.02.004.

[72] R. Glavinović, M. Krčum, L. Vukić, and I. Karin, “Cold Ironing Implementation Overview in European Ports—Case Study—Croatian Ports,” vol. 15, no. 11, pp. 8472–8472, May 2023, doi: https://doi.org/10.3390/su15118472.

[73] Θ. Γ. Παπούτσογλου, “A Cold Ironing Study on Modern Ports, Implementation and Benefits Thriving for Worldwide Ports,” Digital Library of NTUA, Athens, 2012. doi: https://doi.org/10.26240/heal.ntua.12134.

[74] Y. Peng, X. Li, W. Wang, K. Liu, X. Bing, and X. Song, “A Method for Determining the Required Power Capacity of an On-Shore Power System Considering Uncertainties of Arriving Ships,” *Sustainability*, vol. 10, no. 12, p. 4524, Nov. 2018, doi: https://doi.org/10.3390/su10124524.

[75] C. Faust, “Simplified Life Cycle Assessment of Onshore Power Supply for Cruise Ships,” Master of Science Thesis, WESTERN NORWAY UNIVERSITY OF APPLIED SCIENCES, 2021.

[76] J. Kizielewicz, “Onshore power supply–trends in research studies,” *Frontiers in energy research*, vol. 12, Mar. 2024, doi: https://doi.org/10.3389/fenrg.2024.1383142.

[77] L. Osipova and C. Carraro, “Shore power needs and CO2 emissions reductions of ships in European Union ports: Meeting the ambitions of the FuelEU Maritime and AFIR,” International Council on Clean Transportation (ICCT), 2023. Available: https://theicct.org/wp-content/uploads/2023/10/Shore-power-ships-EU-Fit-for-55-working-paper-24-v3.pdf

[78] D. Duffy and J. Bollerman, “Onshore power: simple questions with complex answers,” *Lr.org*, 2023, Available: https://www.lr.org/en/knowledge/horizons/june-2023/onshore-power-raises-simple-questions-with-complex-answers/

[79] K. Li and K. Du, “Research on Onshore Power Supply System in Port for Ships,” *IOP Conference Series: Earth and Environmental Science*, vol. 558, p. 052022, Sep. 2020, doi: https://doi.org/10.1088/1755-1315/558/5/052022.

[80] J. Williamsson, N. Costa, V. Santén, and S. Rogerson, “Barriers and Drivers to the Implementation of Onshore Power Supply—A Literature Review,” *Sustainability*, vol. 14, no. 10, p. 6072, May 2022, doi: https://doi.org/10.3390/su14106072.

[81] J. Kumar, L. Kumpulainen, and K. Kauhaniemi, “Technical design aspects of harbour area grid for shore to ship power: State of the art and future solutions,” *International Journal of Electrical Power & Energy Systems*, vol. 104, pp. 840–852, Jan. 2019, doi: https://doi.org/10.1016/j.ijepes.2018.07.051.

[82] “European Maritime Transport Environmental Report 2021,” *European Maritime Safety Agency; European Environment Agency*, 2021. https://www.eea.europa.eu/publications/maritime-transport/

[83] ABB, “Shore-To-Ship Power,” ABB, 2010.

[84] B. Καρακατσάνης, “Implementation of cold ironing in modern ports - Case study of cargo vessels,” Digital Library of NTUA, Athens, 2021. Available: https://dspace.lib.ntua.gr/xmlui/handle/123456789/54132

[85] OAR and US EPA, “Shore Power Technology Assessment at U.S. Ports,” *www.epa.gov*, May 25, 2023. https://www.epa.gov/ports-initiative/shore-power-technology-assessment-us-ports

[86] D. Gürer, “Pioneering Women in Computer Science,” *ACM SIGCSE Bulletin*, vol. 38, no. 1, Jun. 2002, doi: https://doi.org/10.1145/204865.204875.

[87] D. Crockford, *JavaScript : the Good Parts*. Sebastopol: O’Reilly Media, Inc., 2008.

[88] D. Malhotra and N. Malhotra, *Data Structures and Program Design Using Python*. Mercury Learning and Information, 2020.

[89] “Folium — Folium 0.1.dev1+g57e8eae documentation,” *python-visualization.github.io*. https://python-visualization.github.io/folium/latest/

[90] Pandas, “Python Data Analysis Library,” *Pydata.org*, 2018. https://pandas.pydata.org/

[91] “http — HTTP modules — Python 3.10.5 documentation,” *docs.python.org*. https://docs.python.org/3/library/http.html

[92] “socketserver — A framework for network servers,” *Python documentation*. https://docs.python.org/3/library/socketserver.html

[93] “webbrowser — Convenient Web-browser controller — Python 3.9.1 documentation,” *docs.python.org*. https://docs.python.org/3/library/webbrowser.html

[94] J. Grus, *DATA SCIENCE FROM SCRATCH : First Principles with python.* O’Reilly Media, 2019.

[95] J. Duckett, *Html & CSS : Design and Build Websites*. Indianapolis, In: John Wiley and Sons, 2014.

[96] E. Meyer and E. Weyl, *CSS: The Definitive Guide*. “O’Reilly Media, Inc.,” 2017.

[97] “Main Ports (Goods Traffic 1997-2023),” *Europa.eu*, 2023. https://emodnet.ec.europa.eu/geoviewer/

[98] “Ports and Infrastructure | European Alternative Fuels Observatory,” *alternative-fuels-observatory.ec.europa.eu*. https://alternative-fuels-observatory.ec.europa.eu/transport-mode/maritime-sea/ports-and-infrastructure

[99] IMO, “Fourth Greenhouse Gas Study 2020,” International Maritime Organization, 4 Albert Embankment, London SE1 7SR, 2020. Available: https://www.imo.org/en/ourwork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx

[100] MAN, “Compact MAN Diesel and Gas Engines as Auxiliary Engines | MAN Engines,” *www.man.eu*. https://www.man.eu/engines/en/products/marine/auxiliary-motors/auxiliary-motors.html

[101] Volvo Penta, “D16 Marine Engine - Genset | Volvo Penta,” *www.volvopenta.com*. https://www.volvopenta.com/marine/all-marine-engines/d16-mg-rc/

[102] Wärtsilä, “Wärtsilä 31 - The Most Efficient 4-stroke Marine Engine,” *Wartsila.com*. https://www.wartsila.com/marine/products/engines-and-generating-sets/dual-fuel-engines/wartsila-31

[103] IPCC, “The Sixth Assessment Report - Climate Change 2021: The Physical Science Basis,” Intergovernmental Panel on Climate Change, 2021. Available: https://report.ipcc.ch/ar6/wg1/IPCC_AR6_WGI_FullReport.pdf

[104] “Greenhouse Gas Emissions by Source Sector,” *Europa.eu*, 2024. https://ec.europa.eu/eurostat/databrowser/view/env_air_gge__custom_11185662/default/table?lang=en

[105] “Production of Electricity and Derived Heat by Type of Fuel,” *Europa.eu*, 2024. https://ec.europa.eu/eurostat/databrowser/view/NRG_BAL_PEH__custom_11185678/default/table?lang=en

[106] “Handbook on the external costs of transport,” European Commission, B-1049 Brussels, 2019. Available: https://publications.europa.eu/resource/cellar/e021854b-a451-11e9-9d01-01aa75ed71a1.0001.01/DOC_1