National Technical University of Athens

School of Naval Architecture and Marine Engineering

Division of Marine Engineering

Study for Power increase of local electrical grid in ports of European Economic Area (EEA) and United Kingdom (UK)

Postgraduate Thesis

of

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Abbreviations

Term	*Abbreviation*
ABS	*American Bureau of Shipping*
AC	*Alternating Current*
AE	*Auxiliary Engines*
AIS	*Automatic Identification System*
AMP	*Alternate Marine Power*
BDC	*Bottom Dead Centre*
BHP	*Break Horse Power*
BMEP	*Brake Mean Effective Pressure*
CFC	*Chlorofluorocarbons*
CH_4	*Methane*
CI	*Cold Ironing*
CII	*Carbon Intensity Indicator*
CMS	*Cable Management System*
CO	*Carbon Monoxide*
CO_2	*Carbon Dioxide*
DC	*Direct Current*
DCS	*Data Collection System*
DWT	*Deadweight*
ECA	*Emission Control Area*
EEA	*European Economic Area*
EEDI	*Energy Efficiency Design Index*
EEXI	*Energy Efficiency Existing Ship Index*
EF	*Emission Factor*
EMEP	*European Monitoring and Evaluation Programme*
ETS	*Emissions Trading System*
EU	*European Union*
GHG	*Greenhouse Gas*
GPS	*Global Positioning System*
GUI	*Graphical User Interface*
GWP	*Global Warming Potential*
H_2O	*Water*
HC	*Hydrocarbon*
HFO	*Heavy Fuel Oil*
HVSC	*High Voltage Shore Connection*
IAPP	*International Air Pollution Prevention*
ICCT	*International Council on Clean Transportation*
ICE	*Internal Combustion Engine*
IEC	*International Electrotechnical Commission*
IEEE	*Institute of Electrical and Electronics Engineers*
IFO	*Intermediate Fuel Oil*
IMO	*International Maritime Organization*
IPCC	*Intergovernmental Panel on Climate Change*
ISO	*International Organization for Standardization*
LDC	*Load Duration Curve*
LNG	*Liquefied Natural Gas*

LSFO	*Low Sulphur Fuel Oil*
LVSC	*Low Voltage Shore Connection*
MARPOL	*International Convention for the Prevention of Pollution from Ships*
MCR	*Maximum Continuous Rating*
MDO	*Marine Diesel Oil*
MEPC	*Marine Environment Protection Committee*
MGO	*Marine Gas Oil*
MRV	*Monitoring, Reporting and Verification*
NECA	*Nitrogen Emission Control Area*
NO_x	*Nitrogen Oxides*
O_3	*Ozone*
ODS	*Ozone-Depleting Substances*
OOP	*Object Oriented Programming*
OPS	*Onshore Power Supply*
PM	*Particulate Matter*
SECA	*Sulphur Emission Control Area*
SEEMP	*Ship Energy Efficiency Management Plan*
SO_2	*Sulphur Dioxide*
SOLAS	*International Convention for the Safety of Life at Sea*
SSE	*Shore Side Electricity*
SSP	*Shore-to-Ship Power*
TDC	*Top Dead Centre*
TEN-T	*Trans-European Transport Network*
UK	*United Kingdom*
UN	*United Nations*
UNFCCC	*United Nations Framework Convention on Climate Change*
US	*United Nations*
UV	*Ultraviolet*
VLCC	*Very Large Crude Carrier*
VLSFO	*Very Low Sulphur Fuel Oil*
VOC	*Volatile Organic Compound*
WHO	*World Health Organization*

Abbreviations and Letter Symbols for Units

Unit	*Abbreviation*
ampere	A
cubic meter	m^3
degree Celsius	℃
gram	g
gross tonnage	GT
hertz	Hz
hour	h
joule	J
kilogram	kg
kilojoule	kJ
kilometer	km
kilopascal	kPa
kilovolt	kV
kilowatt	kW
kilowatthour	kWh
megajoule	MJ
megawatt	MW
meter	m
millimeter	mm
millisecond	ms
nautical mile	nm
newton	N
ohm	Ω
pound per square inch	lbf/in^2
revolution per minute	rev/min
second	s
tesla	T
tonne	t
volt	V
voltampere	VA
watt	W

Abstract

Shipping is an important economic sector of a state, through which the social and economic development of a country is directly affected. It consists of various economic activities such as transport of goods and passengers, fishing, leisure transport, etc. Transport is a particularly important economic pillar of the international economy, as they contribute to the movement of trade, foreign exchange and cargo to other countries, offer thousands of jobs directly or indirectly related to shipping, and provide an increase in the country's national income.

Transportation in the economic or commercial sectors is generally called any movement of passengers or material goods from one place to another. Usually, these transfers are made for a fee, the so-called fare. In general, transport methods can be divided into three large categories: land, air and sea. The last category of transport, maritime transport, comprises the largest category in the field of transport, in terms of the volume of transport but also the possibility of transporting heavy cargo. This constitutes the category of maritime transport, as the most advantageous economical way of transporting goods, considering the distances of sea voyages and their carrying capacity.

Maritime transport emits around 940 million tonnes of CO_2 annually and is responsible for about 2.5% of global greenhouse gas (GHG) emissions [1]. If mitigating measures are not implemented quickly, these emissions are expected to rise dramatically. According to the ***Third IMO GHG assessment***, shipping emissions might rise by 50 percent to 250 percent by 2050 under a business-as-usual scenario, undermining the Paris Agreement's goals.

Sector of Maritime transport and all its related activities, mainly through the ***International Maritime Organization (IMO)***, is trying to limit emissions of hazardous greenhouse gases, sulphur oxides (SO_x), nitrogen oxides (NO_x) and particulate matter (PM) produced associated with ships. These substances make a great contribution in environmental pollution and are linked to climate change. All of these are derivatives of combustion in diesel engines which propel ships or generate energy for the different functions of the ship.

Polluting internal combustion engines have a direct impact on inhabitants' quality of life and health in towns with big ports. Yes, there is economic growth and job opportunities in port communities, but the health consequences of the gases released by ships can be significant. In coastal cities, the need to control these pollutants is greater due to the already "heavy" urban atmosphere created by cars and motor vehicles.

The energy required by ship in ports, the so-called hoteling condition (otherwise berthing condition), is a big problem in local communities, as auxiliary generators use fossil fuels to generate electricity. As a result, it adds to the already filthy environment in locations with ports. The technique of supplying on-shore electric power to vessels at berth is known as ***Cold Ironing (CI)***. As a result, vessels' electricity consumption while berthing is satisfied by connecting them to the on-shore power grid. As a result, the vessels' auxiliary engines, which normally produce electricity to keep the vessel running, are turned off after berthing, resulting in reduced emissions due to the engines not burning fuel [2].

The present study aims to contribute to the effort to reduce pollution of the planet from the exhaust gases and at the same time in the automation of the naval industry. Thus, a program that presents the energy needs of ports in Europe (Including overseas territories that belong to European countries,

United Kingdom, Iceland and Norway), estimating cost of developing the port electricity infrastructure and pros and cons of investing resources in ports' grid expansion.

The program is a continuation of another diploma on subject: ***"Issues of Electricity in Ships and Ports"*** [3].

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1. Introduction

1.1. Background of the Study

Because the atmosphere is more transparency to visible radiation from the sun than to infrared radiation emitted from the planet's surface, the Greenhouse Effect traps the sun's warmth in the planet's lower atmosphere.

The average rise in temperature near the earth's surface is known as Global Warming, whereas the Greenhouse Effect refers to the increased concentration of gases in the earth's atmosphere.

Primary greenhouse gas is CO_2, which the vast majority of anthropogenic CO_2 emissions come from combustion of fossil fuels.

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).

The marine diesel engine is certainly nothing new; its roots go back to the early 1900s when they were used to power ships and submarines. Early diesel engines were considered a logical replacement for steam engines.

The shipping industry's emissions of air pollutants and greenhouse gases have grown dramatically in the previous two decades, adding to the threat of climate change. Gaseous pollutants released by shipping are damaging to human health, increasing the prevalence of heart disease and respiratory disorders, in addition to the disastrous impacts on the environment.

For the near future, there will be no lack of oil or gas in the ground, and if future usage declines, it will not be due to supply issues. 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.

Despite being one of the least carbon-intensive modes of transport, shipping accounted for 2.9% of global anthropogenic CO_2 emissions in 2018 [4]. With increasing pressure from governments, regulatory organizations, and consumers, the shipping sector is experiencing a "green revolution", rethinking how to carry millions of tonnes of goods across seas without contributing to global emissions.

Despite a reduction in emissions activity owing to the coronavirus pandemic in 2020, shipping is predicted to rise, driven by increased demand for raw materials and container transportation.

Through automation and digitalization, the marine sector has been in a constant state of evolution. Automation refers to a group of technologies that reduce the need for humans to intervene in operations, such as process control systems, safety systems, power manager systems, propulsion control systems, and other monitoring or control systems. These are all examples of marine automation systems.

Tools such as programming and automation, either in various ship systems or in a variety of applications directly or indirectly related to shipping, will further help in understanding and giving the necessary importance of the basic problems that prevent pollution-free shipping.

While electric propulsion for large displacement vessels appears to be experiencing some difficulties, the use of Cold-Ironing (or otherwise Onshore Power Supply) is a solution that should be implemented as soon as possible.

This research aims to analyse the alarming problem of the emission of pollutants from shipping in ports, to give solutions to solve or even reduce the phenomenon and through a literature review to describe the way in which a program was developed that contains important information for all ports in European Economic Area[1] (EEA) and United Kingdom (UK).

1.2. Explanation of the Issues and the Objectives

Essentially, this postgraduate diploma is an extension of the diploma named ***"Issues of Electricity in Ships and Ports"*** [3]. An interactive map program was originally developed in that diploma, thus in this postgraduate diploma the interactive map is extended, with respect to features that the map offers.

The goal of this thesis is to give emphasis on the severe problems caused by the wastefulness use of fossil fuels by ships at berth and at the same time present data of the emissions produced, the consequences, been both economical and health-related for societies and estimate an expected expense for electrical grid growth, in each port.

Cooperation with national and international laws that specify the requirements for defining and designing a novel technological solution for clean auxiliary power generation.

Forecast emissions, if the "Fit for 55" [2] (see ***Chapter 5.2***) legislative package is successive, to compare the results with present situation and guide the maritime industry in the EU in the direction of decarbonisation.

Refer all forthcoming EU directives, from the perspective of the ports, for the implementation of alternative fuel infrastructure.

Consider the societal benefits of reducing ship emissions in ports, while approaching the expenditure of investments like Onshore Power Supply (OPS) in ports.

An interactive map of Europe and its ports was designed up with a lot of useful information for each port.

This map is composed of different layers, which each layer contains data about port activity.

[1] The EEA includes EU countries and also Iceland, Liechtenstein and Norway.
[2] On 14 July 2021, the European Commission launched its "Fit for 55" package of proposals intended to reduce the EU's total GHG emissions by 55% by 2030.

1.3. Composition of the Study

APPENDIX I

The composition of this study is divided in two appendixes, ***Appendix I*** which is concerns mostly the theoretical background of the study and ***Appendix II***, mainly referred to the most practical part of the study. The whole research would be arranged in the following form:

- ***Chapter 2 (Internal Combustion Engines)***

The operation of Internal Combustion Engines, the fuel they use, and other difficulties with this existing technology employed in typical ships are all investigated in this chapter.

- ***Chapter 3 (Auxiliary Engines)***

Electric generator technology, principles of operation and consequences auxiliary engines have to ports are all covered in Chapter 3.

- ***Chapter 4 (Human and Environment)***

This chapter refers to the detailed analysis of the main gaseous emissions in international shipping and the effects of gaseous emissions on the human-environment ecosystem.

- ***Chapter 5 (Regulations and Legislation by the Competent Institutions and Organizations)***

Chapter 4 deals with the issue of regulations and legislation by the competent authorities, where the international and local regulatory framework for dealing with the issue is developed.

- ***Chapter 6 (Onshore Power Supply (OPS))***

Cold Ironing technology will be discussed in this specific chapter, mentioning the technology's advantages and obstacles to be overcome, in order to have notable impact on the environment.

APPENDIX II

- ***Chapter 7 (Development of Interactive Map Program)***

In the 7^{th} Chapter, will be explained how the interactive program map was constructed using a programming language, how data was imported, and the different levels were generated. There will be a description of how the program works, its possibilities and the simplicity of how a user can utilize the program.

- ***Chapter 8 (Conclusions)***

Finally, conclusions on map program layers and recommendations for future progress are presented.

APPENDIX I

2. Internal Combustion Engines

The examination and presentation of internal combustion engines, with an emphasis on the Diesel Engines that dominate the shipping industry, is required for the subsequent explanation of analysing in further emissions and its impact on humans and environment. The acronym ICE (Internal Combustion Engines) has been used to name this group of engines.

2.1. Historical Background of Diesel Engines

The modern diesel engine came about as the result of the internal combustion principles first proposed by Sadi Carnot in the early 19th century. German mechanical engineer and inventor Rudolf Diesel, applied Sadi Carnot's principles into a patented cycle or method of combustion that has become known as the "Diesel" cycle [5].

Dr. Diesel's first engine ran on coal dust and used a compression pressure of 1,500 $[lbf/in^2]$[3] to increase its theoretical efficiency. Also, his first engine did not have provisions for any type of cooling system. Consequently, between the extreme pressure and the lack of cooling, the engine exploded and almost killed its inventor. After recovering from his injuries, Diesel tried again using oil as the fuel, adding a cooling water jacket around the cylinder, and lowering the compression pressure to approximately 550 $[lbf/in^2]$. This combination eventually proved successful.

Approximately two decades after Diesel's first engine, the *MS Selandia*, typically considered as the world's first oceangoing motor vessel [6], entered into service, the diesel engine has nearly complete domination in merchant ship propulsion sectors. The steam turbine has long been replaced by low and medium speed engines on large Container ships, Bulk carriers, VLCCs and Cruise liners in mainstream sectors.

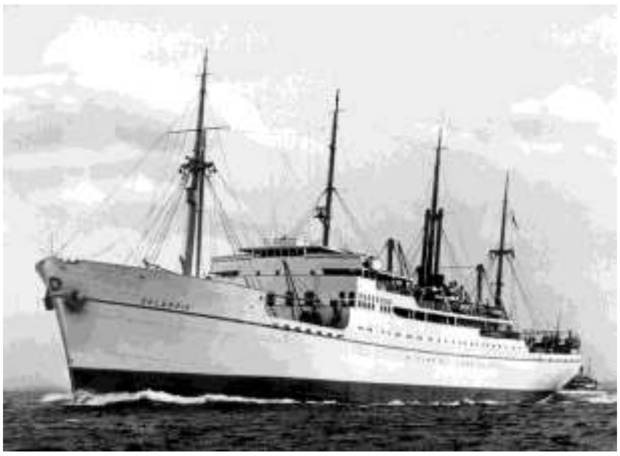


Figure 2.1: MS Selandia, the most advanced ocean-going diesel motor ship in its time

[3] $1\ [lbf/in^2] = 6.894\ [kPa]$

2.2. Operating Principles of Internal Combustion Engines

By far the most prevalent type of engine or prime mover is the reciprocating internal combustion engine. The normal goal, like with most engines, is to generate a high work output while maintaining high efficiency [7].

The two basic types of internal combustion engines are:

- ***Spark Ignition (SI)*** engines, where the fuel is ignited by a spark,
- ***Compression Ignition (CI)*** engines, in which the fuel ignites spontaneously due to an increase in temperature and pressure during compression.

The spark ignition engine is also known as the petrol engine (because of the fuels it uses) or the "Otto" engine, because of its German creator Nicolaus Otto. The Compression Ignition engine is also referred as "Diesel" engine, taken its name, as mentioned before, from its inventor Rudolf Diesel.

Fuel ignites in the combustion chamber (either with Spark Ignition or Compression Ignition), creating a combustion force that pulls the piston down, in other words combustive gases do the work in the cylinder. The rotational motion of the crankshaft is converted from the reciprocating motion of the piston owing to combustive gas forces. The connecting rod and crank mechanism are used to accomplish this.

2.2.1. Main Diesel Engine Categories

One of the places where diesel engines play an important role is the shipping industry. There are several ways of classification of marine diesel engines based on various parameters and two (2) of these classifications are as follows:

- <u>Operating cycle:</u> Two-stroke or four-stroke engine,
- <u>Speed:</u> Slow, medium or fast speed.

These main categories will be examined moreover in the following lines.

2.2.1.1. Operating Cycle: Two-Stroke Engine

There are two basic types of diesel engines, two-stroke and four-stroke [5]. An understanding of how each cycle operates is required to understand how to correctly operate and maintain a diesel engine.

In two-stroke engines a period of operation lasts only one rotation (360 degrees crankshaft angle) i.e., includes 2 piston strokes.

The operation cycle of a two-stroke engine in a nutshell, is consisted of:

1) <u>Compression:</u> The piston moves toward the Top Dead Centre (TDC) 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 TDC, the fuel is injected into the air of high temperature and pressure so that it sprinkles, evaporates and the combustion begins.

2) <u>Detonation:</u> The piston moves toward the Bottom Dead Centre (BDC) driven by the products of combustion factor work while as it approaches the BDC it also reveals the valves in order to start the exchange of gases.

It should be noted that in two-stroke engines instead of valves can be used ports, 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 exhaust port.

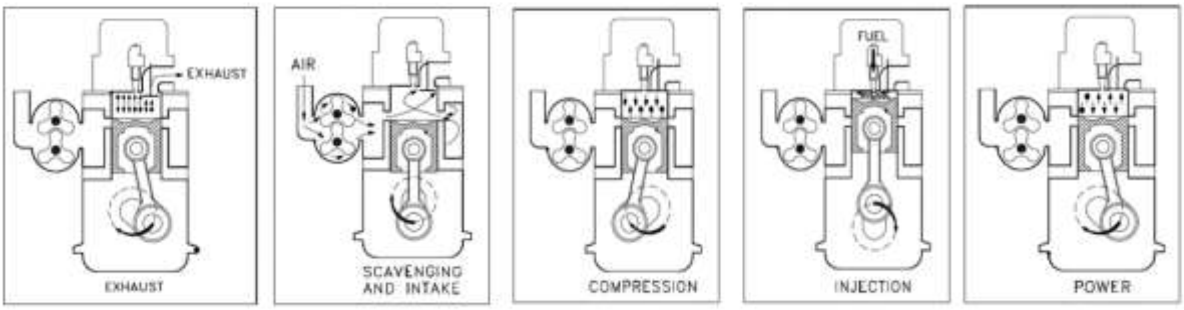


Figure 2.2: Typical Two-Stroke cycle in a Diesel Engine [5]

Operating Cycle: Four-Stroke Engine

With Similar way, a period of operation in four-stroke engines lasts two rotations (720 degrees crankshaft angle), in other words, it includes 4 full piston strokes.

The four operating times of a four-stroke engine are as follows:

1) <u>Intake:</u> The piston moves towards the BDC and the cylinder is filled with air through the open intake valve.
2) <u>Compression:</u> The piston moves towards the TDC while the valves are closed so that the air is compressed inside the cylinder and increase its temperature which is far above the auto-ignition temperature of the fuel.
3) <u>Combustion-Denotation:</u> The fuel has been injected into the combustion chamber, just before the TDC, resulting in dripping and evaporation of fuel, when combustion begins. Due to the combustion, there is an abrupt rise in pressure which causes the piston to move towards the BDC and produce work.
4) <u>Extraction</u>: The piston moves towards the TDC while the exhaust valve is open resulting in the extrusion of the exhaust gas into the exhaust.

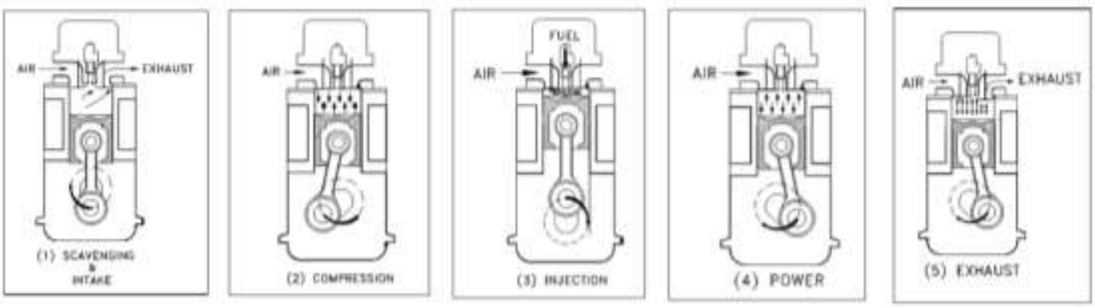


Figure 2.3: Typical Four-Stroke cycle in Diesel Engine [5]

2.2.1.2. Engine Speed: Slow speed Engines

Another way that Diesel engines can be categorised is from the speed developed in the crankshaft. The crankshaft transforms the linear motion of the pistons into a rotational motion that is transmitted to the load. The speed clarification is very important for Diesel marine engines, because this ultimately determines the engine power range, whether a reduction gearbox will need to be installed, to reduce the speed of the main engine and the special fuel consumption which is a basic parameter of the emission produced from an engine.

Slow speed Diesel Engines usually have a top speed up to 250 $[rev/min]$, although the working range of most is between 80÷140 $[rev/min]$. They are usually two-stroke, with a large piston travel to piston diameter ratio and the number of cylinders most of the times are ranging from 4 to 12. The maximum Brake Mean Effective Pressure (BMEP) is up to 20 $[bar]$ and the specific fuel consumption is about 165 $[g/kWh]$. They are capable of developing power up to 109,000 $[BHP]$. Within the shipping industry, these engines are used exclusively for primary propulsion purposes and constitute the largest percentage of installed power, and hence largest fuel consumption of all engines, in the industry.

2.2.1.3. Engine Speed: Medium speed Engines

Medium speed Diesel engines often have a speed range of 400÷900 $[rev/min]$ and are operated in a four-stroke cycle. They are smaller in volume and weight compared to two-stroke slow-speed diesel Engines of the same power, even if we take into account the need for a gearbox. The maximum BMEP is up to 25 $[bar]$ and has a specific fuel consumption of 185 $[g/kWh]$. They are usually arranged in 5÷9 cylinders in a row, or 8÷12 cylinders in a "V" type arrangement and can develop up to 47,500 $[BHP]$. Engines of this type can be used both for main propulsion and for auxiliary purposes in the marine industry. For propulsion purposes these engines can be used in multi-engine installations and will normally be coupled to the propeller via a gearbox.

2.2.1.4. Engine Speed: High speed Engines

This type of engines is used to describe marine Diesel engines with an operating speed of more than 1,000 $[rev/min]$. They are all four-stroke, supercharged if their power is greater than 125÷250 $[BHP]$. They are small engines used in fishing boats or for mobile emergency generators and fire pumps. There is a wide variety of dimensions, speeds and manufacturers. High-speed engines are mainly used as main propulsion engines in smaller vessels. Their power, for narrow limits operation, for the larger engines reaches up to about 6,000 $[BHP]$ per engine.

In ***Table 2.1*** below are given all the above information about speed categorization [8].

Type of Engine	**Speed [rev/min]**	**Power [BHP]**	**Special Fuel Consumption [g/kWh]**
Slow Speed	60÷250	2,000÷109,000	165
Medium Speed	400÷900	200÷47,500	185
High Speed	1,000÷4,000	up to 6,000	185

Table 2.1: Marine Diesel Engine's characteristics classified by speed

2.2.2. Characteristics of Marine Two-Stroke Engines

MAN ES, Mitsubishi Heavy Industries, and *Winterthur Gas & Diesel* are the only three engine designers left in the low-speed two-stroke engine market today. They all follow the same ideas when designing low-speed two-stroke engines: All modern slow speed engines share some common characteristics: they are two-stroke, have a cross head, are turbocharged and uniflow scavenged, according to Kyrtatos [9].

Large crosshead two-stroke engines are available in a variety of sizes, speeds, and power outputs. Before the introduction of the IMO EEDI index (see ***Chapter 5.1.1.1***) to reduce CO_2 emissions, these engines used to be bigger, but nowadays there is a trend for downsizing [10]. The piston bores are in the range of 300÷950 $[mm]$, and strokes from 1.3÷3.7 m. The number of engine cylinders is 5 to 12. The Maximum Continuous Rating (MCR) speeds are between 60÷250 revolutions per minute, with corresponding power outputs in the range from 2,000 $[kW]$ to 82,000 $[kW]$.

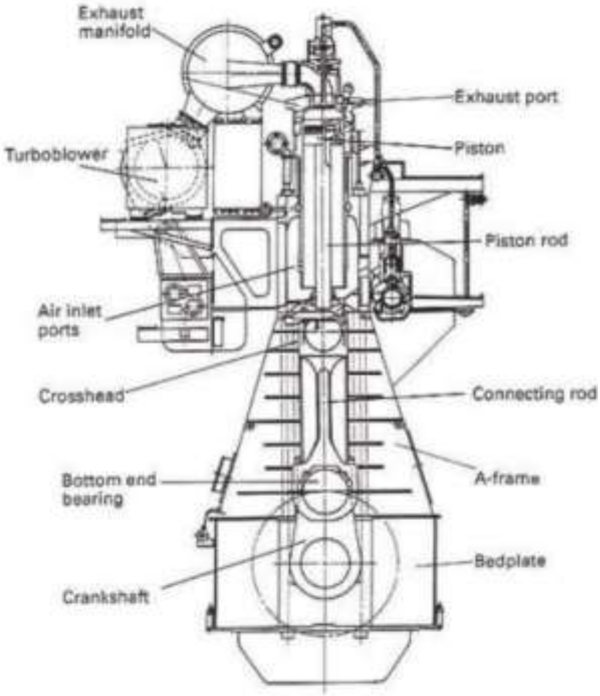


Figure 2.4: Marine Diesel Engine main components [11]

2.2.3. Comparison of Four-Stroke and Two-Stroke Marine Engines

As stated before, the main difference between a four-stroke engine and a two-stroke engine is that a four-stroke engine goes through four stages, or two complete revolutions, to complete one power stroke, while a two-stroke engine goes through 2 stages, or one complete revolution, to complete one power stroke.

While the two-stroke engine consumes fuel per two strokes, as opposed to the per four strokes of the four-stroke engine, it also has the advantage of being able to burn low-grade fuel oil [12]. In such circumstances, a significant cost reduction may be implemented, making the ship more economical, which is a significant benefit for merchant ships.

Assume two identical engines, one two-stroke and one four-stroke, with equal combustion volumes, both operating on the same rounds per minute and hence having the same angular speed. Theoretically, two-stroke should provide double the power of four-stroke, because it performs double cycles from four-stroke at the same time. This is not happening, however, due to clean air entering into the combustion space and helping push out the exhaust gasses in a process called scavenging.

Scavenging takes some time and space to occur, thus reducing the volume available for compression. Reduced volume means reduced work (W_i $[J]$) for each cylinder, since the following applies:

$$W_i = \oint p \, dV$$

Where:

- p $[Pa]$ is pressure in a cylinder,
- V $[m^3]$ is volume.

Reduced work means reduced engine power, since:

$$P_i = z \cdot W_i \cdot \frac{n}{30 \cdot k}$$

Where:

- z is number of cylinders,
- n $[rev/min]$ is number of revolves per minute,
- $k = 2$ for a two-stroke engine or $k = 4$ for a four-stroke engine.

The index i refers to the "Indicated" values, so they are not taken into account the losses of pressure and power due to friction that occur during the movement of moving parts of the ICE.

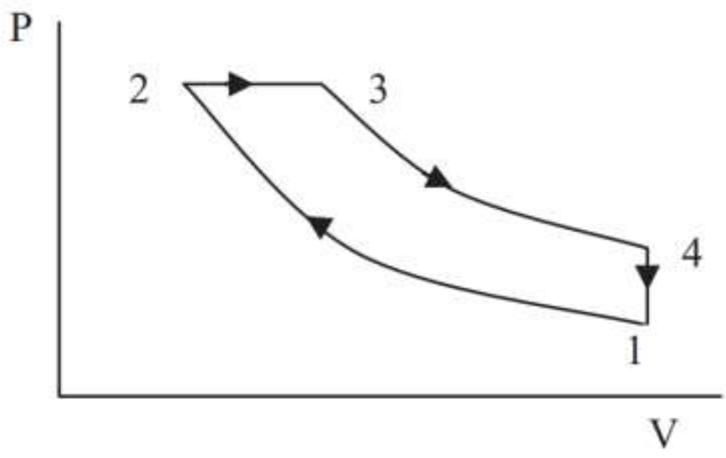


Figure 2.5: Ideal Diesel Cycle p-V diagram [14]

In practice, the area of the p-V diagram determines how much work each cylinder produces, as seen in ***Figure 2.5***, for an ideal Diesel cycle [13].

Equation above is the indication of Net Work that is equal to the area inside the closed loop of the p-V diagram [14] as depicted in ***Figure 2.5***, and this is because of the following: Riemann sum of work done on the substance due to expansion, minus the work done to re-compress.

In an ideal Diesel Cycle, all the processes are all reversible and are as follows:

- 1-2 isentropic compression of air through a volume ratio V_1/V_2,
- 2-3 addition of heat Q_{23} at constant pressure while the volume expands through a ratio V_2/V_3,
- 3-4 isentropic expansion of air to the original volume,
- 4-1 rejection of heat Q_{41} at constant volume to complete the cycle.

Ships that use two-stroke engines instead of four-stroke engines can load more cargo with the same amount of power because two-stroke engines are lighter and have a greater power-to-weight ratio, according to [12]. Because ships are frequently used to transport large materials, the two-stroke engine vessels would have a significant benefit. It should be emphasized, however, that a four-stroke engine has a greater maneuverability than a two-stroke engine. There's also a big difference between the expense of installing a two-stroke engine and the cost of maintaining a four-stroke engine. However, when all aspects are considered, the two-stroke engine is the definite recommendation for merchant and cargo ships.

2.3. Diesel Engines Fuel

Because of their economic efficiency, diesel engine-powered ships capable of using residual fuel oil gained popularity, and by the second half of the 1960s, motor ships had surpassed steamships in terms of both numbers and gross tonnage. Motor ships accounted for 98% of the global fleet at the turn of the century [15].

The generally accepted theory is that crude oil was formed over millions of years from the remains of plants and animals that lived in the seas. As they died, they sank to the seabed, were buried with sand and mud and became an organic-rich layer. Steadily, these layers piled up, tens of meters thick. The sand and mud became sedimentary rock, and the organic remains became droplets of oil and gas. Oil and gas passed through the porous rock and were eventually trapped by an impervious layer of rock, collecting at the highest point, as specified by Spreutels and Vermeire [15].

It is very important for the reader to become familiar with terminology of Marine Fuels. In general, the following applies:

- "Distillate Fuels" are commonly called "Gas Oil" or "Marine Gas Oil",
- "Residual Fuels" are called "Marine Fuel Oil" or "Residual Fuel Oil",
- "Intermediate" types are called "Marine Diesel Oil" or "Intermediate Fuel Oil".

While the term "Diesel fuel" for land-based automobile and truck use is 100% distillate, in the marine industry Marine Diesel Oil is the blend of distillate and residual oils (Intermediate types). The 100% distillate type fuel in the marine industry is the Marine Gas Oil (implying that it was boiled into a gas and then condensed into a liquid).

2.3.1. Types and Characteristics of Marine Fuel

According to the relevant ***ISO 8217:2017*** [16], marine fuels are separated into two categories:

- Distillate fuels,
- Residual fuels.

There are seven different types of distillate fuels, one of which is for emergency diesel engines and six types for residual fuels.Residual Fuel

The term Residual Fuel, or also known as Heavy Fuel Oil (HFO), are used to describe both a category of marine fuels and certain marine fuel oil blends. HFOs (as a category of marine fuels) are created from residuum, the tar-like sludge that is the end product of upgrading crude oil. The quality and chemical makeup of HFO is highly variable, depending on its components and the way they are blended to achieve the desired viscosity and flow characteristics [17].

HFO is a black, viscous fluid, particularly difficult to dispense and use. Over time, HFO has been used in shipping, such as the continuous operation of the main engines as the ship travels and the electric motors and boilers operation in the port, creates great savings in operating costs by consuming a cheaper fuel. Also, since the ships are equipped with all the auxiliary systems and installations required to operate on such fuel (Purifiers, Heaters), there are no operational reasons to prefer another better-quality liquid fuel. However, with the gradual adoption of regulations for better quality fuel, the use of distillate fuels is gaining ground [18].

So, the main source of HFO is the part of Crude Oil that will not distil up to 360 [℃] [19]. It is often mixed with lighter products, such as Marine Gasoil or Marine Diesel Oil, in order to be able to meet the operational requirements. The resulting blends are also referred to as Intermediate Fuel Oils (IFO) or Marine Diesel Oil, which belong to the HFO category. A blend can be classified to the HFO category, if there is predominance of heavy fuel oil.

“Marine Diesel Oil” is sometimes used synonymously with the term “Intermediate Fuel Oil”. In the strict sense, the term Marine Diesel Oil mainly refers to blends with a very small proportion of HFO. This type of Marine Diesel Oil (MDO) is therefore also classified as a distillate in some textbooks, which means it is also categorized as a middle distillate.

The main factor that will determine, how IFOs are classed and named, is kinematic viscosity. IFO 180 and IFO 380 are the most often used varieties, having viscosities of 180 $[mm^2/s]$ and 380 $[mm^2/s]$ at 50 [℃], respectively. It also contains increased levels of pollutant gases compared to other fuels, with sulphur as the main representative.

Heavy Fuel Oil use as a fuel, stems from the fact that:

- It accounts for nearly half quantity of all crude oil,
- HFO is much cheaper than diesel oil,
- It may be used in a variety of diesel engines.

According to ISO 8217:2017 [16], the typical specifications and characteristics of HFOs in shipping are reflected in the ***Table 2.2***.

Characteristic	**Unit**	**Limit**	**Category ISO -F-**											**Test method reference**
			RMA	**RMB**	**RMD**	**RME**	**RMG**				**RMK**			
			10	**30**	**80**	**180**	**180**	**380**	**500**	**700**	**380**	**500**	**700**	
Kinematic viscosity at 50 °C	mm²/s	Max	10.00	30.00	80.00	180.0	180.0	380.0	500.0	700.0	380.0	500.0	700.0	ISO 3104
Density at 15 °C	kg/m³	Max	920.0	960.0	975.0	991.0	991.0				1010.0			ISO 3675 or ISO 12185; see 6.1
CCAI	–	Max	850	860	860	860	870				870			see 6.2
Flash point	°C	Min	60.0	60.0	60.0	60.0	60.0				60.0			ISO 2719; see 6.4
Hydrogen sulfide	mg/kg	Max	2.00	2.00	2.00	2.00	2.00				2.00			IP 570; see 6.5
Acid number	mg KOH/g	Max	2.5	2.5	2.5	2.5	2.5				2.5			ASTM D664; see 6.6
Total sediment – Aged	mass %	Max	0.10	0.10	0.10	0.10	0.10				0.10			ISO 10307-2; see 6.9
Carbon residue – Micro method	mass %	Max	2.50	10.00	14.00	15.00	18.00				20.00			ISO 10370
Pour point (upper) winter	°C	Max	0	0	30	30	30				30			ISO 3016
Pour point (upper) summer	°C	Max	6	6	30	30	30				30			
Water	volume %	Max	0.30	0.50	0.50	0.50	0.50				0.50			ISO 3733
Ash	mass %	Max	0.040	0.070	0.070	0.070	0.100				0.150			ISO 6245
Vanadium	mg/kg	Max	50	150	150	150	350				450			IP 501, IP 470 or ISO 14597; see 6.14
Sodium	mg/kg	Max	50	100	100	50	100				100			IP 501, IP 470; see 6.15
Aluminium plus silicon	mg/kg	Max	25	40	40	50	60				60			IP 501, IP 470 or ISO 10478; see 6.16
Used lubricating oil (ULO): – Calcium and zinc; or – Calcium and phosphorus	mg/kg	–	Calcium > 30 and zinc > 15 or Calcium > 30 and phosphorus > 15											IP 501 or IP 470, IP 500; see 6.17

Table 2.2: Requirements for Marine Residual Fuels [16]

2.3.1.1. Distillate Fuel

Distillates are all those components of crude oil that evaporate in fractional distillation and are then condensed from the gas phase into liquid fractions. Marine Gas Oil (MGO) describes marine fuels that consist exclusively of distillates.

MGO was the first fuel that could be used in diesel engines due to its properties and in particular its low viscosity, as a result of which it is possible to better disperse the fuel molecules, as well as the high degree of purity that ensured a combustion process without harmful residues [19].

Distillate Fuels are having boiling points ranging from 200 to 360 degrees Celsius. It has the benefit of not requiring additional processing after distillation, allowing it to be utilized in the form and qualities gained from the distillation process.

Marine Gas Oil is produced with varying degrees of sulphur content. The regulation limits fuels with a sulphur content of up to 0.10% to be used within the Emission Control Areas (ECAs) from January 1st, 2015 and a sulphur content of up to 0.50% to be used globally from January 1st, 2020. As defined in ***Regulation 2.9 of Annex VI*** [20], SO_x emission controls apply to all fuel oil used in combustion equipment and devices on board unless an approved exhaust gas cleaning system, such as a scrubber system, is installed. Alternatively, vessels may choose to utilize low sulphur content MGO or 0.10% HFO specifically developed for use in ECAs.

The above feature ranks MGO among the best, but at the same time, the most expensive fuels currently used in internal combustion engines. This increased cost leads to the use of this type of fuel when there are special reasons that make it impossible to use HFO products. These reasons are:

- Need for high rotation speeds,
- Existence of low horsepower,
- Need to adapt the combustion process to the requirements of the cargo (e.g., handling of a vessel or ship) usually during special operations where a rapid change of engine power is required, with MGO being the only fuel type that can respond efficiently in that requirement.

Based on ISO 8217:2017 [16], the typical specifications and characteristics of MGOs in shipping are given in the ***Table 2.3***.

Characteristic		Unit	Limit	Category ISO -F- DMX	DMA	DFA	DMZ	DFZ	DMB	DFB	Test method(s) and references
Kinematic viscosity at 40 °C		mm^2/s	Max	5,500	6,000		6,000		11,00		ISO 3104
			Min	1,400	2,000		3,000		2,000		
Density at 15 °C		kg/m^3	Max	–	890.0		890.0		900.0		ISO 3675 or ISO 12185; see 6.1
Cetane index		–	Min	45	40		40		35		ISO 4264
Sulfur		mass %	Max	1.00	1.00		1.00		1.50		ISO 8754 or ISO 14596, ASTM D4294; see 6.3
Flash point		°C	Min	43.0	60.0		60.0		60.0		ISO 2719; see 6.4
Hydrogen sulfide		mg/kg	Max	2.00	2.00		2.00		2.00		IP 570; see 6.5
Acid number		mg KOH/g	Max	0.5	0.5		0.5		0.5		ASTM D664; see 6.6
Total sediment by hot filtration		mass %	Max	–	–		–		0.10		ISO 10307-1; see 6.8
Oxidation stability		g/m^3	Max	25	25		25		25		ISO 12205
Fatty acid methyl ester (FAME)		volume %	Max	–	–	7.0	–	7.0	–	7.0	ASTM D7963 or IP 579; see 6.10
Carbon residue – Micro method on the 10% volume distillation residue		mass %	Max	0.30	0.30		0.30		–		ISO 10370
Carbon residue – Micro method		mass %	Max	–	–		–		0.30		ISO 10370
Cloud point	winter	°C	Max	–16	report		report		–		ISO 3015; see 6.11
	summer	°C	Max	–16	–		–		–		
Cold filter plugging point	winter	°C	Max	–	report		report		–		IP 309 or IP 612; see 6.11
	summer	°C	Max	–	–		–		–		
Pour point (upper)	winter	°C	Max	–	– 6		– 6		0		ISO 3016; see 6.11
	summer	°C	Max	–	0		0		6		
Water		volume %	Max	–	–		–		0,30		ISO 3733
Ash		mass %	Max	0.010	0.010		0.010		0.010		ISO 6245
Lubricity, corrected wear scar diameter (WSD) at 60 °C		µm	Max	520	520		520		520		ISO 12156-1

Table 2.3: Requirements for Marine Distillate Fuels [16]

2.4. Combustion in Diesel Engines

2.4.1. Geometrical Characteristics of Diesel Engines

Several geometrical characteristics must be computed in order to represent the in-cylinder combustion. The geometrical relationships for ICEs were based on *John B. Heywood* [21] and are presented in detail below.

At first, the Compression Ratio (symbolized by r_c) is displayed, which is the ratio between the maximum and minimum cylinder volumes. To put it another way, it's the ratio of the combustion chamber volume when the piston is at Bottom Dead Center (BDC) to the volume when the piston is at Top Dead Center (TDC). It's one of an engine's most essential features, and it's computed using the formula below:

$$r_c = \frac{maximum\ cylinder\ volume}{minimum\ cylinder\ volume} = \frac{V_d + V_c}{V_c}$$

Where:

- V_d $[m^3]$ is displayed or swept volume,
- V_c $[m^3]$ is the clearance volume.

Typical values of r_c are ranging from 10:1 to 12:1 for marine diesel engines.

As it can be seen in ***Figure 2.6***, the in-cylinder volume (V $[m^3]$) constantly changes and can be mathematically expressed by the following formulas:

$$V = V_c + \frac{\pi B^2}{4} \cdot (l + a - s)$$

Where:

- B $[m]$ is the bore diameter,
- l $[m]$ is the connecting rod length,
- a $[m]$ is the crank radius,
- s $[m]$ is the distance between the crank axis and the piston pin axis, and is given by:

$$s = a \cdot \cos(\theta) + \sqrt{(l^2 - a^2 \cdot \sin{(\theta)}^2}$$

Where θ $[rad]$, defined as shown *in **Figure 2.6***, is called the crank angle.

Ratio (R) of connecting rod length to crank radius is given by:

$$R = \frac{l}{a}$$

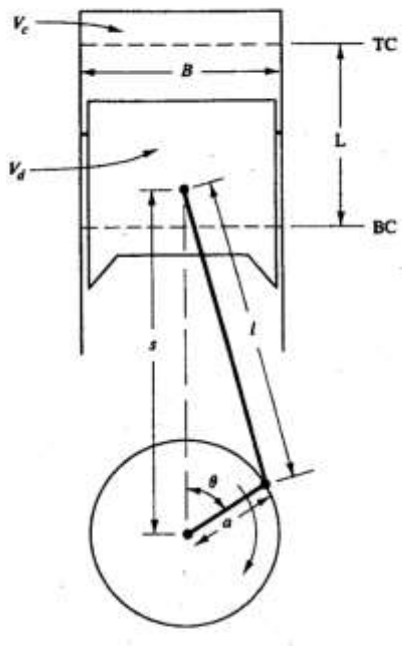


Figure 2.6: Geometry of cylinder, piston, connecting rod and crankshaft [21]

In addition, the stroke and crank radius are related by the following expression:

$$L = 2a$$

Where L $[m]$ is the stroke distance.

2.4.2. Fuel and Air ratios

In order to achieve combustion, which is a high-temperature exothermic redox chemical process that creates oxidized, generally gaseous compounds in a mixture known as smoke, liquid fuel is injected into compressed charge in order to conclude into fuel evaporation and mixing with the hot air. Both the air mass flow rate ma and the fuel mass flow rate are routinely monitored during engine testing. When determining engine operating conditions, the ratio of these flow rates is useful, given by the following:

$$AFR = \frac{\dot{m}_a}{\dot{m}_f}$$

$$FAR = \frac{\dot{m}_f}{\dot{m}_a}$$

Where:

- $\dot{m}_a$ $\left[\frac{kg}{s}\right]$ is the mass flow rate of air,
- $\dot{m}_f$ $\left[\frac{kg}{s}\right]$ is the mass flow rate of fuel,
- AFR is the air to fuel mass flow ratio,
- FAR is the fuel to air mass flow ratio.

Diesel engines usually can work in a range between:

$$18 \leq AFR \leq 70$$

$$0.014 \leq FAR \leq 0.056$$

2.4.3. Special Fuel Consumption

Fuel consumption is quantified in engine testing as a flow rate-mass flow per unit time ($\dot{m}_f$). The specific fuel consumption ($sfc\ [g/kWh]$)-fuel flow rate per unit power output-is a more relevant metric. It assesses how effectively an engine uses the fuel it is given to create work, as specified below:

$$sfc = \frac{\dot{m}_f \cdot 3600}{P}$$

Where $P\ [kW]$ is the power delivered by the engine, given by:

$$P = 2\pi nT$$

Where:

- $n\ [rev/min]$ is the crankshaft rotational speed,
- $T\ [kNm]$ is the torque exerted by the engine.

2.4.4. Composition of Air and Fuels

Fuels are normally burnt with air in engines. Dry air is a combination of gases that contains 20.95% oxygen, 78.09% nitrogen, 0.93% percent argon, and trace quantities of carbon dioxide, neon, helium, methane, and other gases in a typical composition by volume. The relative proportions of the primary elements of dry air are shown in ***Table 2.4***.

Gas	ppm[4] by volume	Molecular weight [g/mol]	Mole fraction [%]	Molar ratio
O_2	209,500	31.998	0.2095	1
N_2	780,900	28.012	0.7905	3.773
Ar	9,300	39.948	-	-
CO_2	300	44.009	-	-
Air	1,000,000	28.962	1.0000	4.773

Table 2.4: Principal Constituents of dry air [21]

On the other hand, no further hydrogen (H) can be added to single-bonded open-chain saturated hydrocarbon molecules. There are straight-chain and branched-chain arrangements for bigger molecules. Normal (n-) and iso compounds are the terms for these different types of compounds. CH_4 methane;C_2H_6, ethane; C_3H_8, propane; C_8H_{18}, n-octane and isooctane.

Because the combustion products differ significantly between fuel-lean and fuel-rich mixtures, and because the stoichiometric fuel/air ratio is affected by fuel composition, the ratio of the actual fuel/air ratio to the stoichiometric ratio (or its inverse) is a more useful parameter for defining mixture composition: The fuel/air equivalence ratio φ:

[4] parts per million – 1 [ppm] = 0.0001%

$$\varphi = \frac{FAR_{actual}}{FAR_{stoichiometric}}$$

The inverse of φ, the relative air/fuel ratio λ is:

$$\lambda = \varphi^{-1} = \frac{AFR_{actual}}{AFR_{stoichiometric}}$$

- For fuel-lean mixtures: $\varphi < 1, \lambda > 1$
- For stoichiometric mixtures: $\varphi = 1, \lambda = 1$
- For fuel-rich mixtures: $\varphi > 1, \lambda < 1$

3. Auxiliary Engines

Electricity is increasingly critical to the ship's operation and the safety of its passengers. The ship's installation is a full system for producing, distributing, and consuming power that is self-sufficient and reliable. Power, lighting, and communications-navigation are the three core subsystems of a well-functioning ship. Even if a subsystem does not work or under-function, it may cause serious problems for the ship and its travelers, whether they are crew or passengers.

Because of the severe consequences an accident could had, 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[5] Regulations.

Marine machinery is designed to keep a ship's primary engines, piping systems, and equipment operating normally. Pumps, compressors, and blowers are used in auxiliary marine machinery to pump fuel, fresh water, and seawater used in cooling systems, to provide air to the main engine's starting system, to cool refrigerated holds, and to air-condition various parts of the ship and refrigeration machinery.

Being familiar with terminology is important for understanding the basic principles of auxiliary equipment on board. An electric motor converts electrical energy into mechanical or kinetic energy, whereas the electric generator transforms the mechanical/kinetic energy into electric energy. Thus, the second one, electric generator will be the main topic of this chapter, in order to supply ship's needs with electric power.

3.1. Operating Principles of Auxiliary Engines

3.1.1. Major Parts of Electric Generators

Electric generators are used to convert mechanical energy into electric energy. All electric generators have two basic parts [22]:

- The stator (stationary part),
- The rotor (rotating part).

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.

3.1.2. Operation

The generators described in this chapter; they all operate on the principle of electromagnetism. Other generators based on electrostatic and Piezoelectric principles exist, but they will not be described because the focus will be on those constructed with an electromagnetic theoretical basis.

To begin with, almost every generator makes use of the force produced on a current-carrying conductor in a magnetic field. An experiment that can be demonstrated even at home, is to place a bar

[5] The International Convention for the Safety of Life at Sea (SOLAS)

magnet near a current-carrying wire and by observing a force will be acted on the wire, as seen in ***Figure 3.1***.

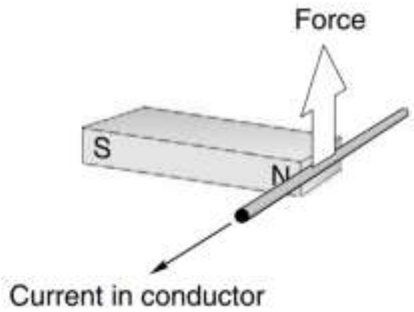


Figure 3.1: Mechanical force produced on a current-carrying wire in a magnetic field [23]

The magnitude of the force in electric generators is proportional to the intensity of the magnetic field and the quantity of current flowing in the conductor. This force (F) is known as Laplace Force: is a force applied on a conductor traversed by an electric current, and it's in a uniform magnetic field. We apply the right-hand rule to identify its direction. The Laplace force magnitude (F $[N]$) can be calculated by the following law:

$$F = I \cdot L \cdot B$$

Where:

- I $[A]$ is the current,
- L $[m]$ is the conductor length,
- B $[T]$[6] is the magnetic flux.

Generally, a magnetic field formed by the stator surrounds the rotor of an electric generator. The magnetic field creates a current within the rotor, and the resulting force (and consequently torque) created by the magnetic fields in the stator and rotor causes it to rotate.

3.2. Categorization of Electric Generators

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. In the following lines will be analysed in much more detail each one separately.

3.2.1. Direct Current (DC) Generators

A DC generator turns mechanical energy into direct current electricity. The creation of dynamically induced electromotive force is the basis for this energy conversion [24].

[6] $1\ [T] = 1\ [N/A \cdot m]$

When a conductor is put in a changing magnetic field (or moved in a magnetic field), an electromotive force is generated in the conductor, according to Faraday's laws of electromagnetic induction.

There are mainly three categories of DC generators, according to the way their magnetic field is developed in the stator of the machine:

- Permanent-magnet,
- Separately-excited,
- Self-excited.

Generally, the main components of a DC generator are the following [25]:

- Armature: Purpose of armature is to provide the energy conversion from kinetic to electric. An external mechanical force, such as a steam turbine or an ICE, rotates the armature in a DC generator. In the armature, this rotation causes a voltage and current flow. As a result, mechanical energy is converted to electrical energy via the armature,
- Rotor: This part is responsible for providing the rotational element. The rotor, also known as the armature, is the component of a DC generator that is turned by an external force,

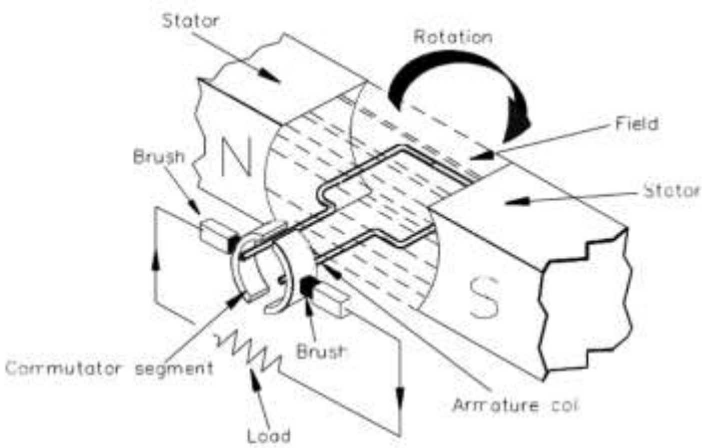


Figure 3.2: Basic DC generator components [91]

- Stator: The stator is the immovable portion of a generator. The stator's job in DC generators is to generate a magnetic field. A permanent magnet powers the stator in ***Figure 3.2***,
- Magnetic Field: In a DC generator, produces voltage. A permanent magnet or an electromagnet generates the field in a DC generator. Electromagnets are typically utilized because they have a higher magnetic strength and can be changed more readily using external equipment. The stator provides the field in ***Figure 3.2***.

3.2.2. Alternating Current (AC) Generators

With some exceptions, most electric power supplies on ships are AC Synchronous three-phase generators. A Synchronous generator is one in which the inductor winding leaks from a direct current. The name is due to the fact that the frequency of the alternating current is equal to the frequency of the rotating magnetic field of the excitation. Often these generators can be found in the literature under the name "Alternators" [26].

Traditional AC generators fall into one of two categories [27]:

- Synchronous,
- Induction or Asynchronous.

But also, can be arranged as:

- Single-phase,
- Three-phase.

An AC generator includes many components, so it will be decomposed, in order to be simplified:

- <u>Magnetic field:</u> The magnetic field is created when generator, which is made up of coils of conductors, receive a voltage from a source (known as excitation). The armature is cut by the magnetic flux in the field, which produces a voltage. This voltage is ultimately the output voltage of the AC generator,
- <u>Armature:</u> It is consisting the part of an AC generator that produces voltage, such as DC generator occasion. This component is made up of multiple wire coils that are large enough to carry the generator's full load current,
- <u>Rotor:</u> The rotor of an AC generator is the rotating component of the generator. The generator's prime mover, which might be a steam turbine, gas turbine, or diesel engine, rotates the rotor. This component may be the armature or the field, depending on the kind of generator. If the voltage output is created there, the rotor will be the armature; if the field excitation is applied there, the rotor will be the field,
- <u>Stator:</u> It is the stationary part of an AC generator. Depending on the kind of generator, this component might be the armature or the field, much like the rotor. If the voltage output is created there, the stator will be the armature; if the field excitation is applied there, the stator will be the field.

First and foremost, auxiliary medium or high-speed diesel engines are mostly used as prime movers for generators aboard ships, but they can also be linked together to give direct drive for big pumps, bow thrusters, or other gear [28].

On ships, AC three-phase power is preferred over DC as it gives more power for the same size. In addition, a three-phase system offers steady power, whereas a single-phase system produces pulsing power, resulting in a smooth and vibration-free functioning of a three-phase machine, as opposed to noise and vibration in one-phase equipment.

The power distribution system on board a ship is made up of many components that ensure the system's distribution and safe functioning. This system's primary components are [29]:

- Generator: It involves the prime mover (usually diesel engine) and the alternator,
- Main Switchboard: It is a metal enclosure that receives electricity from the diesel generator and distributes it to various equipment systems is known as the main switchboard,
- Bus Bars: Bus bars serve as a power carrier and allow load to be transferred from one location to another,
- Circuit Breakers: These components operate as a switch that can be tripped in dangerous situations to prevent breakdowns and accidents,
- Fuses: Fuses are machine safety devices,
- Transformers: Transformers are used to increase or decrease voltage. A step-down transformer is utilized in the distribution system to provide power to the lighting system.

Today's installations employ alternating current (AC), with direct current (DC) used only in exceptional circumstances. In the most popular AC systems, the frequency and voltage are given with details in ***Table 3.1***.

Type of Operation	**Frequency [Hz] / Voltage [V]**	
Power generation and movement	60/440	50/380
Luminance	60/110	50/220

Table 3.1: Frequency and Voltage for AC ship facilities [26]

However, on ships with high electrification and high energy-consuming systems, the rated operating voltage rises above 1000 $[V]$ (a value above which the voltage is referred to as "High Voltage", despite the fact that it corresponds to "Medium Voltage" according to existing data from land electrical grid networks) and is found at the following levels [26]:

$$3\ [kV], 3.3\ [kV], 4.17\ [kV], 6\ [kV], 6.6\ [kV], 11\ [kV], 15\ [kV]\ at\ 60\ [Hz]\ invariably$$

From the above values, it becomes applicable that:

- The most frequent voltage is 6.6 $[kV]$, which may be found aboard ships transporting liquefied natural gas, container ships, and other vessels,
- Large cruise ships have a voltage of 11 $[kV]$,
- High voltage is very common because not only reduces the current flowing, that leads to smaller and lighter wirings and equipment, but also there are some constructional constraints where manufacturers cannot provide to auxiliary machinery and equipment sector,
- The losses in the electrical network (which are inversely proportional to the square of the operating voltage) are greatly decreased with increased voltage, for example switch from 440 $[V]$ to 6.6 $[kV]$, that is 15 times higher, the corresponding losses are reduced by 225 times, something reflected in fuel consumption, given by the following formula:

$$P_{loss} = I^2 \cdot R$$

Where:

- P_{loss} $[kW]$ is the Power loss,
- I $[A]$ is the current carried by the conductor,
- R $[\Omega]$ is the resistance of the conductor.

3.2.3. Emergency Generator

An emergency source of energy is necessary for crucial services in the case of a main generating system breakdown. Batteries can provide this, but most cargo ships include a backup generator. The diesel-powered unit is positioned outside of the machinery area.

The emergency generator must be rated to operate:

- The emergency bilge pump,
- Fire pumps,
- Steering gear,
- Watertight doors,
- Firefighting equipment's drive motors,
- Emergency lighting for occupied areas,
- Navigation lights,
- Communication Systems,
- Alarm Systems.

Usually, the power of a marine generator does not outdo 4000 $[kW]$. In ships of high installed power (equal to or greater than 6 $[MVA]$), generators of power greater than 4000 $[kW]$ but high voltage 3.3÷15 $[kV]$, can be installed.

4. Human and Environment

The ***UN Human Rights Council*** approved a resolution on October 8, 2021, recognizing the human right to a clean, healthy, and sustainable environment as a fundamental human right. While this right has previously been recognized in more than 150 countries, its worldwide recognition opens the door to its effective incorporation into international law and better local application [30].

As the ancient Greek "Father of Medicine" Hippocrates said that [31]:

"Preventing is better than treating."

- Hippocrates of Kos (460 - 377 BC)

This may have been said by Hippocrates more than 2 millennia ago having human in the back of his mind, but it is still a quote that should concern people in the case of the environment, since as is often understood the human health and the state of the environment are directly involved.

By the 1980s, the scientific community had established knowledge of and awareness of a wide spectrum of local, regional, and global environmental public opinion. The fast rise of the world's population in the twentieth century, which had a variety of effects on natural resources, and the advancement of technology, which amplified the scope of anthropogenic affects, were both contributing to the problems of Greenhouse Effect [32].

4.1. Air Pollution

Both natural and artificial causes contribute to air pollution emissions. The anthropogenic portion of air pollution is caused by human-driven activities aimed at providing vital commodities and services to society [33]. Air pollution emissions occur at several phases in the marine industry, from an ocean-going cargo ship to a berthing Cruise ship. Both scenarios result in emissions, with one producing more and the other producing fewer.

It's not easy to define "air pollution". It is possible to argue that air pollution originated when humanity began to use fossil fuels. In other words, because they change the chemical makeup of the natural atmosphere, all man-made (anthropogenic) emissions into the air can be classified as air pollution. Using this technique, a rise in worldwide concentrations of greenhouse gases CO_2, CH_4, and N_2O [34] can be classified as air pollution, even if the quantities have not been shown to be hazardous to humans or the ecosystem. This technique may be refined by simply considering anthropogenic emissions of harmful substances as air pollution.

Gas	**Symbol**	**Percent by Volume [%] (Current Atmosphere)**	**ppm (Natural Atmosphere)**	**ppm (Current Atmosphere)**
Nitrogen	N_2	78.1		
Oxygen	O_2	20.9		
Argon	Ar	0.92		
Neon	Ne		18.2	
Helium	He		5.2	
Krypton	Kr		1.14	
Xenon	Xe		0.09	
Carbon Dioxide	CO_2		280.0	370.0
Methane	CH_4		0.750	1.77
Nitrous Oxide	N_2O		0.270	0.318
Water Vapor	H_2O	Variable (0.004 to 4)		

Table 4.1: Atmospheric Chemical pre-industrial and present Compositions [34]

It is clear that from ***Table 4.1***, there is increase of 33% in CO_2, 136% in CH_4 and 18% in N_2O in current atmospheric composition, in comparison with pre-industrial data of atmospheric composition.

4.1.1. Air pollution from Ships

Air pollution from the shipping industry can be considered to have started when the first fossil fuel engines were used. This was in the late 19th century, when the first steam engine was used to propel a ship, replacing pre-existing oars and sails. With the passage of time and the rapid growth of technology in ships, the widespread use of diesel engines in the mid-20th century, raised some questions about whether it is harmful to the environment since they were now established on large cargo ships.

Although ship pollution does not have the same direct cause and effect as, perhaps, an oil spill, it has a cumulative effect that contributes to general air quality issues faced by communities in many regions, as well as having an impact on the natural environment, such as acid rain.

The International Maritime Organization designed ***MARPOL 73/78*** (International Convention for the Prevention of Pollution from Ships) with the goal of reducing pollution of the oceans and seas, including waste, oil, and air pollution.

MARPOL Annex VI, initially enacted in 1997, sets limitations on the principal air pollutants found in ship exhaust gas, including as SO_x and NO_x, as well as forbids intentional emissions of Ozone Depleting Compounds (ODS).

MARPOL Annex VI entered into force on May, 2005, but was later revised with the aim of significantly strengthening the emission limits. The result was that the ***Marine Environment Protection Committee (MEPC)*** adopted revised ***MARPOL Annex VI*** and the associated NO_x technical code, which entered into force on 1^{st} of July, 2010.

4.1.2. Basic Air Emissions

Air emission are split into two large categories, depending on the nature of the effects they have on environment [35]:

- Those that produce air pollution,
- Those that induce climate change.

In the first category are classed emissions such as SO_x, NO_x, PM and VOC (emissions that produce air pollution). The second category is represented by three representatives which are CO_2, CFCs and CH_4 (emissions that cause climate change).

According to ***EMEP/EEA***, on a European scale, SO_2 and NO_x emissions from national shipping can be important with respect to total national emissions [36].

4.1.2.1. Sulphur Dioxides (SO_2)

SO_2 in shipping industry is produced during the combustion process in the engines. The content of sulphur in marine fuels has been decreased dramatically in the last decade, benefitting environment and human health.

According to studies, a proportion of individuals with asthma suffer changes in pulmonary function and respiratory symptoms after only 10 minutes of SO_2 exposure. Over average periods of 10 minutes, a SO_2 concentration of 500 $[g/m^3]$ should not be exceeded, while the 24-hour mean should not exceed 20 $[g/m^3]$. The change in the 24-hour SO_2 recommendation from 125 to 20 $[g/m^3]$ reflects the fact that health impacts are now recognized to be connected with far lower levels of SO_2 than previously thought, necessitating a higher level of protection. SO_2 has the potential to harm the respiratory system and lungs' functioning, as well as irritate the eyes. Inflammation in the respiratory tract causes coughing, mucus production, asthma flare-ups, and chronic bronchitis, as well as making patients more vulnerable to respiratory infections. On days with greater SO_2 levels, hospital admissions for cardiac disease and mortality rise [33].

When SO_2 reacts with water, sulfuric acid is formed, which is the major component of acid rain, which harms sensitive ecosystems.

4.1.2.2. Nitrogen Oxides (NO_x)

NO_x is produced when fuels are burned at high pressures (ratios) and temperatures. It's one among the key components in the creation of ground-level ozone, which can cause significant respiratory issues. It reacts to generate nitrate particles and acid aerosols, both of which are harmful to the respiratory system. It also contributes to acid rain formation and nutrient overload, both of which degrade water quality [37].

NO_2 has a main effect on the respiratory system [36]. Short-term NO_2 exposure can alter lung function in vulnerable populations, whereas long-term exposure can have more significant consequences, such as increased susceptibility to respiratory infection [36]. Long-term exposure to NO_2 has been linked to an increase in bronchitis symptoms in asthmatic children, according to epidemiological research. Because NO_2 is so closely linked to other pollutants (particularly PM), it's difficult to tell the difference between their impacts [36]. There is no evidence for direct health effects of NO_2, except perhaps for morbidity in children, therefore it appears that the major harm caused by NO_x is caused by its second pollutants, O_3 and nitrates [38].

Ship engines are a major source of NO_x emissions, which induce acidification and eutrophication (overfertilization) of the sea and land, damaging biodiversity in land and coastal waterways. The Baltic Sea region is particularly affected [39].

4.1.2.3. Particulate Matter (PM)

Particulate Matter (PM), also known as atmospheric aerosol particles or atmospheric particulate matter, are microscopic particles of solid or liquid matter suspended in the air.

The mass concentration of particles with a diameter of less than 10 $[\mu m]$ (PM_{10}) and particles with a diameter of less than 2.5 $[\mu m]$ ($PM_{2.5}$) are two commonly used indicators for describing PM that are relevant to health. $PM_{2.5}$, also known as fine PM, comprises ultrafine particles with a diameter of less than 0.1 $[\mu m]$. $PM_{2.5}$ accounts for 50÷70% of PM_{10} in most European regions [40].

Particles can be released directly into the atmosphere (primary PM) or generated in the atmosphere from gaseous precursors like sulphur dioxide, nitrogen oxides, ammonia, and non-methane volatile organic compounds (secondary particles) [40].

Primary PM and the precursor gases can have both man-made (anthropogenic) and natural (non-anthropogenic) sources.

Combustion engines (both diesel and petrol) in ships is a typical example of anthropogenic sources, while chemical reactions of gaseous pollutants produce secondary particles in the air. They are the outcome of the atmospheric transformation of nitrogen oxides and sulphur dioxide [40].

PM causes air pollution more than any other pollutant, affecting more people than any other pollutant. PM has negative health impacts at levels of exposure now encountered by the majority of urban and rural residents in both developed and developing nations [33].

It’s also worth noting that, in comparison to offshore emissions, air emissions at ports are concentrated to a lesser extent, resulting in higher atmospheric concentrations and, as a result, increasing human exposure. As a result, information at the local level is critical, as 80% of ships in Norway go fewer than 200 nautical miles from land [32].

PM bigger than 10 $[\mu m]$, are trapped in the nose or throat, where they are easily removed or swallowed. Smaller particles, particularly those with a diameter of less than 2.5 $[\mu m]$, however, penetrate the lungs, where they remain and are difficult to remove, causing lung issues [32]. According to a study [41], shipping causes approximately 60,000 early deaths worldwide each year due to cardiorespiratory problems and lung cancer, with the majority of these deaths occurring near the coasts of Europe, East Asia, and South Asia, where intense maritime activity coexists with high population density.

4.1.2.4. Volatile Organic Compounds (VOCs)

VOCs (which also include hydrocarbons) are formed by incomplete combustion and fuel evaporation, and when they chemically react with NO_x, they play a key part in the formation of ground-level ozone [37]. Shipyard painting operations are also responsible for VOC emissions. Hydrocarbons (HC) are present in VOC emissions, some of which are carcinogenic. Long-term exposure to benzene (C_6H_6), for example, can harm cells' genetic material, leading to cancer [36]. Chronic exposure to C_6H_6 can also harm bone marrow and induce haematological effects including lower red and white blood cell counts [36].

4.1.2.5. Carbon Monoxide (CO)

CO is a gas released as a result of incomplete combustion of fossil fuels and biofuels, and it is thus expelled straight from the ship's funnel. CO has a three-month lifespan in the atmosphere because it progressively oxidizes into CO_2, generating O_3 in the process [36].

Because CO is colourless and odourless, it is dangerous to people and undetectable. It affects not just the most vulnerable members of society, such as those with respiratory problems, babies, and the elderly, but also healthy people [37]. CO enters the body through the lungs and is tightly bonded to haemoglobin, limiting the quantity of oxygen that can be delivered to the body [36]. People with cardiovascular disease are particularly vulnerable, as a further reduction in oxygen to the heart might result in myocardial ischemia [36]. Even in a healthy individual, high CO concentrations can induce suffocation and death.

Exercise capacity, learning functions, ability to complete complex activities, affected coordination, problems concentrating, and disturbed visual perception are some of the most typical impacts of a minimal rise in carbon monoxide levels [37]. In many research, CO is not regarded as a possible causal pollutant, whereas in others, it is evaluated but no CO-related impact is found [38].

4.1.2.6. Carbon Dioxide (CO_2)

The complete combustion of fossil fuel produces CO_2. The hydrogen in the fuel is transformed to water vapor in each case (H_2O). Incomplete combustion of fuels can result in a variety of exhaust gases, including PM, CO, and so on, because internal combustion engines do not always have perfect combustion conditions.

CO_2 is naturally part of the atmosphere but it can also be produced from the combustion process of fossil fuels and like CO it is also emitted directly from the ship's funnel.

CO_2 is a greenhouse gas, which implies that it may cause global warming in high amounts. Global warming is a phenomenon in which rising greenhouse gas concentrations create a steady rise in the average temperature of the Earth's climate system [38].

4.2. Greenhouse Effect

The greenhouse effect is a natural phenomenon that occurs when different gases in the atmosphere hold the earth's temperature at high enough levels to support life. Carbon dioxide (CO_2), methane (CH_4), water vapor (H_2O), and nitrous oxide (N_2O) are examples of greenhouse gases that allow solar radiation (with wavelengths mostly in the part of the visible spectrum) to permeate the atmosphere and reach the earth's surface [32].

The earth absorbs this radiation and re-emits infrared radiation, which is absorbed by the atmosphere's greenhouse gases. Long-wave thermal radiation is emitted by these gases, and some of it is absorbed by the earth's surface. The earth's surface and troposphere are heated in this way. The average temperature on the earth's surface would be 30 [℃] cooler if there was not this natural phenomenon, and life would be impossible [32].

4.2.1. Global Warming Potential

The warming of the earth may be influenced by a variety of greenhouse gases. The ability to absorb energy (their "radiative efficiency") and the length of time they stay in the atmosphere are two fundamental ways in which these gases differ from one another (also known as their "lifetime").

The ***Global Warming Potential (GWP)*** is an index that describes the radiative properties of greenhouse gases that stay in the atmosphere, as well as their relative efficiency in absorbing outgoing infrared radiation. This index approximates the time-integrated warming effect of a unit mass of a specific greenhouse gas in comparison to CO_2 in today's atmosphere [42]. In other words, it is a measure of how much energy the emissions of 1 $[t]$ of a gas will absorb over a given period of time, relative to the emissions of 1 $[t]$ of CO_2.

The ***Table 4.2*** shows the GWP for CO_2 across a 100-year time horizon. This table is adapted from the IPCC Fifth Assessment Report, 2014 (AR5) [43].

Industrial designation or common name	**Chemical formula**	**GWP values for 100-year time horizon**		
		Second Assessment Report (SAR)	Fourth Assessment Report (AR4)	Fifth Assessment Report (AR5)
Carbon Dioxide	CO_2	1	1	1
Methane	CH_4	21	25	28
Nitrous Oxide	N_2O	310	298	265

Table 4.2: Global Warming Potential (GWP) values relative to CO_2 [43]

As seen in ***Table 4.2***, CO_2, by definition, has a GWP of 1 because it is the gas being used as the reference.

Methane (CH_4) is estimated to have a GWP of 28 over 100 years. Today's CH_4 emissions last approximately a decade on average, which is much less time than CO_2. However, CH_4 absorbs a lot more energy than CO_2. The GWP reflects the net effect of the shorter lifetime and increased energy absorption. The CH_4 GWP also takes into account certain indirect impacts, such as the fact that CH_4 is a precursor of ozone, which is a GHG by itself.

4.2.2. CO_2-equivalent emission

The quantity of CO_2 emitted that would have the same integrated radiative forcing as GHG or a mixture of GHGs over a specified time horizon is called CO_2-equivalent emission [43].

Multiplying the amount of gas by the relevant GWP index converts the amount of GHG into CO_2-equivelant emission.

For example:

1 [kg] of Methane (CH_4) corresponds to 28 [kg] of CO_2-eq.

$$1\ CH_4\ [kg] \xrightarrow{\hspace{3cm}} 1\ [kg] \times 28\ [GWP] = 28\ CO_2 - eq\ [kg]$$

According to IMO, total shipping (international, domestic, and fishing) has increased its GHG emissions, which include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), expressed in CO_2-eq, from 977 million tonnes in 2012 to 1,076 million tonnes in 2018. (9.6% increase). In 2012, CO_2 emissions totalled 962 million tonnes, however this figure increased by 9.3% to 1,056 million tonnes in 2018 [44].

5. Regulations and Legislation for emissions by the Competent Institutions and Organizations

This chapter deals with the issue of emissions of regulations and legislation by the competent authorities. An international regulatory framework is being developed to manage this matter with the assistance of ***MARPOL Annex VI***. Reference is made to the regulations, such as NO_x and SO_x, which are already into full force for all areas since January 1st, 2020. As will be seen below, emissions can be controlled by two mechanisms: combustion technology control, combined with exhaust gas treatment, and fuel quality control. Both of these measures are used.

Also, on 14th of July, 2021, the European Commission published its ***"Fit for 55" package***, which includes several important proposals for shipping. 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 requiring the purchase of emission permits, so setting a price on emissions [45].

Another powerful tool is the ***Energy Efficiency Design Index (EEDI)*** for newly built ships which reduces the greenhouse gases produced by ships. Except of EEDI, new index will come into force on 1st of January, 2023, the ***Energy Efficiency eXisting ship Index (EEXI)***, which is a new IMO regulation that aims to reduce CO_2 emissions of existing vessels by setting minimum requirements for technical efficiency.

The new regulations will require all ships to calculate EEXI index and establish their annual operational ***Carbon Intensity Indicator (CII)*** and CII rating using technical means to improve their energy efficiency. GHG emissions are linked to the amount of cargo carried over the distance travelled by carbon intensity.

5.1. International Maritime Organization

Imagine living in a world where everyone does as they please, even if it infringes the rights of others or affects society's tasks as a whole, without implications or sanctions. This would obviously couldn't work constructively for the members of the society. An authorized body's laws are essential in the society. Law is there to guide the society towards happiness without bloodshed and in peace and harmony.

As in an organized society, so in shipping there had to be intervention by the government, in order to ensure that travel is done in a safe way, something that changed the way maritime industry was traditionally operated, since before governmental interference, maritime safety was a private matter and was ensured through a system where stakeholders took on a share of the (financial) consequences of an accident [46].

The maritime community was hesitant to accept government action to increase security since it was seen as a violation of the principles of free international trade and a potential advantage for those who followed less strict rules. This free trade attitude lasted until the mid-19th century [46].

Various nations recommended that a permanent international organization should be formed to promote more effectively marine safety, but these expectations were not realized until the establishment of United Nations. In 1948, an international conference in Geneva enacted a convention formally creating the ***International Maritime Organization (IMO)*** [47]. It was still 11 years before it met for the first time (1959).

The ***International Convention for the Prevention of Pollution from Ships***, 1973, as modified by the Protocol of 1978 (MARPOL 73/78), was the most important of all these measures. It includes pollution from chemicals, packaged products, sewage, garbage, and air pollution, in addition to accidental and operational oil pollution [47].

5.1.1. IMO procedures for reducing Greenhouse Gases emissions

In September 1997, an International Conference of Parties to the MARPOL Convention adopted ***Resolution 8*** regarding CO_2 emissions from ships, as part of the Protocol of 1997 to update the ***MARPOL Convention (MARPOL Annex VI)***. [48].

In view of the relation between CO_2 and other atmospheric and marine pollutants, this resolution invited the ***Marine Environment Protection Committee (MEPC)*** to investigate what CO_2 reduction measures would be viable [48].

The MEPC was compelled to recognize and establish the essential mechanism to accomplish the targeted emission reduction in international shipping after the IMO Assembly adopted its practices relating to the reduction of GHG emissions from ships in December 2003, giving importance to:

- Creating a benchmark for greenhouse gas emissions,
- In the development of a methodology, to describe the efficiency of the greenhouse gases of ships, where at the same time MEPC had to recognize that CO_2 is the main greenhouse gas emitted by ships,
- In the evaluation of technical, operational and market-based solutions.

In July 2011, very important amendments of ***Annex VI of MARPOL*** were adopted introducing measures to reduce air pollution through consumption energy restrictions. A package of technical measures aimed at controlling greenhouse gases. The two main measures adopted are: the calculation of the EEDI index and the ***Ship Energy Efficiency Management Plan***, which will be discussed in more detail below. Also, reference will be made to the indexes EEXI and CII.

5.1.1.1. Energy Efficiency Design Index (EEDI)

MEPC created the ***Energy Efficiency Design Index*** after a series of discussions. EEDI is a mathematical formula that expresses the relationship between the cost of operating a ship (i.e., CO_2 emissions) and the profit made (i.e., ability to transport goods). After removing emissions corresponding to the given power by using appropriate innovative technologies, CO_2 emissions are deemed to emanate from the main engines and auxiliary engines. The profit generated is considered to consist of the cargo carried at the speed of the ship [48].

The index is calculated for each new design and expresses the production of CO_2, in grams per unit of capacity-distance, in tonne-miles. The lower the value, the more energy efficient is the ship. The energy efficiency criterion requires the value of the EEDI index to be less than or equal to the reference line value multiplied by a reduction factor [49]:

$$EEDI \leq \left(1 - \frac{X}{100}\right) \times (Reference\ line\ value)$$

Where:

- Reduction factor X of the required value of the index is calculated, for different types of ships, based on the following ***Table 5.1***,
- Reference line value shall be calculated as follows:

$$Reference\ line\ value\ =\ a \times b^{-c}$$

Where a, b and c are the parameters given in ***Table 5.2***.

Ship Type	**Size**	**Phase 0 1 Jan 2013 – 31 Dec 2014**	**Phase 1 1 Jan 2015 – 31 Dec 2019**	**Phase 2 1 Jan 2020 – 31 Dec 2024**	**Phase 3 1 Jan 2025 and onwards**
Bulk carrier	20,000 DWT and above	0	10	20	30
	10,000 – 20,000 DWT	n/a	0-10*	0-20*	0-30*
Gas carrier	10,000 DWT and above	0	10	20	30
	2,000 – 10,000 DWT	n/a	0-10*	0-20*	0-30*
Tanker	20,000 DWT and above	0	10	20	30
	4,000 – 20,000 DWT	n/a	0-10*	0-20*	0-30*
Container ship	15,000 DWT and above	0	10	20	30
	10,000 – 15,000 DWT	n/a	0-10*	0-20*	0-30*
General Cargo ships	15,000 DWT and above	0	10	15	30
	3,000 – 15,000 DWT	n/a	0-10*	0-15*	0-30*
Refrigerated cargo carrier	5,000 DWT and above	0	10	15	30
	3,000 – 5,000 DWT	n/a	0-10*	0-15*	0-30*
Combination carrier	20,000 DWT and above	0	10	20	30
	4,000 – 20,000 DWT	n/a	0-10*	0-20*	0-30*
** Reduction factor to be linearly interpolated between the two values dependent upon vessel size. The lower value of the reduction factor is to be applied to the smaller ship size.*					
n/a means that no required EEDI applies.					

Table 5.1: Reduction factors (in percentage) for the EEDI relative to the EEDI Reference line [49]

Ship Type	**a**	**b**	**c**
Bulk carrier	961.79	DWT of the ship	0.477
Gas carrier	1120.00	DWT of the ship	0.456
Tanker	1218.80	DWT of the ship	0.488
Container ship	174.22	DWT of the ship	0.201
General cargo ship	107.48	DWT of the ship	0.216
Refrigerated cargo carrier	227.01	DWT of the ship	0.244
Combination carrier	1219.00	DWT of the ship	0.488

Table 5.2: Parameters for determination of reference values for the different ship types [49]

The generalized expression of the EEDI index is [46]:

$$EEDI = \frac{CO_2\ emission}{Transport\ Work} = \frac{P \cdot t \cdot sfc \cdot f_{CO_2}}{C \cdot V \cdot t} \left[\frac{gCO_2}{t \cdot nm}\right]$$

Where:

- $P\ [kW]$ is power which is needed for the propulsion of the ship,
- $t\ [h]$ is the time,
- $sfc\ \left[\frac{g_{fuel}}{kW \cdot hr}\right]$ is the special fuel consumption,
- $f_{CO_2}\left[\frac{gCO_2}{g_{fuel}}\right]$ is the emission factor of CO_2,
- $C\ [t]$ is the load carrying capacity,
- $V \cdot t\ [nm]$ is the velocity V multiplied by the time t, expressing the distance covered.

In its full form, the EEDI index is calculated based on the strengths and consumptions of main and auxiliary equipment, taking into account power recovery facilities, at service speed. These nominal consumptions are divided by the transport project. Details of the calculation are in the IMO directive [50].

5.1.1.2. Energy Efficiency Existing Ships Index (EEXI)

The main Difference between the two indexes, EEDI and EEXI, is that EEDI applies to vessels built after 2013, while EEXI to vessels built before 2013.

After January 1st, 2023, the EEXI will be used in the first annual, intermediate, or renewal IAPP[7] survey. For ships of 400 $[GT]$ and above, the EEXI index must be calculated in accordance with the different values provided for ship types and size categories [51].

MEPC 76th session adopted a combined short-term measure consisting of the so-called ***Energy Efficiency Existing Ships Index (EEXI)***, the ***Carbon Intensity Indicator (CII)***, which includes an A to E ship rating system, and the strengthening of the ***Ship Energy Efficiency Management Plan (SEEMP)***, as expected and planned since MEPC 75th session (November 2020).

The EEXI calculation guidelines have been developed but so far remain in draft form. The calculation methodology is aligned with that used for EEDI.

The requirement and guidelines for calculating the needed EEXI and verifying that a vessel's attained EEXI is lower than the required EEXI will be provided in Regulation 21A [52]. The Required EEXI would be the regulation limit for EEXI, and it would be calculated using EEDI reference line values and EEXI-specific reduction factors, as stated in ***Table 5.3***.

[7] IAPP-International Air Pollution Prevention

Ship Type	**Size**	**Reduction Factor**
Bulk Carrier	200,000 DWT and above	15
	20,000 and above but less than 200,000 DWT	20
	10,000 and above but less than 20,000 DWT	0-20*
Gas Carrier	15,000 DWT and above	30
	10,000 and above but less than 15,000 DWT	20
	2,000 and above but less than 10,000 DWT	0-20*
Tanker	200,000 DWT and above	15
	20,000 and above but less than 200,000 DWT	20
	4,000 and above but less than 20,000 DWT	0-20*
Containership	200,000 DWT and above	50
	120,000 and above but less than 200,000 DWT	45
	80,000 and above but less than 120,000 DWT	35
	40,000 and above but less than 80,000 DWT	30
	15,000 and above but less than 40,000 DWT	20
	10,000 and above but less than 15,000 DWT	0-20*
General Cargo Ship	15,000 DWT and above	30
	3,000 and above but less than 15,000 DWT	0-30*
Refrigerated Cargo Carrier	5,000 DWT and above	15
	3,000 and above but less than 5,000 DWT	0-15*
Combination Carrier	20,000 DWT and above	20
	4,000 and above but less than 20,000 DWT	0-20*
LNG Carrier	10,000 and above	30
Ro-ro Vehicle Carrier	10,000 and above	15
Ro-ro Cargo Ship	2,000 and above	5
	1,000 and above but less than 2,000 DWT	0-5*
Ro-ro Passenger Ship	1,000 DWT and above	5
	250 and above but less than 1,000 DWT	0-5*
Cruise Passenger Ship with Non-conventional Propulsion	85,000 GT and above	30
	25,000 GT and above but less than 85,000 GT	0-30*
** Reduction factor to be linearly interpolated between the two values dependent upon ship size. The lower value of the reduction factor is to be applied to the smaller ship size.*		

Table 5.3: Reduction factor specific to EEXI in line with the EEDI reference line values [52]

5.1.1.3. Carbon Intensity Indicator (CII)

Also, ***MEPC 76th session*** agreed on a compromise proposal to set a gradual, non-linear CII reduction scale of 1% per year until 2023, followed by a 2% per year reduction between 2023 and 2027, and to leave further CII reductions until 2030 open, to be examined and decided as part of a review by 2026, as seen in the ***Table 5.4*** [53].

The CII rules will apply to all cargo, Ro-pax, and Cruise vessels over 5,000 $[GT]$ that trade internationally starting in 2023.

In its most uncomplicated form, an individual ship's attained operational CII is determined as the ratio of total CO_2 emitted to total transport work done in a particular calendar year, as described in the following [54]:

$$CII_{att} = \frac{FC \cdot f_{CO_2}}{C \cdot D_t} \left[\frac{gCO_2}{t \cdot nm}\right]$$

Where:

- FC $[g]$ is the total mass of consumed fuel oil type in the calendar year, as reported under IMO DCS[8],
- f_{CO_2} $\left[\frac{gCO_2}{g_{fuel}}\right]$ is the fuel oil mass to CO_2 mass conversion factor for fuel oil type,
- C $[t]$ is the ship's capacity,
- D_t $[nm]$ is the total distance travelled, as reported by IMO DCS.

In a similar way, like indexes EEDI and EEXI, the required CII indicator of a ship is calculated, in accordance with ***Regulation 28 of MARPOL Annex VI***, as follows:

$$CII_{req} = \left(1 - \frac{Z}{100}\right) \times CII_{ref}$$

Where:

- Z [%] is a Reduction factor relative to 2019 reference line, given at ***Table 5.4***,
- CII_{ref} $\left[\frac{gCO_2}{t \cdot nm}\right]$ is reference line value determined as follows:

$$CII_{ref} = a \cdot Capacity^{-c}$$

[8] DCS - Data Collection System for fuel oil consumption of ships referred to in Regulation 27 and related provisions of MARPOL Annex VI.

Where a, $Capacity$ and c are parameters determined at ***Table 5.5***.

Year	**Reduction factor (Z%) relative to 2019**
2023	5%*
2024	7%
2025	9%
2026	11%
2027	-**
2028	-**
2029	-**
2030	-**

Table 5.4: Reduction factor (Z%) for the CII relative to the 2019 reference line [55]

* Reduction factors of 1%, 2% and 3% are set for the years of 2020 to 2022, similar as business as usual until entry into force of the measure.

** Reduction factors for the years of 2027 to 2030 to be further strengthened and developed taking into account the review of the short-term measure.

Ship type		**Capacity**	***a***	***c***
Bulk carrier	279,000 DWT and above	279,000	4,745	0.622
	less than 279,000 DWT	DWT	4,745	0.622
Gas Carrier	65,000 and above	DWT	$14{,}405\times10^{7}$	2.071
	less than 65,000 DWT	DWT	8,104	0.639
Tanker		DWT	5,247	0.610
Container ship		DWT	1984	0.489
General Cargo Ship	20,000 DWT and above	DWT	31,948	0.792
	less than 20,000 DWT	DWT	588	0.3885
Refrigerated cargo carrier		DWT	4,600	0.557
Combination carrier		DWT	40,853	0.812
LNG Carrier	100,000 DWT and above	DWT	10	0.000
	65,000 DWT and above, but less than 100,000	DWT	$14{,}479\times10^{10}$	2.673
	less than 65,000 DWT	65,000	$14{,}479\times10^{10}$	2.673
Ro-ro cargo ship (vehicle carrier)		GT	5,739	0.631
Ro-ro cargo ship		DWT	10,952	0.637
Ro-ro passengership		GT	7,540	0.587
Cruise passenger ship		GT	930	0.383

Table 5.5: Parameters for determining the 2019 ship type specific reference lines [56]

Based on the attained yearly operational carbon intensity indicator, a ranking label from among the five grades (A, B, C, D, and E) is assigned to the ship, representing a major superior, minor superior, moderate, minor inferior, or inferior performance level [57].

The boundaries are based on the CII distribution of individual ships in the year 2019. The appropriate rating boundaries are expected to produce the following results: the middle 30% of individual ships across the fleet segment will be assigned rating C, while the upper 20% and further upper 15% of individuals will be assigned rating D and E, and the lower 20% and further lower 15% of individuals will be assigned rating B and A, respectively, as shown in ***Figure 5.1***.

For determining the rating boundaries of ship types, the estimated dd vectors (denoted as dd vectors indicating the direction and distance they deviate from the required value) after exponential transformation, are as follows:

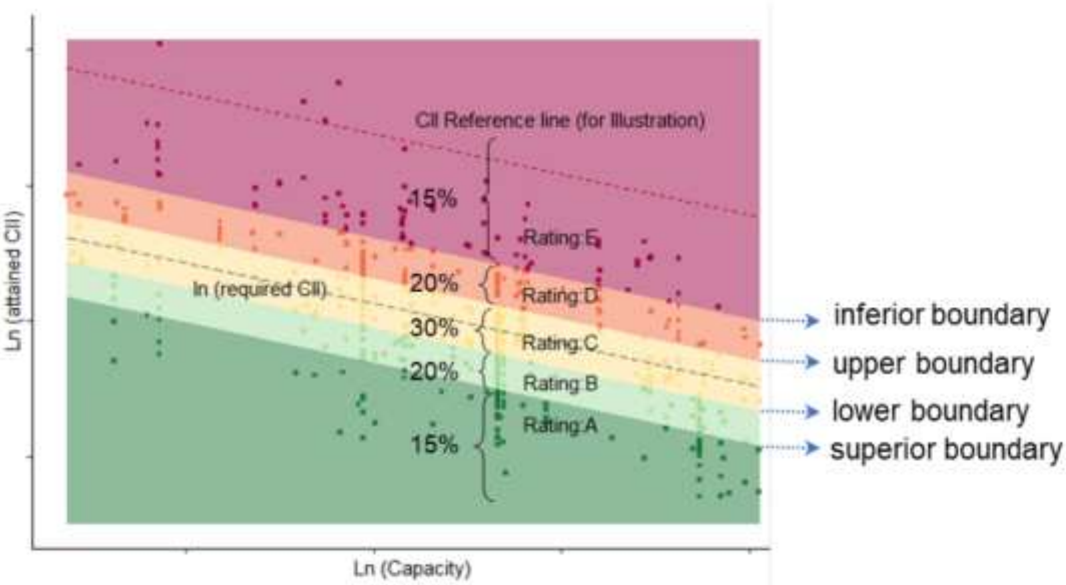


Figure 5.1: Operational energy efficiency performance rating scale [57]

The boundaries for determining performance ratings should be synchronized in accordance with the incremental operational carbon intensity reduction factors over time, however the relative distance between the boundaries should not alter. The attained CII and the predetermined rating boundaries, rather than the attained CII of other ships, would define a ship's rating [57].

The estimated dd vectors after exponential transformation for determining the rating boundaries of ship types are as follows:

Ship type		Capacity in CII calculation	*dd* vectors (after exponential transformation)			
			exp(d1)	exp(d2)	exp(d3)	exp(d4)
Bulk carrier		DWT	0.86	0.94	1.06	1.18
Gas carrier	65,000 DWT and above	DWT	0.81	0.91	1.12	1.44
	less than 65,000 DWT	DWT	0.85	0.95	1.06	1.25
Tanker		DWT	0.82	0.93	1.08	1.28
Container ship		DWT	0.83	0.94	1.07	1.19
General cargo ship		DWT	0.83	0.94	1.06	1.19
Refrigerated cargo carrier		DWT	0.78	0.91	1.07	1.20
Combination carrier		DWT	0.87	0.96	1.06	1.14
LNG carrier	100,000 DWT and above	DWT	0.89	0.98	1.06	1.13
	less than 100,000 DWT		0.78	0.92	1.10	1.37
Ro-ro cargo ship (vehicle carrier)		GT	0.86	0.94	1.06	1.16
Ro-ro cargo ship		DWT	0.66	0.90	1.11	1.37
Ro-ro passenger ship		GT	0.72	0.90	1.12	1.41
Cruise passenger ship		GT	0.87	0.95	1.06	1.16

Table 5.6: dd vectors for determining the rating boundaries of ship types [57]

5.1.1.4. Example of Calculating CII

For example, let ship Bulk carrier, with the following characteristics:

Measurement	**Value**
Type of Ship	Bulk Carrier
DWT [t]	62,000
Total Distance Travelled in a year (D_t) [nm]	60,045
CO_2 Emissions [t]	17,447

Table 5.7: Bulk Carrier characteristics for CII calculation

It is considered that the current vessel has a steady amount of CO_2 emissions, a constant distance travelled and Deadweight, every year.

At first, the attained CII_{att} is calculated as:

$$CII_{att} = \frac{FC \cdot f_{CO_2}}{C \cdot D_t} = \frac{17{,}447 \times 10^6}{62{,}000 \cdot 60{,}045} = 4.69 \left[\frac{gCO_2}{t \cdot nm}\right]$$

The values of parameters $a = 4{,}745$ and $c = 0.622$ and $Capacity = 62{,}000\ [t]$ are taken from ***Table 5.5***, to calculate CII_{ref}:

$$CII_{ref} = 4{,}745 \cdot (62{,}000)^{-0.622} = 4.96 \left[\frac{gCO_2}{t \cdot nm}\right]$$

For 2023, reduction factor $Z = 5$, while CII_{req} is calculated as:

$$CII_{req} = \left(1 - \frac{5}{100}\right) \times 4.96 = 4.71$$

The following ratio equals:

$$\frac{CII_{att}}{CII_{req}} = \frac{4.69}{4.71} = 0.99$$

Where for Bulk carrier:

$$\exp(\mathrm{d2}) = 0.94 \leq \frac{CII_{att}}{CII_{req}} \leq 1.06 = \exp(\mathrm{d3})$$

If the vessel keeps their CO_2 emissions same, the rating will be slightly worse year by year, and the rating will be as follows:

Reporting Year	**Reduction factor (Z%)**	$CII_{req}\left[\frac{gCO_2}{t \cdot nm}\right]$	$\frac{CII_{att}}{CII_{req}}$	**Rating**
2023	5	4.71	0.996	C
2024	7	4.61	1.017	C
2025	9	4.51	1.040	C
2026	11	4.41	1.063	D

Table 5.8: Rating due to CII indicator and reporting year

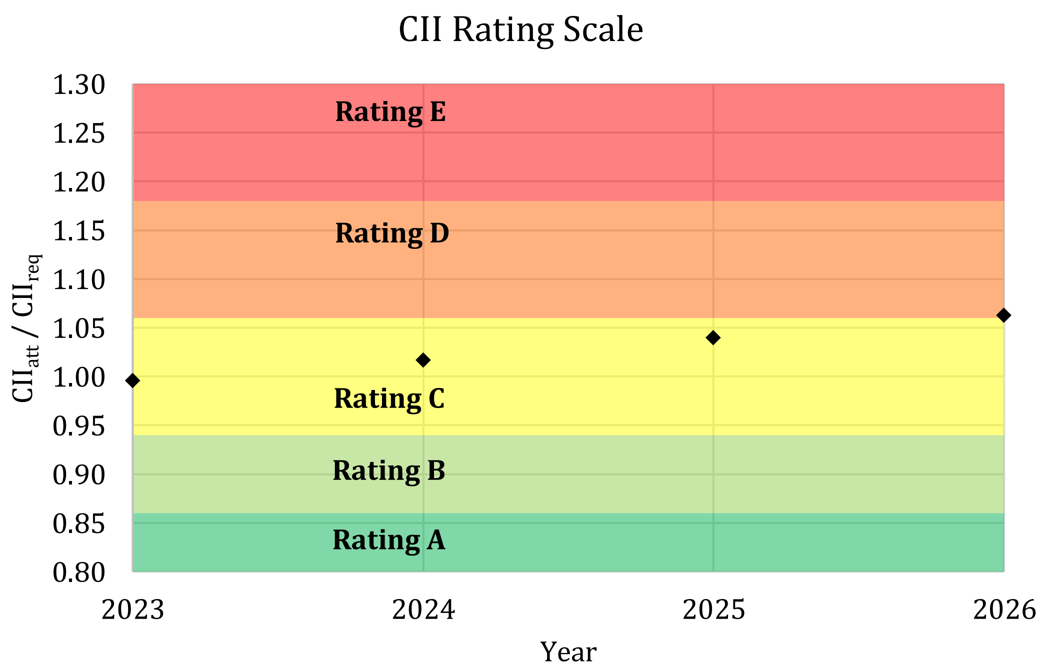


Figure 5.2: CII Rating scale due to reporting year

Due to reduction factor changing each year, in the above example, a vessel with constant CO_2 emissions each year's degree can be degraded, if measures won't be taken.

5.1.1.5. Ship Energy Efficiency Management Plan (SEEMP)

The ***Ship Energy Efficiency Management Plan's*** goal is to create a system for a company to increase the energy efficiency of a ship's operation. It is necessary for new and existing vessels. The company must create a SEEMP that aims to increase the ship's energy efficiency in four steps: planning, implementation, monitoring, and self-evaluation. The SEEMP is designed by the ***International Maritime Organization (IMO)*** to be a dynamic ship-specific document that must be kept on board and actively employed in the ongoing endeavour to improve the energy efficiency of daily operations on board. The regulation, on the other hand, merely demands the presence of an energy efficiency plan on board and makes no demands for the plan's content [58].

Weather routing, just-in-time arrival, optimal trim, and waste heat recovery are all suggested goals in the SEEMP standards, however certain goals are not appropriate for all types of vessels. The guidelines highlight the importance of collaboration among all stakeholders when it comes to energy efficiency. The emphasis on human resources is another factor. Raising awareness and providing the crew with the requisite training are essential parts. Goals are the final component, and they serve as guidelines for involving people, generating an incentive for proper implementation, and improving dedication to energy efficiency operations [58].

5.1.2. IMO Regulations for reducing NO_x and SO_x

The ***International Maritime Organization (IMO)*** is the world's official body for international maritime governance. The ***MARPOL Convention***, which consists of six annexes, was signed by the ***Committee for the Protection of the Marine Environment (MEPC)*** as part of the effort to prevent pollution caused by ships. The first five annexes, first adopted in 1973 and then revised in 1978, concentrate on measures to prevent contamination of ship cargo by oil or other harmful liquids. These annexes also include procedures for preventing maritime pollution caused by waste generated by ships [19].

Annex VI of the Convention, which was adopted in 1997, specifies exhaust emissions such as SO_x, NO_x, and PM, as well as control areas for Volatile Organic Compounds (VOCs) emissions in tankers [59].

In October 2008, the MEPC approved the proposed amendments to ***MARPOL Annex VI***, on regulations to reduce harmful emissions from ships.

IMO, who currently has 174 Member States and three Associate Members, established emission control areas to further restrict the environmental impact of emissions from certain places (ECAs[9]). Different restrictions apply to different regions; As shown in ***Figure 5.3*** depicts the permitted NO_x emission limits, while ***Table 5.9*** lists the IMO's precise emission values. Diesel engine's NO_x emission limitations are set based on the engine's maximum operating speed. Clearly, the most recent Tier III reduces NO_x emission restrictions by 80% when compared to the Tier I [60].

[9] ECAs - Emission Control Areas

Emission regulation of IMO	**Effective date**	**Marine NO_x limits of IMO[g/kWh]**		
		n < 130 [rev/min]	**130 [rev/min] ≤ n < 2000 [rev/min]**	**n ≥ 2000 [rev/min]**
Tier I	1/1/2000	17.0	$45 \cdot n^{-0.2}$	9.8
Tier II	1/1/2011	14.4	$44 \cdot n^{-0.23}$	7.7
NO_x Tier III out of NECAs[10]	1/1/2016	14.4	$44 \cdot n^{-0.23}$	7.7
Tier III	1/1/2016	3.4	$9 \cdot n^{-0.2}$	1.96

Table 5.9: Marine NO_x limits of IMO [60]

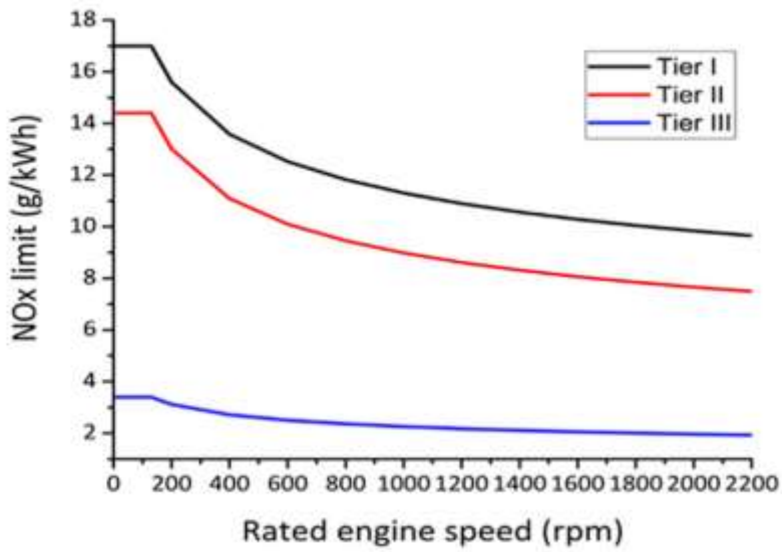


Figure 5.3: MARPOL allowable limit for NO_x emissions [60]

The sulphur in diesel fuel is converted to SO_3 and SO_2 during the combustion process. As a result, reducing sulphur content in fuel is an important source control approach for reducing SO_x emissions [60].

Table 5.10 shows the related legislation and regulations governing SO_x emissions. The sulphur content of fuel is already limited to 0.1% by mass in ***SO_x Emission Control Areas (SECAs)*** from 2015, and to 0.5% globally from 2020, as shown in ***Figure 5.4***.

[10] NECAs - NOx Emission Control Areas

Convention/regulation	Sulphur content in fuel [%m/m]	Effective date	Effective areas
Annex VI of MARPOL 73/78 Convention	3.50	1/1/2012	Out of SECAs
	0.50	1/1/2020	
	1.00	1/7/2010	In SECAs
	0.10	1/1/2015	
EU Law	0.10	1/1/2010	The EU ports
CARB Regulation	0.50	1/8/2012	California waters
	0.10	1/1/2014	

Table 5.10: The various laws and regulations limits for Sulphur content in fuel [60]

According to a study of 2021 [61], Abstract Changes in SO_x and NO_x depositions from ship exhaust gas emissions were simulated and assessed for the Baltic Sea region for the years 2014 and 2016 to estimate the value of the environmental benefits of the Sulphur Emission Regulation (SECA), which went into effect in 2015. The reduction in ship-generated SOx deposition from 38,068 $[t]$ to 3,345 $[t]$, a reduction of almost 88% was achieved.

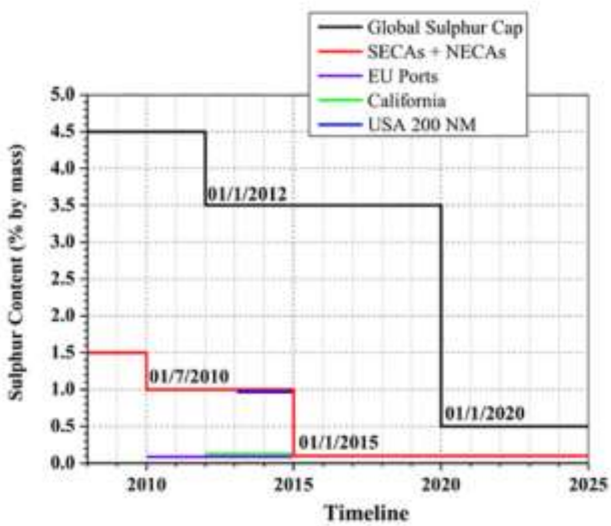


Figure 5.4: Sulfur content change in fuel [60]

5.2. European Union's "Fit for 55" climate package in maritime transportation

Although the name "Fit for 55" may sound like a physical exercising program for people with age above 55 years old, it is actually European Commissions future plan to guide EU to reduce 55% by 2030, compared to 1990.

Countries from all across the world committed to undertake efforts to keep global warming far below 2 degrees Celsius, preferably 1.5 degrees Celsius, relative to pre-industrial levels, as part of the Paris agreement. Countries must reduce their greenhouse gas emissions to "net zero" by 2050 to achieve this.

More than 10 legislative proposals and policy initiatives are included in the ***"Fit for 55" package***, four of which are directly related to the maritime sector.

5.2.1. FuelEU Maritime Initiative

The European Commission proposed the ***"Fit for 55" package*** of legislative proposals in July 2021, with the goal of ensuring the European Green Deal's success. One of these suggestions is the ***FuelEU Maritime*** regulation, which, along with four other measures, focuses on promoting the EU maritime sector toward decarbonization.

By promoting the use of greener fuels by ships, the proposal on the use of renewable and low-carbon fuels in maritime transport (FuelEU Maritime) aims to lower the greenhouse gas intensity of the energy consumed on-board by up to 75% by 2050. Despite recent progress, the maritime sector continues to rely almost exclusively on fossil fuels and is a major source of greenhouse gas and other harmful pollution emissions.

Every year, around 400 million passengers embark or disembark in EU ports, including around 14 million on Cruise ships [62].

Passenger ships and containerships, according to statistics collected under ***Regulation (EU) 2015/757*** in 2018 [63], are the ship types that produce the most emissions per ship at berth.

The usage of OPS minimises both the quantity of air pollution created by ships and the amount of GHG emissions produced by maritime transportation [62].

5.2.1.1. Scope of the Regulation

This Regulation applies to all ships with a gross tonnage of more than 5,000 $[GT]$, regardless of flag, when [62]:

- The energy is consumed in a port of call under the jurisdiction of a Member State,
- The total amount of energy expended on trips between ports of call under the jurisdiction of a Member State and ports of call under the authority of another Member State,
- Half of the energy (50%) is consumed on trips departing from or arriving at a Member State port of call, where the last or next port of call is under the jurisdiction of a third country.

A note of prime importance is that warships, navy auxiliaries, fish-catching or fish-processing ships, primitively built wooden ships, ships not propelled by mechanical means, and government ships used for non-commercial reasons are exempt from this regulation.

5.2.1.2. Greenhouse gas intensity limit of energy used on-board by a ship

By referring the term “Well-to-wake”, is a technique of measuring emissions that considers the greenhouse gas impact of energy generation, transportation, distribution, and consumption on-board, including combustion.

The amount of greenhouse gas emissions, given in grams of CO_2-eq established on a well-to-wake basis, per $[MJ]$ of energy used on-board is referred to as the “Greenhouse gas intensity of the energy used on-board”.

The GHG intensity limit shall be calculated by reducing the reference value [62]:

$$\left[\frac{(X\ grams\ of\ CO_2 - eq)}{MJ}\right] \cdot Y$$

Where the reducing percentage Y is:

- -2% from 1 January 2025,
- -6% from 1 January 2030,
- -13% from 1 January 2035,
- -26% from 1 January 2040,
- -59% from 1 January 2045,
- -75% from 1 January 2050.

During a reporting period, the annual average greenhouse gas intensity of the energy consumed on board by a ship must not exceed the limit set out in the previous lines.

5.2.1.3. Additional zero-emission requirements of energy used at berth

According to ***Article 5 of the Regulation*** [62], a ship at berth at a port of call within the authority of a Member State must connect to on-shore power and utilise it for all energy demands while at berth beginning from January 1st, 2030.

The preceding arrangement concerns the following type of ships:

- Container ships,
- Passenger ships.

This adjustment has some exceptions for ships that:

- That are at berth for less than two hours,
- That use zero-emission technologies,
- Which need the use of on-board energy generation for a short amount of time in emergency conditions posing an imminent threat to life, the ship, or the environment, or for other causes of unforeseen circumstances,
- That have to make an unscheduled port call for reasons of safety or saving life at sea,
- That are unable to connect to on-shore power supply due to a port's lack of connection points.

The last two (2) points of the aforementioned exceptions, may not be applied to a given ship, in total, more than five times during one reporting year.

The ***Table 5.11*** provides a list of zero-emission technologies [62]:

Zero-emission technology Criteria	**Criteria for use**
Fuel cells	Fuel cells used on board for power generation while at berth should be fully powered by renewable and low carbon fuels.
On-board Electricity Storage	The use of on-board electricity storage is allowed irrespective on the source of energy that produced the stored power (on-board generation or on- shore in case of battery swapping).
On-board Electricity production from wind and solar energy	Any ship that is capable to sustain energy needs at berth through the use of wind and solar energy.

Table 5.11: Zero-emission technologies and specific criteria for their use as applicable [62]

5.3. Trans-European Transport Network (TEN-T)

The ***Trans-European Transport Network (TEN-T)*** policy aims to build a Europe-wide network of railways, roadways, inland waterways, maritime shipping routes, ports, airports, and railroad terminals. The ultimate goal is to fill gaps in the EU, erase obstacles and technological challenges, and improve social, economic, and territorial cohesion. Regulation (EU) No 1315/2013 underpins the present TEN-T strategy [64].

The TEN-T policy encourages the use of innovation, modern technology, and digital solutions in all methods of transport, in addition to the creation of new infrastructure facilities. The objective is to optimize infrastructure utilisation, minimise transportation's environmental impact, promote energy efficiency, and enhance safety.

In the Annex 1 **"Maps of The Comprehensive and Core Networks"** of the Regulation, a map of EEA and UK core network of Inland waterways and ports is given, as shown in ***Figure 5.5*** [64].

The TEN-T network is made up of two "layers":

- The Core Network, which will be finished by 2030, contains the most vital links, connecting the most significant nodes.
- The Comprehensive Network, which will be finished by 2050 and will include all European regions.

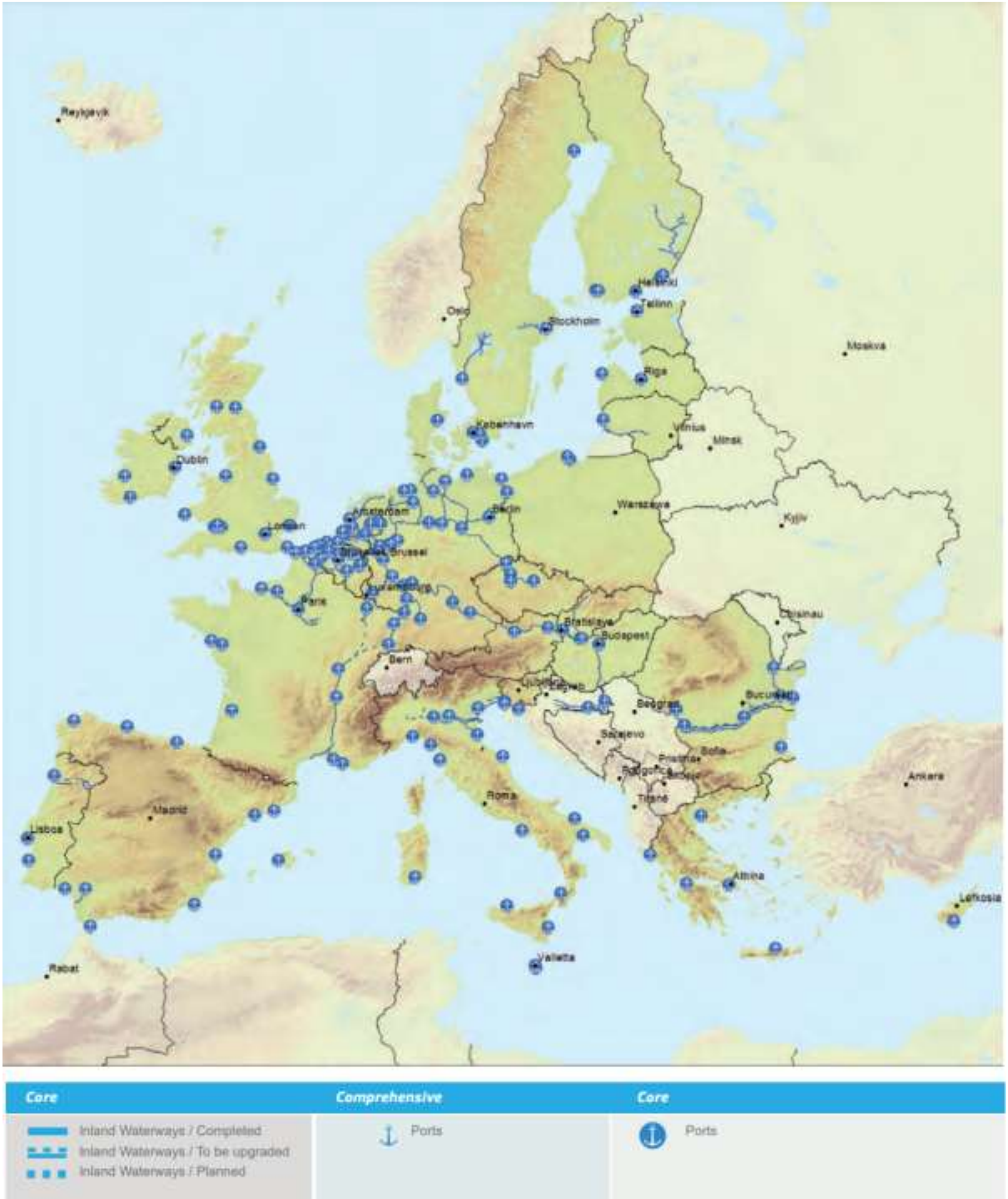


Figure 5.5: Core Network of inland waterways and ports of EEA and UK [64]

6. Onshore Power Supply (OPS)

Onshore Power Supply (OPS), also known as ***Shore-to-Ship Power (SSP)***, ***Alternative Maritime Power (AMP)***, or ***Cold Ironing (CI)***, is a technical method for reducing air pollution in a region near a port when air quality has deteriorated owing to ship activities [65]. For the purpose of this study, the abbreviation OPS will be used.

6.1. Brief history of OPS

The term "Onshore Power Supply", also known as "Cold Ironing", originated in the maritime industry when all ships used coal-fired iron-clad engines. When a ship docked, there was no need to feed the fire, thus the iron engines would actually cool down until they were absolutely cold, hence the term cold ironing. Cold ironing, or shore-to-ship electrification, has historically been adopted by the military at naval facilities when ships are tied for extended periods of time [66].

6.2. OPS as a method of reducing shipping emissions

OPS is one of the carbon reduction techniques which is replacing auxiliary diesel engines with electricity supplied from shore. Air quality and noise will be enhanced and lowered by ships connected to OPS [67]. Ultimately, its basic principle is the provision of shore power to meet the energy requirements of various marine vessels docked at the port [65].

The environmental aspect of Cold Ironing, as well as the health benefits it provides to local communities, are significant advantages. The ship's generators produce power using fossil fuels. As discussed in ***Chapter 4*** of this Thesis, the combustion of fossil fuels produces a variety of ecological issues.

Converters, transformers, and switchgear, protective equipment, control and communication systems, cable management systems and sockets, indoor or outdoor packages, and so on are typically included in OPS.***Figure 6.1*** shows a typical shore-to-ship power supply system described in this work, which is made up of hardware components [68]. Equipment required for an OPS system in a port will be decomposed after in ***Chapter 6.4***.

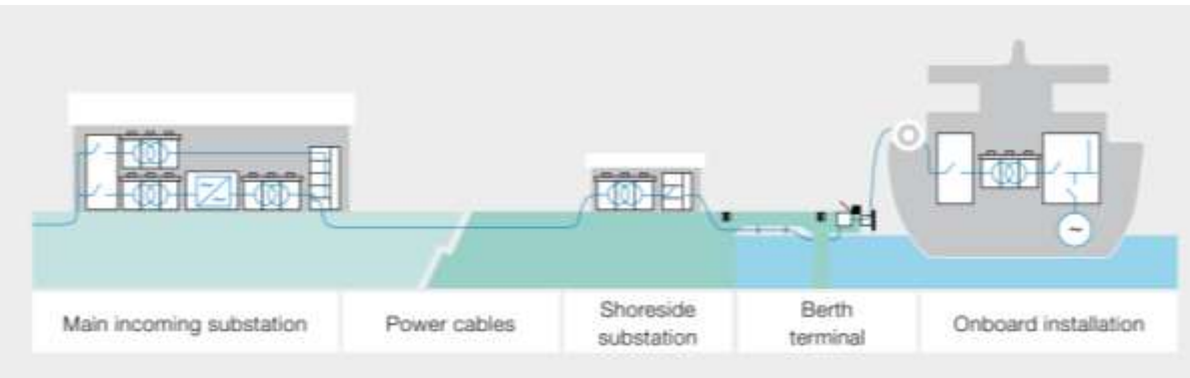


Figure 6.1: Overview of a shore-to-ship power connection [69]

6.3. Main Issue of OPS

The primary issue encountered while connecting the vessel's electric supply system to a land electric grid while anchored in the port is the electric grid's diverse ratings and lack of standardisation of the land electric grid's performance. The nominal ratings of the low voltage land grid fluctuate by port, and even more by country. The frequency of the grid is more essential than its rated voltage. Overall, the electric grid voltage frequency in Europe, Asia, and Africa is 50 $[Hz]$, but in North America it is 60 $[Hz]$ [70]. High and low voltage shore connection systems, on the other hand, provide a number of obstacles. They need to be compatible between ship and shore connection equipment including plugs, socket-outlets and ships couplers [68].

Also, according to *Jagdesh et al* [71], 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, indicating that the majority of large Cruise ships and a few large Container ships operate on high voltage, while the rest of the vessels operate on low onboard voltage.

So, the main issue is that in most of regions and countries, the frequency of power supply and electrical equipment is 50 $[Hz]$, which goes against the electrical frequency of most international ships that is 60 $[Hz]$. As for inland and coastal ships, the electrical frequency is 50 [Hz].

In fact, according to *Greenberg. R.M.* [72], nine (9) of the ten (10) busiest seaports (informatively 1st was Shanghai, 2nd Singapore and 3rd Shenzhen) in the world in 2017, measured by the number of 20-foot equivalent units (TEU's) moved, were in China and nearby areas of Asia, regions that the electric grid voltage frequency is 50 $[Hz]$.

As it has been examined in ***Chapter 3.2.2*** and from ***Table 3.1***, most vessels the frequency and voltage of 440 $[V]/60\ [Hz]$ or 380 $[V]/50\ [Hz]$ for power generation and movement. Nevertheless, on ships with high electrification and high energy-consuming systems, the rated operating voltage rises above 1 $[kV]$ (a value above which the voltage is referred to as "High Voltage") it is necessary to utilise the benefits of a high voltage (HV) installation. To be able to handle the big amount of power, high-voltage usually varying 6÷11 $[kV]$, is used onboard. When the vessel docks at the berth there is no need to produce the same quantity of power to drive the propulsion motors, so therefore a majority of the maingenerators are shut down and only a few generators are used to manage the power needed during hoteling.

Depending on the kind and size of the vessel, multiple levels of power are required while berthing. ***Table 6.1*** shows the power needs for various ship types and sizes depending on the present draft standard ***IEC/ISO/IEEE 80005-1***, which will be reviewed in the next paragraph [73], [74].

Ship Type	**Voltage [kV]**	**Power [MVA]**
Cruise ships	6.6 or 11	16÷20
Container ships	6.6	7.5
Liquefied Natural Gas carriers	6.6 or 11	10.7
Ro-Ro ships	11	6.5
Tankers	6.6	7.2

Table 6.1: The Power requirements at berth [73]

Ships and their electrical requirements may be divided into the following categories:

- Cruise ships, which need 6.6 $[kV]$ or 11 $[kV]$ and 16÷20 $[MVA]$,

- Container ships, which need 6.6 $[kV]$ and 7.5 $[MVA]$,
- LNG carriers, which need 6.6 $[kV]$ or 11 [kV] and 10.7 $[MVA]$,
- Ro-Ro ships, which need 11 $[kV]$ and 6.5 $[MVA]$,
- Tankers, which need 6.6 $[kV]$ and 7.2 $[MVA]$.

These criteria are summarized in ***Table 6.1***.

6.4. Shore Connection International Standards

A standard refers to a technical system for testing, measuring, or materials that has been established as a norm or required, where the following apply [75]:

- Standards are created to ensure that all parties involved have a consistent understanding,
- International, national, state, or industry-specific standards exist,
- A standard does not become legally binding unless it is implemented into a legal document.

The three (3) standardization committees: ***ISO***, ***IEC*** and ***IEEE*** have been assigned to complete a full standard for OPS. They have different influences in different parts of the world, but the main target of standards is to have the same result and not conflicts. The ISO and IEC standards have a greater impact in Europe, while the IEEE standards seem to be more influential to the US. Note that ISO standard is mainly covering the mechanical aspects, in contrast with the IEC and IEEE standards are ultimately focusing on the electrical aspects of the connection [66].

IEC/ISO/IEEE 80005-1, issued in August 2012, is the first global, worldwide standard specifying voltage shore connections systems.

The previous standard was withdrawn in March 2019 and replaced with a new one, ***"IEC/IEEE 80005-1:2019 Utility connections in ports — Part 1: High voltage shore connection (HVSC) systems — General requirements"***. This document is applicable to the design, installation and testing of HVSC systems and addresses [74]:

- High Voltage (HV) shore distribution systems,
- Shore-to-ship connection and interface equipment,
- Transformers/reactors,
- Semiconductor/rotating frequency convertors,
- Ship distribution systems,
- Control, monitoring, interlocking and power management systems.

There are also another two standards available for AC shore-to-ship connections [75]:

- ***"IEC/IEEE 80005-2:2016 Utility connections in port — Part 2: High and low voltage shore connection systems — Data communication for monitoring and control."***,
- ***"IEC/IEEE DIS 80005-3 Utility connections in port — Part 3: Low Voltage Shore Connection (LVSC) Systems — General requirements.",***
- IEC also have additional standards for High Voltage (HV) and Low Voltage (LV) plugs, socket outlets and ship couplers for shore connection systems [76].

6.5. Required Equipment for OPS

The standard equipment is common and may be utilised as a foundation for any installation based on prior installed cases. All of the components must be connected correctly and used in order to get the intended result.

North America and a few nations in South America utilise 60 $[Hz]$ current, which has already been stated at ***Chapter 6.3***, whereas the rest of the globe uses 50 $[Hz]$ frequency current. Advanced frequency converters are now available for port installations in addition to the standard options.

6.5.1. Frequency Converter

Some national grid currents operate at different frequencies than others, resulting in frequency mismatch when a ship was built in a country that uses 60 $[Hz]$ current and has to be berthed in a country that uses 50 $[Hz]$ current, or vice versa.

To attain large power levels, several frequency converters might be parallel connected. Scalable systems are available in the range of 0.1 $[MVA]$ to 120 $[MVA]$. When the national grid's energy costs are lower than the operating expenses of on-board power production, frequency converter use provides a cost saving option [77]. Frequency converters work in low-noise conditions and they do not emit CO_2. Indoor frequency converters and outdoor containerized frequency converters are also available [77].

6.5.2. Electrical Transformer

A transformer is an electrical device that uses magnetic coupling to swap voltage for current in a circuit without changing the electrical power. It transforms high to low voltage so that power may be used to meet the energy requirements of ships. The size and capacity of the transformer should be determined by the needs of the port [75]. Below in ***Figure 6.2***, a containerized transformer substation is depicted.

Figure 6.2: Containerized Transformer Substation by Altgeld products [78]

6.5.3. Switchgear

To better protect electrical equipment, switchgear is made up of electrical disconnect switches, fuses, and circuit breakers, as seen in ***Figure 6.3***. Switchgear is used to disconnect equipment from a source of electricity so that work may be done on it, as well as to clear faults downstream. The reliability of the electricity supply is closely related to this sort of equipment. As a result, it is essential for the system since it determines the power supply's dependability and controls the safe operation of other systems [75].

Figure 6.3: ABB Air Insulated Switchgear [79]

6.5.4. Cables

Electrical cable is a thick wire, or a group of wires inside a rubber covering, which is used to carry electricity or electronic signals [75].

A central cable will be installed to connect the main substation to the national grid, as well as a cable arrangement of subterranean cables to connect it to the shore-side transformer station. A cable reel system and a davit will create the last step of connection, which will elevate the cables overhead at the proper height based on the vessel's necessities [77].

6.5.5. Cable Management System (CMS)

Cable Management System (CMS) is to provide fast connection and disconnection of the shore supply, as well as total safety for workers participating in the connection procedure and harbour operations. Predicting and compensating for anticipated ship movements caused by tidal ranges and draught is critical. It must also make sure that wires don't get in the way of anchoring and cargo handling procedures [80].

As *Cuculić A. et al* indicates [80], the CMS for ***High Voltage Shore Connection (HVSC)*** may be installed in one of two ways:

a) Onboard ship,
b) At berth terminal.

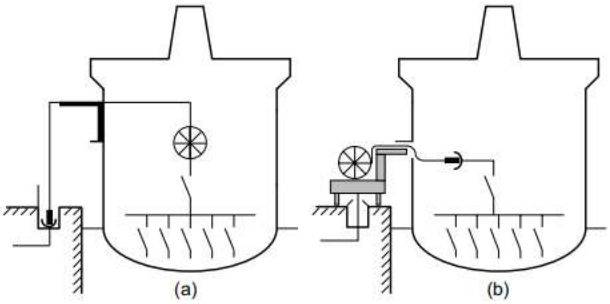


Figure 6.4: HVSC with CMS placed onboard ship (a) and on shore (b) [80]

Connection boxes with one or more sockets must be placed adjacent to the berth in the scenario of onboard CMS installation, as shown in ***Figure 6.4(a)***. They should be in their separate, specially built pits that can resist the tremendous wheel loads of harbour equipment. Connection boxes are located immediately on the edge of each wharf, and the number of them depends on the type of vessels that will be berthed there.

If the CMS is installed on shore, as illustrated in ***Figure 6.4(b)***, the shore connection panel, which includes the main circuit breaker, protection relays, grounding cable, and a proper control interface between the shore side and the ship's integrated automation system, is the basic part of the ship's infrastructure. It must enable completely automatic synchronisation and load transfer between the ship's generators and incoming shore power.

6.6. Shore-Vessel Connection

Connecting cables are used to link the vessel to the shore infrastructure. The following paragraphs are examples of how cables might be used.

6.6.1. Shore-Vessel Connection with Crane Truck

The most uncommon method of connecting is cable elevating by crane truck. The crane truck is wired to the receiving facility and subsequently to the onboard power system. Due to the expensive costs of the crane truck, it is not extensively applied [75].

Figure 6.5: Crane Truck for OPS by Cavotec [81]

6.6.2. Shore-Vessel Connection with Cable System onboard

The ship has a cable system set up. The system has already been placed on several ships' main decks (most often on the port side). It's a hydraulic system that allows cables to be extended and connected to shore. This system may be placed on current or new vessels, and it is a straightforward installation that does not interfere with the systems of the vessel. This is the most effective and fast way of connecting when a vessel has a defined route (Ro-Ro, Containers) between ports that offer shore side connections [75].

Figure 6.6: Onboard Cable System for OPS by Cavotec [81]

6.6.3. Shore-Vessel Connection with immovable Crane

When a ship is anchored, the quay operators oversee the cables and plugs that link the vessel to the shore substation, which are positioned to the ship's entrance using a special immovable crane. ***Figure 6.7*** illustrates the described setup [82].

Figure 6.7: Immovable Crane at quay for OPS [82]

6.6.4. Shore-Vessel Connection with Robot arm

To handle the cable, the operator will first manoeuvre the robot arm to the ship's hatch. The robot arm's own electric motor provides hydraulic energy for all of its motions. The crew ship will then attach the telescopic plug holder to the ship's plug one by one. After connecting all of the telescopic to the socket, the ship is ready for shore power synchronisation and power reception [83].

As *Devi H.S.* states [83]: "The robot arm as a cable management for connecting the cable from shore to ship and can flexibly move from different positions and automatically compensate for tidal range compensation".

APPENDIX II

7. Development of Interactive Map Program

In this Chapter, it will be explained how the Map Program was developed in Python, which is a programming language, and the way data was imported and be presented in an HTML[11] standard [1].

Before describing the development methodology of the program, it is worth noting that the work of this diploma is a continuation of the hard labour of another diploma on subject: ***"Issues of Electricity in Ships and Ports"*** [2].

It's also worth mentioning *B. Stolz's et al* [3] contribution to data collection, since they developed a novel approach for estimating auxiliary power demand at berth for 714 main ports in the European Economic Area (EEA) and the United Kingdom (UK). As a result, data from the European Union's Monitoring, Reporting, and Verification (MRV) scheme and data from the Automatic Identification System's (AIS) ship tracking system are integrated. The work database is comprehensive, containing data on energy requirements and emissions for each ship type, each hour, and each EEA and UK port in 2018.

7.1. Programming and Coding

Starting with the definitions of "programming" and "coding", these terms are often used interchangeably, but there are some differences. Coding is the process of writing code, whereas programming is the process of creating functioning software or a computer program.

By using the terminology "programming" or "coding" the concept is the writing lines of code and construction of a program with the ultimate purpose of serving some functions and tasks from a computer, in order to take advantage of computer calculation-speed. In fact, even early computers such as ENIAC[12], the world's first electronic digital computer, weight over 30 tonnes and required a space of a house of a four person family, still it could complete a multiplication process for two 10-digit numbers in just 2.6 milliseconds, an inconceivable for humans even today [4].

Learning to code teaches you not only how to give machines commands, as well as how to think abstractly and solve problems. In fact, becoming a great computer programmer requires problem-solving abilities and inventiveness.

Thus, Programming is a sector that is systematically growing and in recent years has "penetrated" into almost all sectors of an economic system, from automation in the food production industries to the sophisticated navigation systems placed on ships.

[11] HTML - Hypertext Markup Language, a standardized system for tagging text files to achieve font, color, graphic, and hyperlink effects on World Wide Web pages.
[12] ENIAC - Electronic Numerical Integrator and Computer

7.2. A brief analysis of Python as a Programming Language

Python is a high-level general-purpose programming language suited for usage as a scripting language, Web application implementation language, and so on since code is automatically compiled to byte code and executed [1].

It’s called higher-level language because structures can cut down on the amount of time it takes to construct a “framework” that was previously required [5]. Python helps us to develop clear, logical applications for small and large tasks because to its powerful structural constructs (nested code blocks, functions, classes, modules, and packages) and consistent usage of objects and object-oriented programming [1]. The inclusion of these essential building pieces in the core language encourages their use while also reducing development time and code size, resulting in more understandable code [5].

Figure 7.1: The Python Logo [24]

A Python program is divided into a number of logical lines [6].

7.2.1. Python Libraries

A number of built-in and standard libraries are included with every Python implementation. These are listed in the library-index.

Libraries are a basic organizational unit of Python code, and are created by the `import system` as invoked either by the `import` statement, or by calling functions.

Each library has its own private symbol table, which is used as the global symbol table by all functions defined in the library. Thus, the author of a library can use global variables in the library without worrying about accidental clashes with a user’s global variables.

Some libraries that were used in this study and will be analysed further in the following lines are numpy, folium, pybase64, etc.

7.3. Structure of the Program

The first two (2) layers of the map, were created during the study process of the diploma ***"Issues of Electricity in Ships and Ports"*** [2]. The other five (5) layers were produced throughout this postgraduate diploma, similar way of the methodology of the first two (2).

Initially, the code consisted of scripts that were used to create the charts and tables that would be placed on the interactive map and then these figures were sent through another script to create the program in HTML, as shown in ***Figure 7.2***.

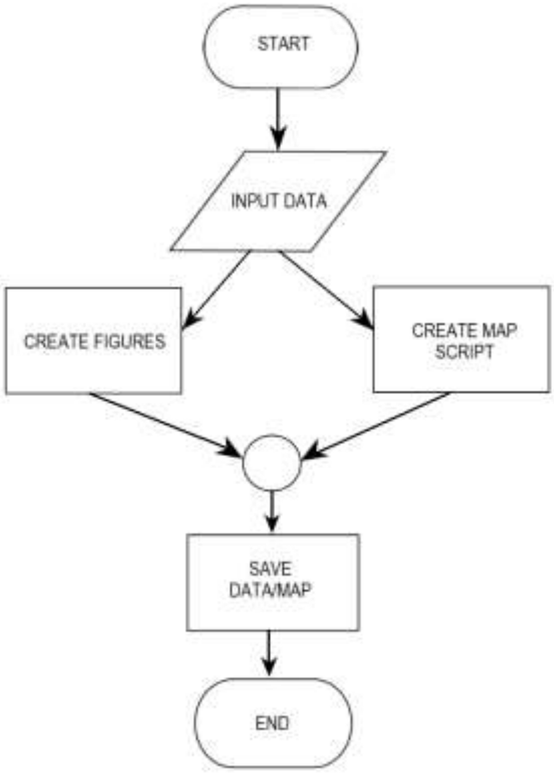


Figure 7.2: Procedure followed to develop the program of interactive map in a flow chart

Following that, an analytical explanation of the data import procedure, the scripts and diagrams developed, and the architecture of the interactive map application will be provided. More focus will be placed on the physical / mechanical portion of the analysis, but the process followed and the programming part will also be highlighted.

The interactive map program is consisted of seven (7) layers, each one containing different type of figures and details. These layers will be inspected further more in the next pages.

7.3.1. Importing Data

Obtaining data is the first stage in any data analysis procedure. Data can come from a variety of places, but the most frequent are text and Excel (xlsx) files. In this case, the data were imported as a comma-separated values (csv) file, which is a delimited text file that uses a comma to separate values. Each line of the file is a data record.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Port ID	Port name	Country abbreviation	Longitude in EPSG:4326	Latitude in EPSG:4326	Y coordinate in EPSG:3035	X coordinate in EPSG:3035	Ship category	Power Sum	Max Power	Min Power	Average Power/year	1	2
2	70	KEFLAVIK	IS	-22.55	64	2787283.74	4910480.92	Passenge	2E+10	1697	0	10.4	0	0
3	100	REYKJAVIK	IS	-21.93333333	64.15	2821794.069	4911874.669	Passenge	6E+11	16060	0	716	0	0
4	105	GRUNDAR	IS	-22	64.266667	2825136.353	4924929.309	Passenge	6E+10	4835	0	48.3	0	0
5	160	BILDUDALU	IS	-23.6	65.683333	2836544.24	5099348.554	Passenge	1E+10	1533	0	2.8	0	0
6	185	BOLUNGA\	IS	-23.23333333	66.166667	2878194.307	5138905.213	Passenge	6E+10	8906	0	32.7	0	0

Figure 7.3: Typical xlsx format of the data that were used

The data, as it was mentioned before, were taken by the study: ***"The CO_2 reduction potential of shore-side electricity in Europe."*** of *B. Stolz et al* [3]. The emission report data were combined taken from the Monitoring, Reporting and Verification (MRV) scheme of the European Union and ship tracking data from the Automatic Identification System (AIS), in the year 2018 [3].

Csv is a plain text format with a series of values separated by commas whereas Excel (xlsx) is a binary file that holds information about all the worksheets in a workbook. Comparing csv with xlsx, csv files are faster and also consume less memory whereas xlsx consume more memory while importing data. So, the main reason of using csv files is because of the large data volume, which will lead to very slow processing speeds of the data.

There are two main csv files that were provided by the study of *B. Stolz et al* [3] are:

- **"AE_power_use_at_berth.csv"**: contains ship energy needs data in every port. More specifically, there are measurements for each port, for each type of ship, for each hour of 2018.
- **"AE_emissions_at_berth.csv"**: contains CO_2 emission data in each port. Especially, there are measurements for each port, for each type of ship, for each hour of 2018.

The format taken from the xlsx files, after converted from csv into xlsx is as shown in the ***Figure 7.3***.

There is several information such as:

- Port ID: an Identity number to distinguish each port i.e., 70,
- Port Name: port's name i.e., KEFLAVIK
- Country Abbreviation: a two-letter code for the country where the port is under jurisdiction i.e., IS (IS stands for Iceland),
- Longitude: Longitude coordinate in World Geodetic System 1984, used in GPS,
- Latitude: Latitude coordinate in World Geodetic System 1984, used in GPS,
- Y Coordinate: Y coordinate in Cartesian System 2D,
- X Coordinate: X coordinate in Cartesian System 2D,
- Ship Category: the type of ship i.e., Passenger Ship,

- Power Sum: the total power sum of a year calendar,
- Maximum Power: the maximum power that was recorded in a year calendar,
- Minimum Power: the minimum power that was recorded in a year calendar,
- Average Power per year: the average power that was recorded in a year calendar,
- Power for each hour of a year[13]: it contains each hour's of the year corresponding power. It consists of 8760 columns, each one representing one hour of a year calendar Load Duration Curves (LDCs)

It is necessary to continue to explain Load Duration Curves (LDCs), many times seen in the sources as Load Demand Curves), in order to understand later the theoretical background that the figures were constructed. A LDC basically, is created by rearranging the hourly chronological electric power load data from the highest to lowest value. In this study, LDC's y-axis contains the Power Demand $[kW]$ of the specified type ship, of the particular port, while the time $[h]$ is included in the x-axis, as shown in ***Figure 7.4***.

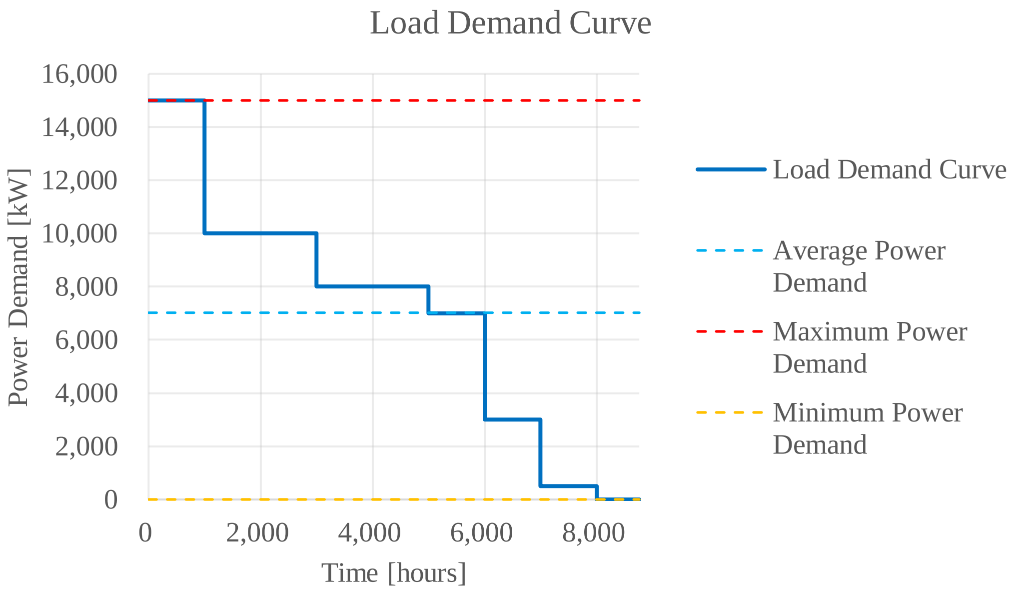


Figure 7.4: Typical Load Duration Curve (LDC)

The power demand recordings per ship type can be well collected and arranged on a regular basis, e.g., for a year, to produce the LDCs.

The diagram's curve is descending, and each point on the x-axis represents the minimum power needed for a certain number of hours or a specific percentage of total study time. The left-hand side of the curve has the highest power demand, while the right-hand side has the lowest power demand. It's worth noting that the curve isn't arranged chronologically, but rather according to the magnitude of the power demand. The area below the curve depicts the quantity of energy needed by the consumer for this time period. Also, the Average Power Demand is defined by the following equation [7]:

$$Average\ Power\ Demand = \frac{Total\ Area\ [kWh]\ under\ LDC}{8{,}760\ [hours]}$$

[13] 1 year = 8760 hours

In ***Figure 7.4***, Average Power Demand will be:

$$Average\ Power\ Demand = \frac{6.15 \times 10^{7}\ [kWh]}{8{,}760\ [hours]} = 7{,}020.5\ [kW]$$

While:

$$Maximum\ Power\ Demand = 15{,}000\ [kW]$$

$$Minimum\ Power\ Demand = 0\ [kW]$$

7.3.2. 1st Layer of Interactive Map

The 1st Layer of the Interactive Map is called ***"Emission, Power Demand and LDCs for each Ship Type"***, which contains the following information for each ship type in every port:

- Port ID,
- Port Name,
- Country,
- Ship Type,
- Emissions $[t/year]$,
- Power Demand $[kWh/year]$,
- Average Power Demand $[kW/h]$.

The layer is also supplemented by the Load Duration Curves (LDCs), by each ship type in every port, which is placed under the above information (Port ID, Port Name, etc), as shown in ***Figure 7.5*** which shows the LDCs of all ship types of the port of Piraeus, Greece.

The figures were created in a Python script with a focus to be inserted in every port in the map.

Firstly, python libraries must be imported in the script **"Load_Demand_Duration_Curves"** by the following lines:

```
import csv
from matplotlib import pyplot as plt
```

Some of the above words, such as `import` or `as` are keywords of the language, and cannot be used as ordinary identifiers. They must be spelled exactly as written [6].

The libraries are used in an effort to:

- `csv` [8]:the `csv` library implements classes to read and write tabular data in CSV format. It allows users to say, "write this data in the format preferred by Excel," or "read data from this file which was generated by Excel," without knowing the precise details of the CSV format used by Excel.
- `matplotlib.pyplot` [9]: `matplotlib` is a comprehensive library for creating static, animated, and interactive visualizations in Python. `pyplot` is a `matplotlib` module which provides a MATLAB-like interface. `matplotlib` is designed to be as usable as

MATLAB, with the ability to use Python, and the advantage of being free and open-source. It can create publication quality plots, make interactive figures that can zoom, pan, update and also customize visual style and layout.

PORT ID: 42230 -PORT NAME: **PIRAIEVS** -COUNTRY: **GR** -DATA FORMAT :[SHIP TYPE, EMISSIONS[t], POWER DEMAND[KWh], AVERAGE ENERGY DEMAND [kW/hour]

[Bulk carrier , 4929.46 (t/year), 6286969.63 (KWh/year), 717.69(kW/hour)]

[Chemical tanker , 5565.71 (t/year), 7098427.95 (KWh/year), 810.32 (KW/hour)]

[Combination carrier , 81.6 (t/year), 104072.81 (KWh/year), 11.88 (KW/hour)]

[Container ship , 37865.28 (t/year), 48979148.33 (KWh/year), 5591.23 (KW/hour)]

[Container_ro-ro cargo ship , 527.9 (t/year), 673279.58 (KWh/year), 76.86 (KW/hour)]

[Gas carrier , 1676.46 (t/year), 2138128.45 (KWh/year), 244.08 (KW/hour)]

[General cargo ship , 504.48 (t/year), 643407.7 (KWh/year), 73.45 (KW/hour)]

[LNG carrier , 135.07 (t/year), 172261.32 (KWh/year), 19.66 (KW/hour)]

[Oil tanker , 12393.55 (t/year), 15806559.25 (KWh/year), 1804.4 (KW/hour)]

[Other ship types , 80.14 (t/year), 102213.81 (KWh/year), 11.67 (KW/hour)]

[Passenger ship , 13894.25 (t/year), 17720533.73 (KWh/year), 2022.89 (KW/hour)]

[Refrigerated cargo carrier , 59.72 (t/year), 76164.15 (KWh/year), 8.69 (KW/hour)]

[Ro-pax ship , 54292.64 (t/year), 69244097.69 (KWh/year), 7904.58 (KW/hour)]

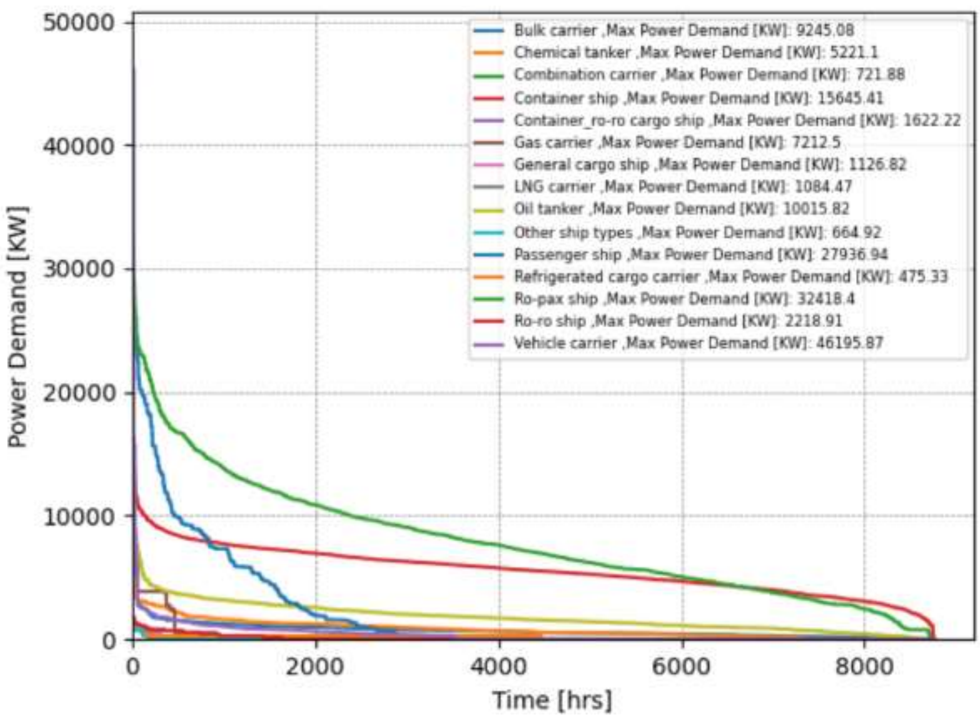


Figure 7.5: 1st Layer Information and LDCs

After collecting all data from the csv files, a “nested list” is created. In Python, a list is used to store multiple items in a single variable. A “nested list” is basically a list of lists, or any list that has another list as an element (a sublist). The nested list in essence is simple, the list contains the 4566 sublists (of 715 ports of EEA and UK), each sublist representing one ship category of a specific port. Every sublist of the nested list contains 8772 other elements. The first twelve (12) elements are:

1. Port ID,
2. Port Name,
3. Country,
4. Longitude,
5. Latitude,
6. Y Coordinate,
7. X Coordinate,
8. Ship Type,
9. Maximum Power,
10. Minimum Power,
11. Power Sum,
12. Average Power per year.

The rest 8760 of the total 8772 elements are showing the power demand (in [kWh]) of each hour in a year calendar of the particular ship type. In ***Figure 7.6*** is shown qualitatively how a nested list is structured.

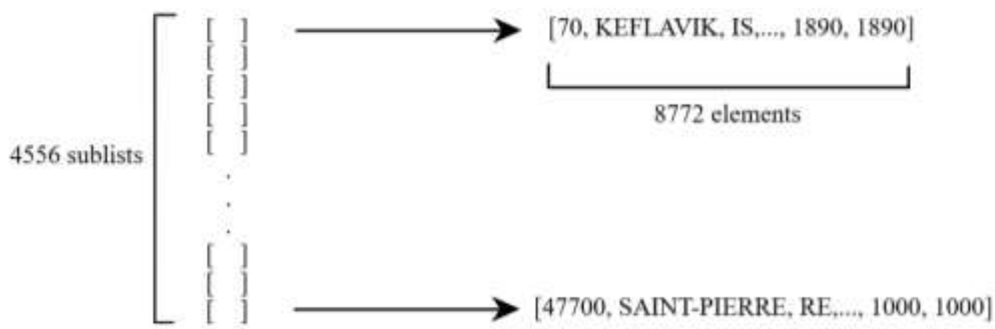


Figure 7.6: Qualitatively Structure of a nested list

With the command:

```
plt.plot(x, y)
```

Python creates the LDCs figures which be later be inserted in the map, while the command:

```
plt.savefig(fname=Port_ID[i] + '.png')
```

Saves all the figures in a folder as images in a PNG (Portable Network Graphics) format, with name “Port ID.png”, i.e., “70.png”.

Below, are shown six (6) big ports of Greece, presenting the LDCs of each ship type in each port. Clearly, ports like Mykonos and Kerkyra have a higher power demand for Passenger and Ro-Ro ships

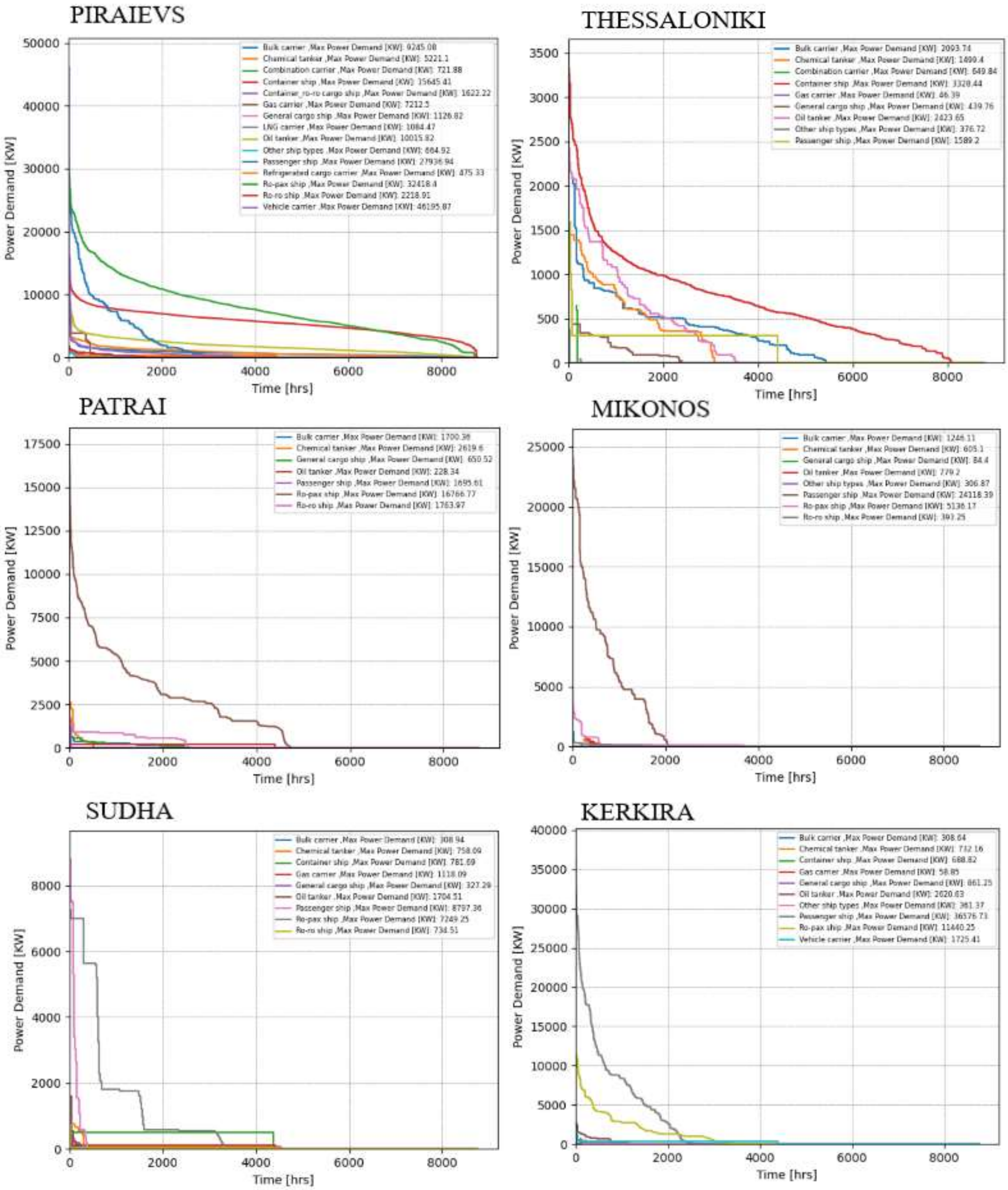


Figure 7.7: LDCs of large ports in Greece

than ports like Thessaloniki, which is mainly a commercial port with the highest power demand been used by Container ships and Bulk carriers. LDCs diagrams are presented in ***Figure 7.7***.

7.3.3. 2nd Layer of Interactive Map

The 2nd Layer of the map is called ***"Total Load Demand Duration Curves"*** and presents a LDC for all the ship types of a port. The area under the LDC, represents the yearly energy needs of the port, in $[kWh]$.

A script was used to create, again as earlier, the desirable figures for the Total LDCs.

Libraries as `csv` and `matplotlib` were used in the 2nd Layer, as before, with the addition of library NumPy, which stands for "Numerical Python", which is imported the same way at the start of the script:

```
import numpy as np
```

Library `numpy` is an open-source Python library that's used in almost every field of science and engineering. It provides array, a homogeneous n-dimensional array object, with methods to efficiently operate on it. numpy can be used to perform a wide variety of mathematical operations on arrays [10].

A numpy array is a grid of values, all of the same type, instead of a python list can consist of elements belonging to different data types. This gives the advantage of working with arrays that are comparatively more compact in memory size than python lists.

To demonstrate the Total LDCs, a for-loop[14] is used to sum up all the Power Demand for each Ship type of each port and then Power Demand is sorted chronologically, in a descending form.

Again, in the 2nd Layer, information is provided such as:

- Port ID,
- Port Name,
- Country.

Also, a LDC for all the port's ship types is exhibited, as the one in ***Figure 7.8*** which demonstrates the LDC of the port of Piraeus, the largest port in Greece.

[14] for-loop - is a control flow statement for specifying iteration, which allows code to be executed repeatedly.

PORT ID: 42230 PORT NAME: PIRAIEVS COUNTRY: GR

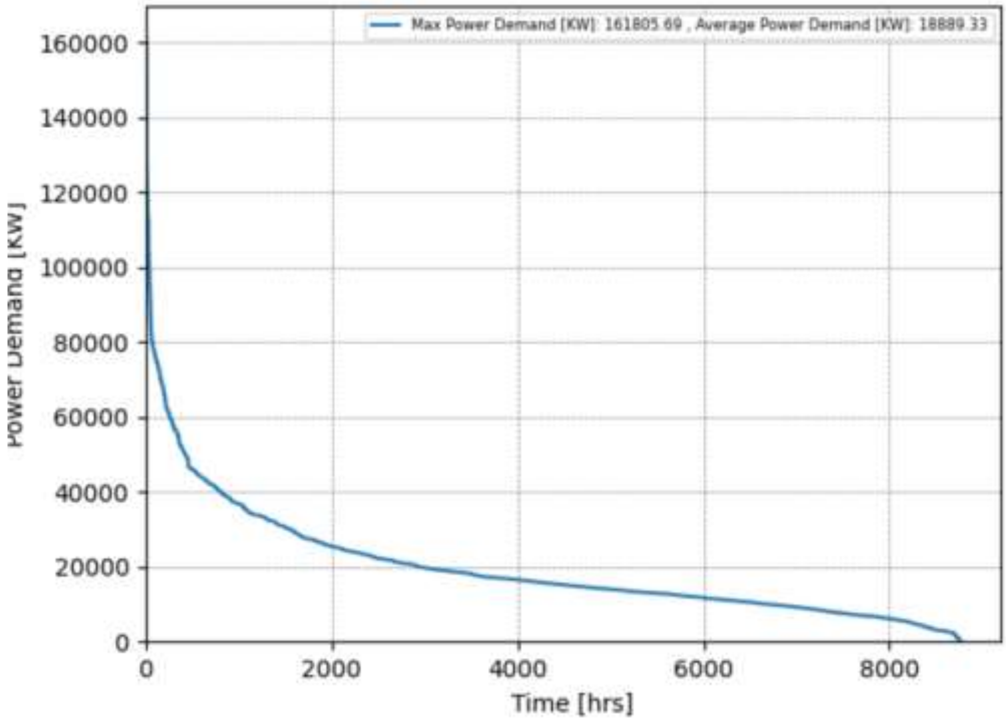


Figure 7.8: 2nd Layer Information and total LDC of Piraeus

Total LDCs of different large ports in Greece is also shown in ***Figure 7.9***, like ports of Thessaloniki, Patra, Mykonos, Suda and Kerkyra.

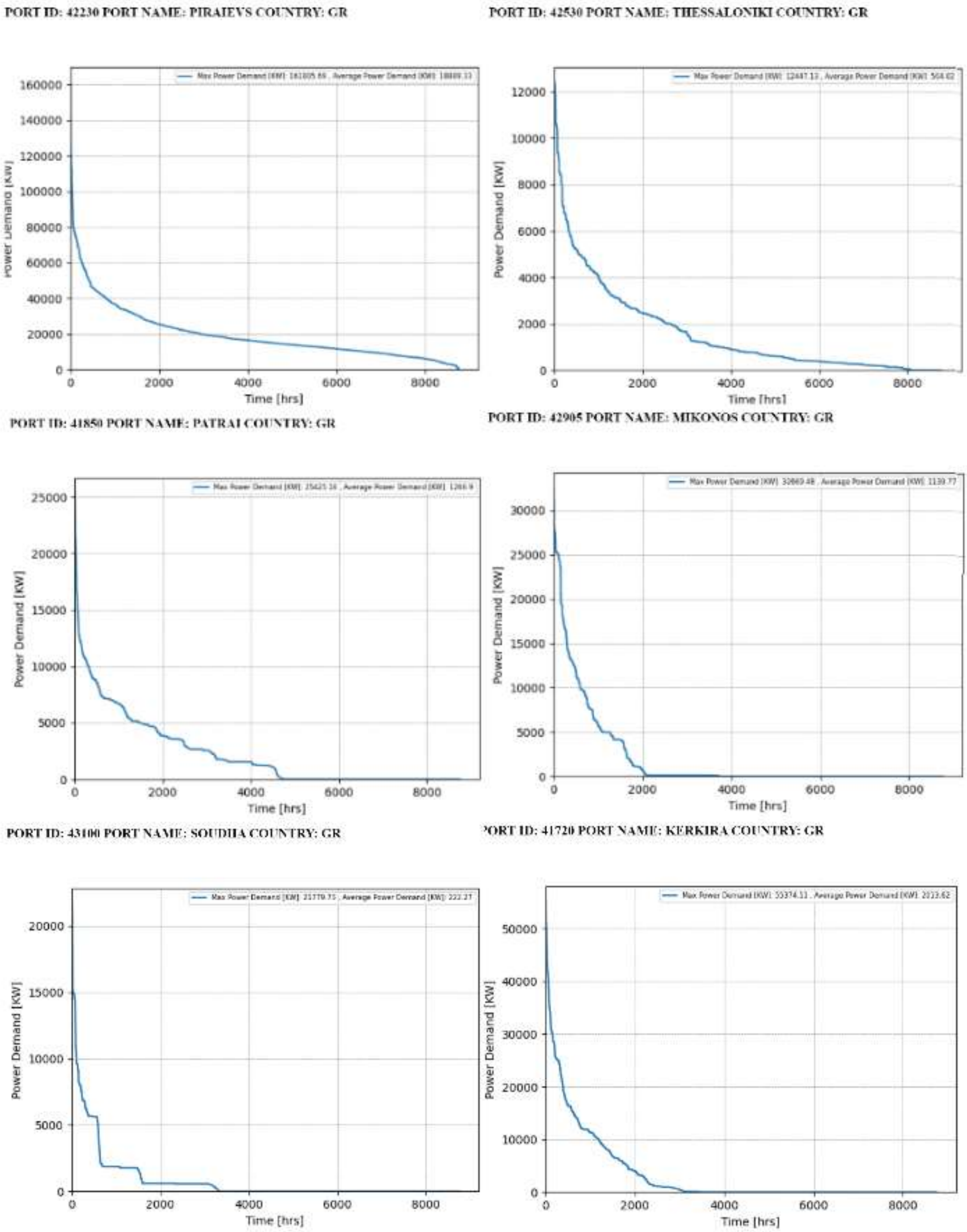


Figure 7.9: Total LDCs of different large ports in Greece

7.3.4. 3rd Layer of Interactive Map

In the 3rd Layer of the Interactive Map is a special case of the first layer which includes only the following categories of ships:

- Container ship,
- Passenger ship which includes:
  - Cruise ships,
  - Ferries,
  - Ro-Ro ship,
  - Ro-Pax ship.

A Passenger ship, according to the definitions of EU Council and Parliament [11], a "Passenger ship" is a ship that carries more than 12 passengers, including cruise ships, high-speed passenger crafts and ships with facilities to enable road or rail vehicles to roll on and roll off the vessel ("Ro-Ro passenger ships").

Also, the EU Institutions [11], interpret the "Ro-Ro passenger ship" as a ship with facilities to enable road or rail vehicles to roll on and roll off the vessel, and carrying more than 12 passengers.

Ro-Pax is a vessel with large ro-ro decks and limited passenger facilities. Usually, the superstructure covers part of the upper deck. The vessel design normally allows for drive-through traffic, i.e., loading aft and unloading forward, or vice versa. The internal distribution of vehicles can be accomplished through deployment of internal ramps or loading on two levels by two-level shore ramps. For flexibility, Ro-Pax vessels are usually equipped with hoistable car decks [12].

The Python script that was used contains two libraries, as the 1st Layer:

- `csv`,
- `matplotlib.pyplot`.

Over again, this layer includes information as the layers before (Port ID, Port name and Country) and below this information, the LDCs of this Container and Passenger ships are set. A typical example of the port of Piraeus is shown once more in ***Figure 7.10***, for the 3rd Layer of the map.

This category of ships is very important, as it has been pointed out in ***Chapter 5.2.1***, because it mandates the use of OPS for two ship types after 1st of January, 2030: Passenger ships and Container ships.

In a study that was carried out in 2022, composed by Gozillon D. (T&E[15]) [13], mentions the following: "The scope of the current SSE[16] mandate is limited to passenger and container ships only. This leaves out 57% of EU emissions at berth, i.e., 5 $[Mt]$ of CO_2 and 3 $[kt]$ of Sulphur Oxide (SO_x) per year, equivalent to the SO_x emissions of the entire EU passenger car fleet (250 million cars)."

[15] European Federation for Transport and Environmet
[16] SSE - Shore Side Electricity

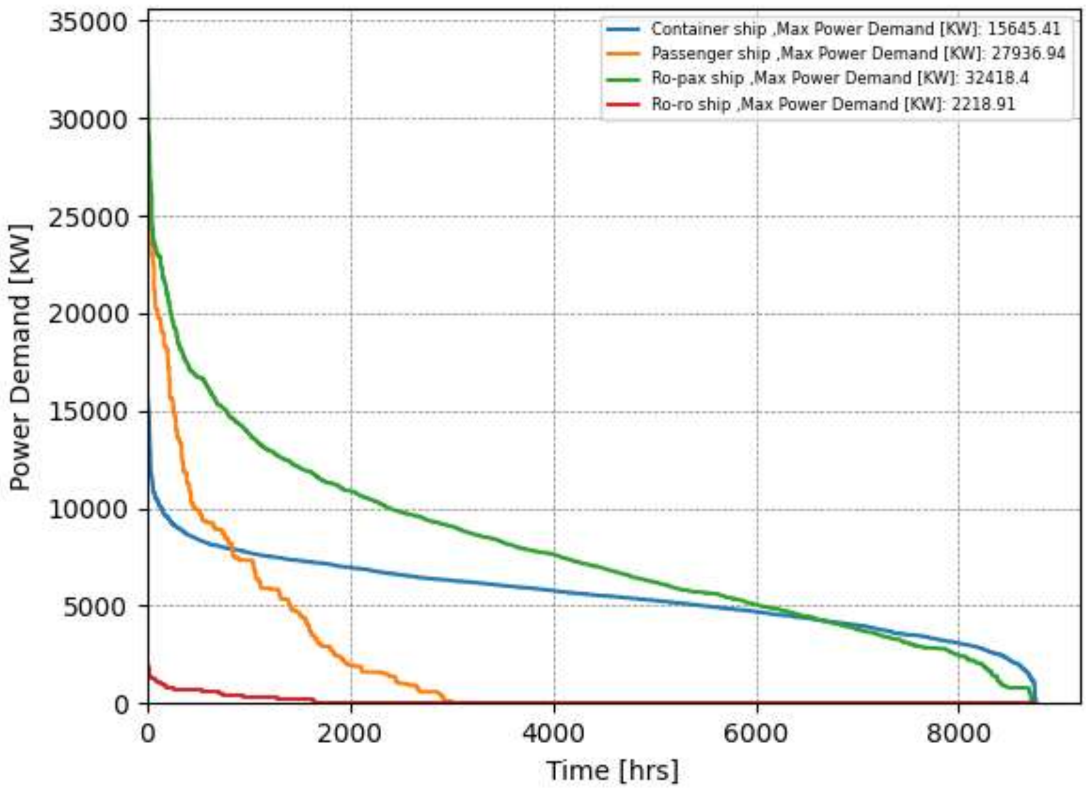


Figure 7.10: 3rd Layer information and LDCs for Container and Passenger ships for the port of Piraeus

Ports like Mykonos, Piraeus and Kerkyra are heavily dependent on Cruise ships, which belong to the category of Passenger ship. Generally, Cruise ships need a huge demand of power when berthing, because of the various facilities that are installed onboard. LDCs for Container and Passenger ships are illustrated in ***Figure 7.11***.

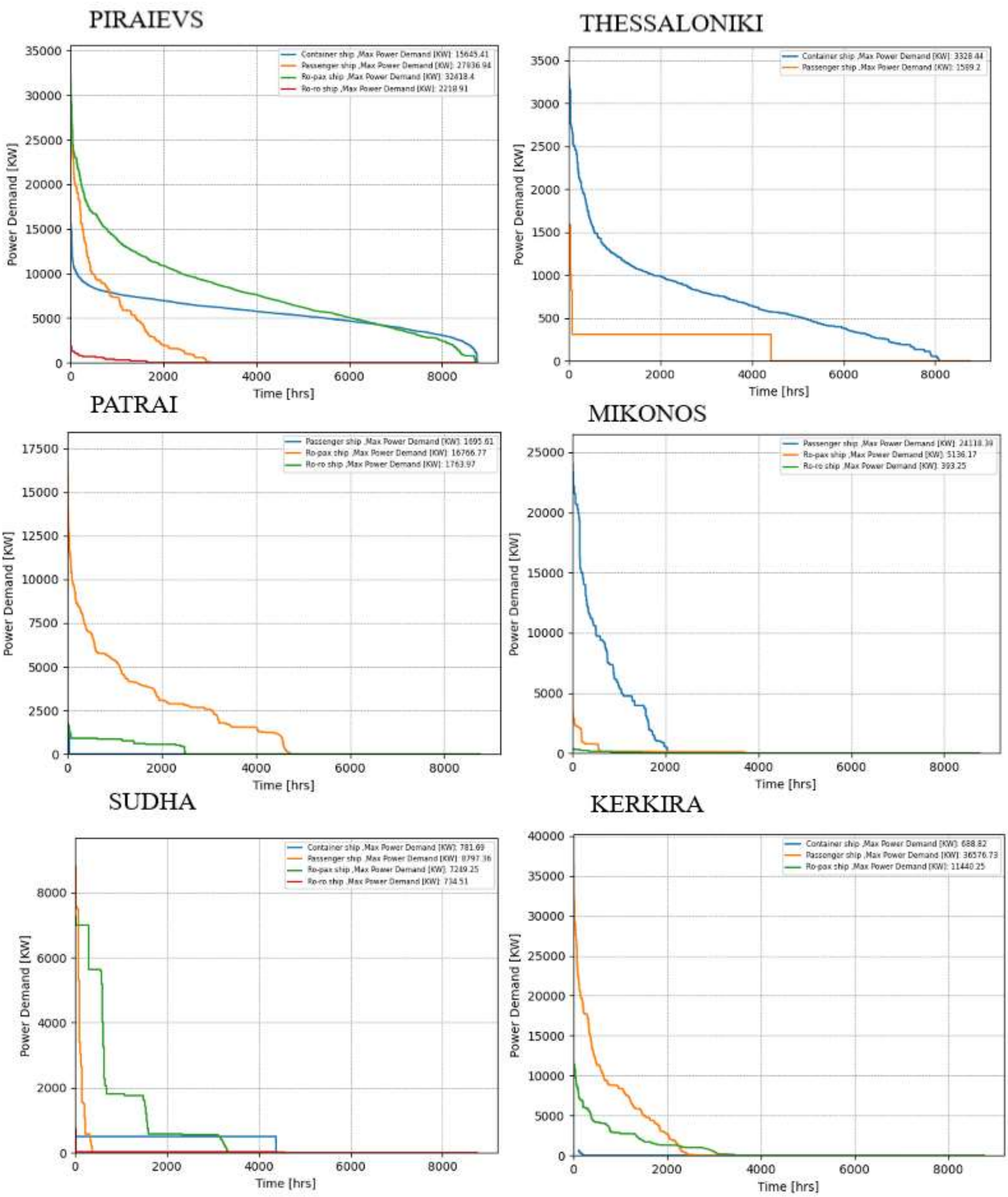


Figure 7.11: LDCs for Container and Passenger ships for different large ports of Greece

7.3.5. 4th Layer of Interactive Map

Once more, 4th Layer of the Interactive Map by the name of "***Total LDCs for Container and Passenger ships***". This layer is a special case of 3rd Layer, similar to that of layers 1 and 2. As seen before, the 3^{rd} Layer shows the LDCs of each type of ship separately, while the 4^{th} Layer shows the total LDC for all types of ships, in each port.

The types of ships involved in the process of creating and calculating the total LDC charts of all the ports in EEA and UK region are the Container ships and Passenger ships.

In the 3rd Layer script, like the 2nd Layer's script, libraries like `csv` and `matplotlib.pyplot` are utilised, with the inclusion of library `numpy`, to construct total LDCs using its functions. At the start of the script, `numpy` is imported in a similar way:

```
import numpy as np
```

LDC of Port of Piraeus is once more presented in ***Figure 7.12***, this time showing the Total LDC of the port, for Passenger and Container ships.

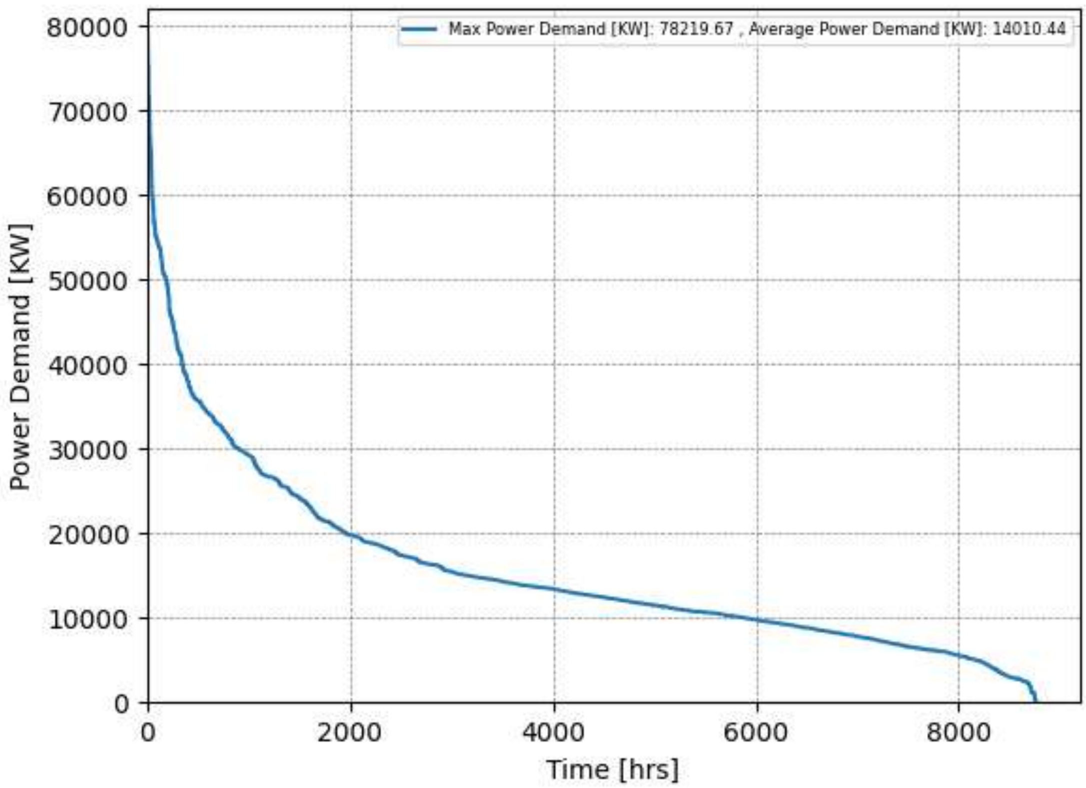


Figure 7.12: 4th Layer information and LDC for Container and Passenger ships for the port of Piraeus

To obtain an order of magnitude of the Total Power Demand in the specific port (Piraeus port), the Maximum and Average Power Demand for all types of ships (from ***Figure 7.8***) are 161,805.69 $[kW]$ and 18,889.33 $[kW]$, respectively, while the Maximum and Average Power Demand for Container and Passenger ships are (from ***Figure 7.12***) 78,219.67 $[kW]$ and 14,010.44 $[kW]$, respectively. These total power requirements of Containers and Passenger ships with respect to total power requirements of all ship types, in the port of Piraeus for example, constitute approximately 48% for Maximum Power Demand, but around 74% of Average Power Demand.

In ***Figure 7.13***, ports of Piraeus, Thessaloniki, Patra, Mykonos, Suda and Kerkyra are displayed

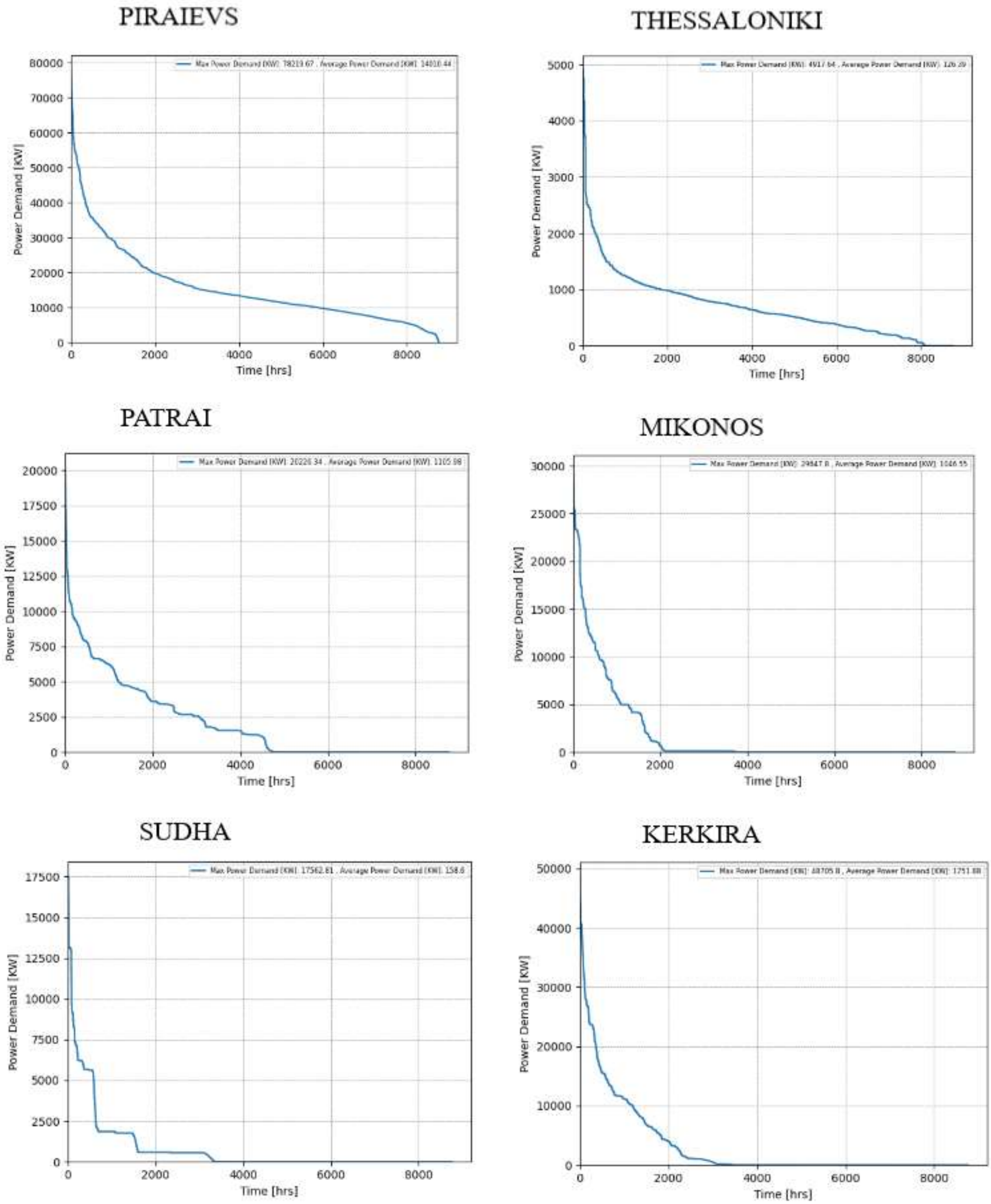


Figure 7.13: Total LDCs for Container and Passenger ships of large ports of Greece

7.3.6. 5th Layer of Interactive Map

5th Layer of the Interactive Map is labelled "***Total LDCs Prediction +25% for 2030***" and presents total LDCs figures of all ports of EEA and UK, including all ship types. This constitutes a realistic scenario, in relation to the Power Demand increment of the ports in EEA and UK, multiplied by a factor of 1.25 (or otherwise +25% increase) would be in 2030.

Again the script for the creation of the figures uses the libraries of `csv` and `matplotlib.pyplot`. Generally, the approach for producing the figures is close to the procedure which was followed in the previous layers.

Below, the Total LDC multiplied by the factor 1.25 is an appreciation for 2030 Piraeus's Power Demand of all ship types, shown in ***Figure 7.14***.

Also, various graphs about the power demand and energy needs of different ports in Greece, are given below in ***Figure 7.15***.

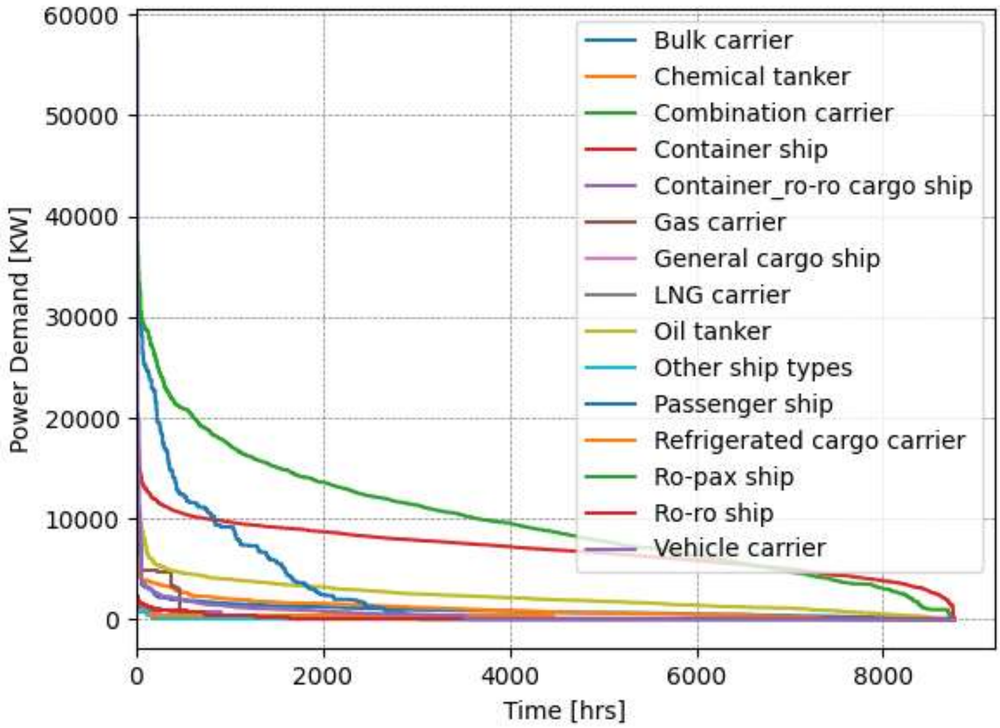


Figure 7.14: 5th Layer information and LDC for the port of Piraeus +25% Power Demand increment appreciation for 2030

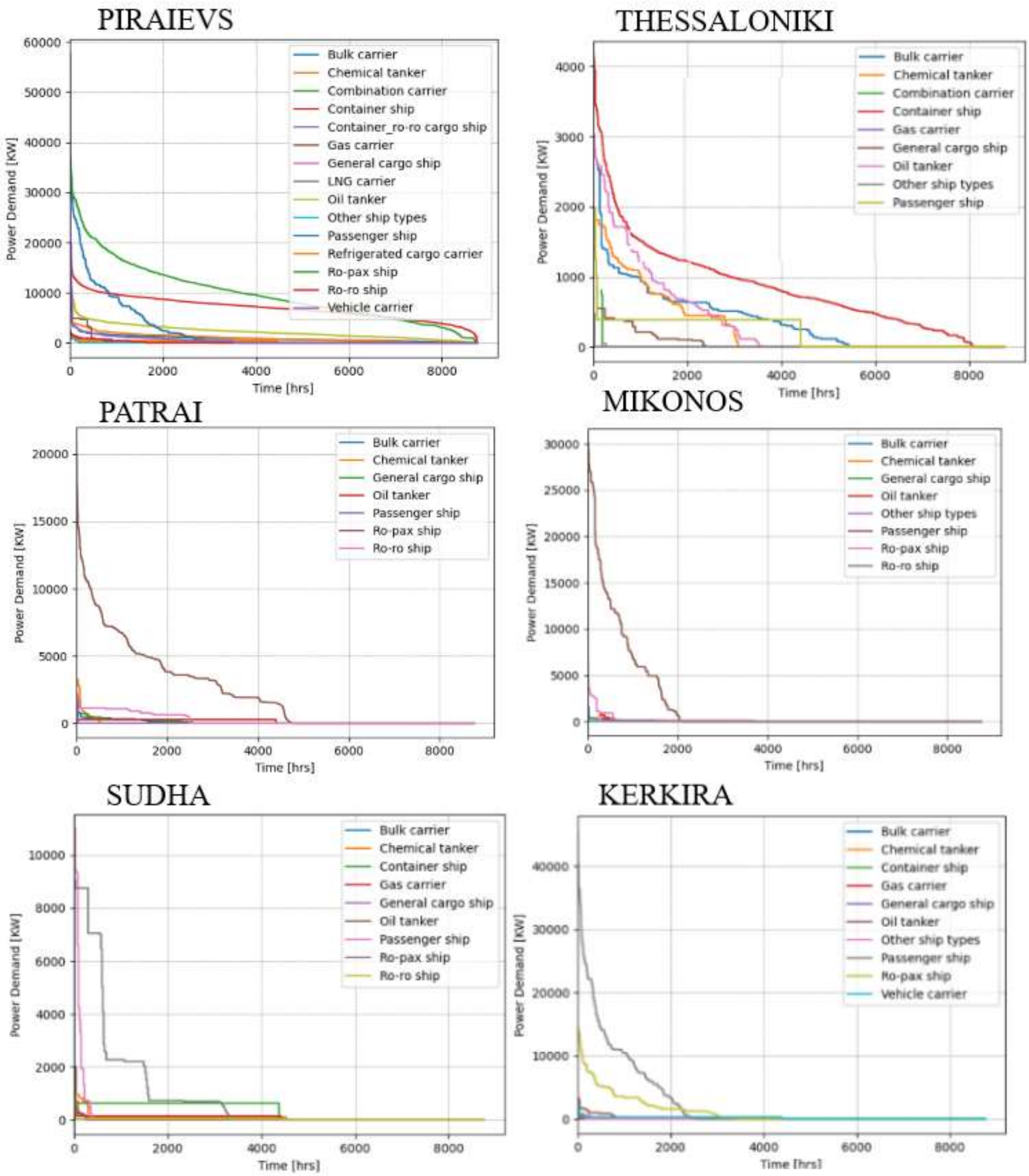


Figure 7.15: LDCs for different large ports of Greece with an approximation increase of +25% in power demand for 2030

7.3.7. 6th Layer of Interactive Map

In this Chapter will be looked over the 6th Layer of the Interactive Map, the so-called "***Total Emission and External Costs***", which exhibits total emission and external costs (as the label reports) of each port in EEA and UK for all ship types. This Layer contains not only figures for the emissions, but also tables that comprise the "External costs" (External Costs definition is explained right below) of these emissions in each port.

7.3.7.1. External Costs and Emission Factor

Firstly, will be defined "External Cost" as *Van Hessen H. et al* [14] reports that: "External Costs, also known as externalities, arise when the social or economic activities of one (group of) person(s) have an impact on another (group of) person(s) and when that impact is not fully accounted, or compensated for, by the first (group of) person(s). In other words, external costs of transport are generally not borne by the transport user and hence not taken into account when they make a transport decision. Cars exhausting NO_x emissions, for example, cause damage to human health, imposing an external cost. This is because the impact on those who suffer damage to their health is not taken into account by the driver of the car when deciding on taking the car."

In general, an emission factor (EF) represents a model for a first order estimate of emissions, which correlates the quantity of pollutant released into the atmosphere with a so-called "activity index" related to the release of that pollutant [15].

7.3.7.2. Emissions and Cost Factors

Furthermore, for the emissions in each port, will be focus on the three (3) most important emissions:

- Nitrogen Oxides (NO_x),
- Sulphur Dioxide (SO_2),
- Particulate Matter ($PM_{2.5}$).

The above emissions were selected pursuant to four types of impacts caused by the emission of transport related air pollutions, as the ones below [14]:

- <u>Health effects:</u> Breathing air pollutants including particles ($PM_{2.5}$) and Nitrogen Oxides (NO_x) increases the risk of respiratory and cardiovascular diseases (e.g., bronchitis, asthma, lung cancer). These unfavourable health impacts result in increased medical expenses, lost productivity at work (due to illness), and, in rare circumstances, even death,
- <u>Crop losses:</u> Ozone (primarily generated by NO_x emissions) and other acidic air pollutants (e.g., SO_2, NO_x) can harm agricultural crops. As a result of the increasing concentration of ozone and other compounds, crop yields may decrease (e.g., for wheat),
- <u>Material and building damage:</u> Air pollutants can cause two forms of damage to buildings and other materials:
  - Particles and dust pollution of building surfaces,
  - Corrosion of building facades and materials caused by acidic compounds (e.g., NO_x, SO_x),
- <u>Loss of biodiversity:</u> Air pollution can affect ecosystems. The most serious consequences are:
  - Soil, precipitation, and water acidification (due to NO_x, SO_2),
  - Ecosystem eutrophication (e.g., by NO_x). Ecosystem damage can result in a loss of biodiversity (flora & fauna).

Cost factors of the examined emissions (NO_x, SO_2, $PM_{2.5}$), are given by the ***Table 7.1*** [14], for average damage cost, in $[€/kg\ of\ emission]$, for maritime emissions in 2016 (all effects: health effects, crop loss, biodiversity loss, material damage).

[$€_{2016}$/kg]	SO_2	NO_x	$PM_{2.5}$
Atlantic	3.5	3.8	7.2
Baltic	6.9	7.9	18.3
Black Sea	11.1	7.8	30.0
Mediterranean	9.2	3.0	24.6
North Sea	10.5	10.7	34.4

Table 7.1: Air pollution costs: average damage cost in [€/kg of emission], national averages for maritime emissions in 2016 (all effects: health effects, crop loss, biodiversity loss, material damage) [14]

The above cost factors should be should be converted in prices of 2018, since the specific ones in ***Table 7.1*** refer to prices of 2016. Yearly inflation rates of European Union were used, in order to make this conversion [16]. Basically, inflation measures how much more expensive a set of goods and services has become over a certain period, usually a year. ***Table 7.2*** lists the annual Inflation Rate of European Union, from 2016 to 2020.

Year	**Inflation rate [%]**
2016	0.17
2017	1.47
2018	1.78
2019	1.64
2020	0.51

Table 7.2: European Union annual inflation rate historical data

The cost of €1 of an amount of emission in 2016, will be costing €1.03 in 2018, if inflation is included in the conversion of the prices of the 2016 to 2018. Ultimately, the values of the examined emissions will be in ***Table 7.3***:

[$€_{2018}$/kg]	SO_2	NO_x	$PM_{2.5}$
Atlantic	3.62	3.93	7.45
Baltic	7.14	8.17	18.93
Black Sea	11.48	8.07	31.04
Mediterranean	9.52	3.10	25.45
North Sea	10.86	11.07	35.59

Table 7.3: Air pollution costs: average damage cost in [€/kg of emission] in 2018, after inflation

7.3.7.3. Geographic Coordinates for specifying Sea Regions

Every port in the EEA and UK is bordered by a different sea, where there are mainly five (5) vast sea areas. In ***Table 7.3*** is seen clearly that each sea region has a different cost factor of an emission, which leads to the conclusion that each port will also have a different cost factor. The five sea regions that are making up the EEA and UK coastal line are:

1. Atlantic,
2. Baltic,
3. Black Sea,
4. North Sea,
5. Mediterranean.

These sea areas are illustrated in the figures below. For specifying the sea region of the EEA and UK ports, geospatial coordinates were used to determine in which sea region the port belongs to.

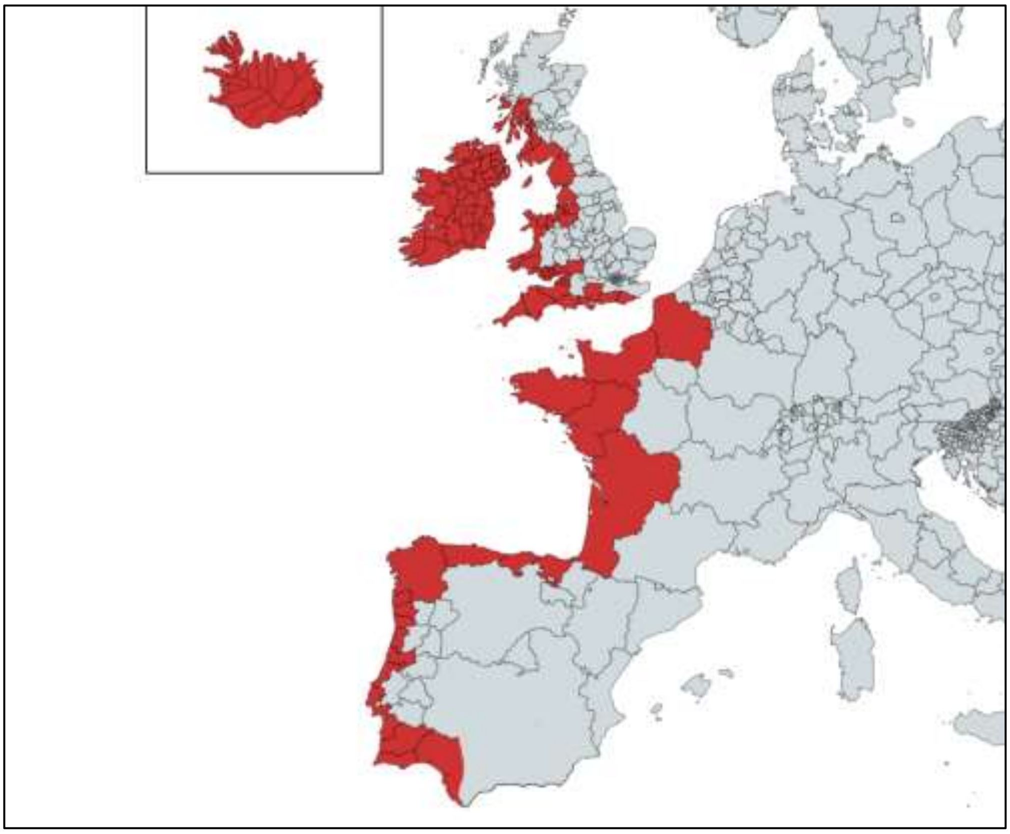


Figure 7.16: Atlantic Sea region

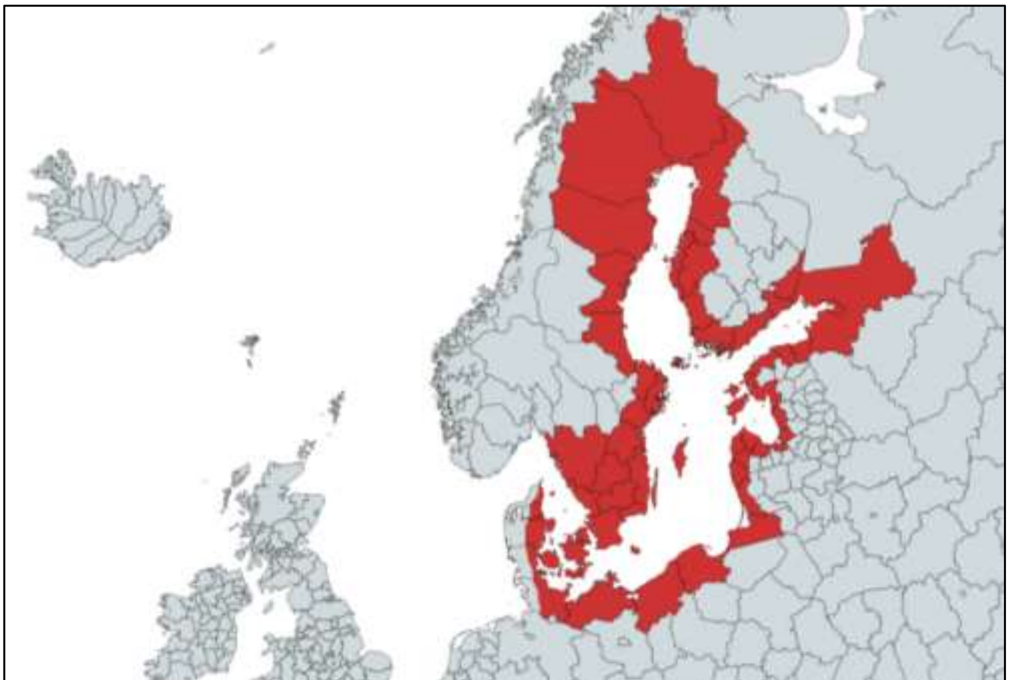


Figure 7.17: Baltic Sea region

Figure 7.18: Black Sea region

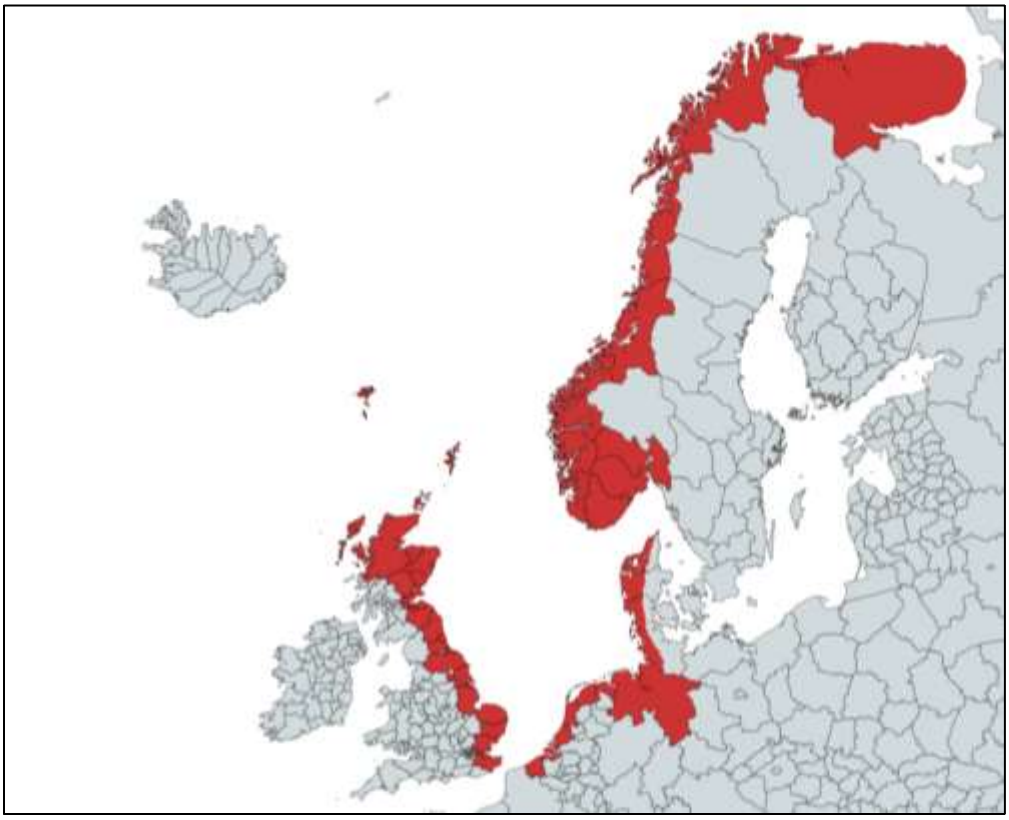


Figure 7.19: North Sea region

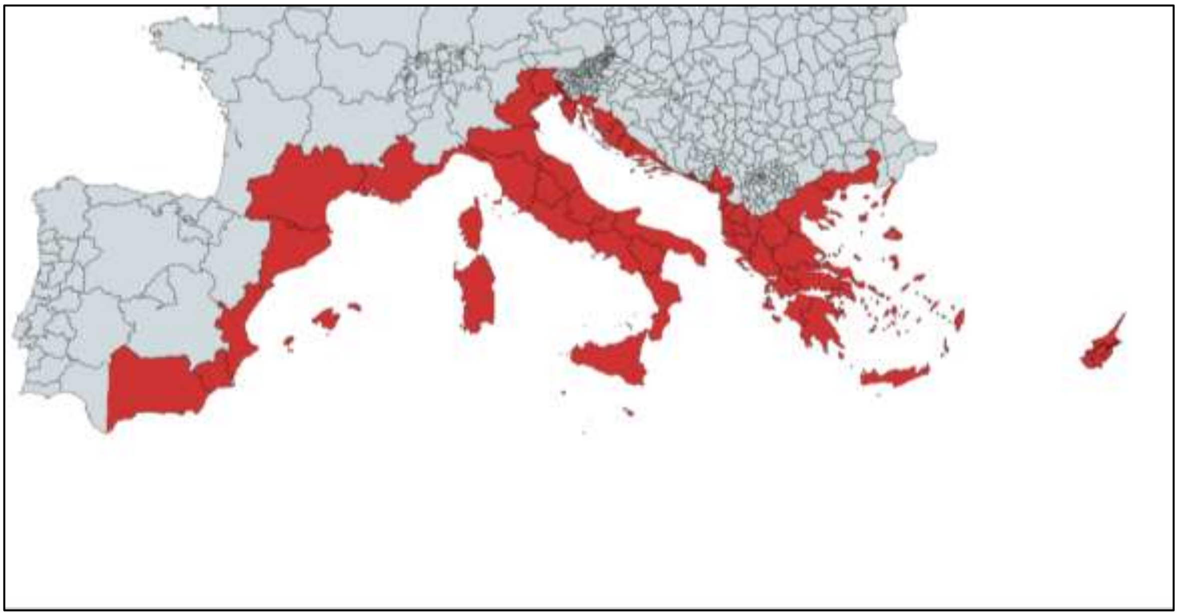


Figure 7.20: Mediterranean Sea region

Points containing two coordinates, latitude and longitude, were inserted with the ultimate goal of determining sea area by closed polygons, by finding the point coordinates of the closed polygons with the online web program https://www.geoplaner.com [17].

For example, Black Sea's area polygon was drawn as the one in ***Figure 7.21***.

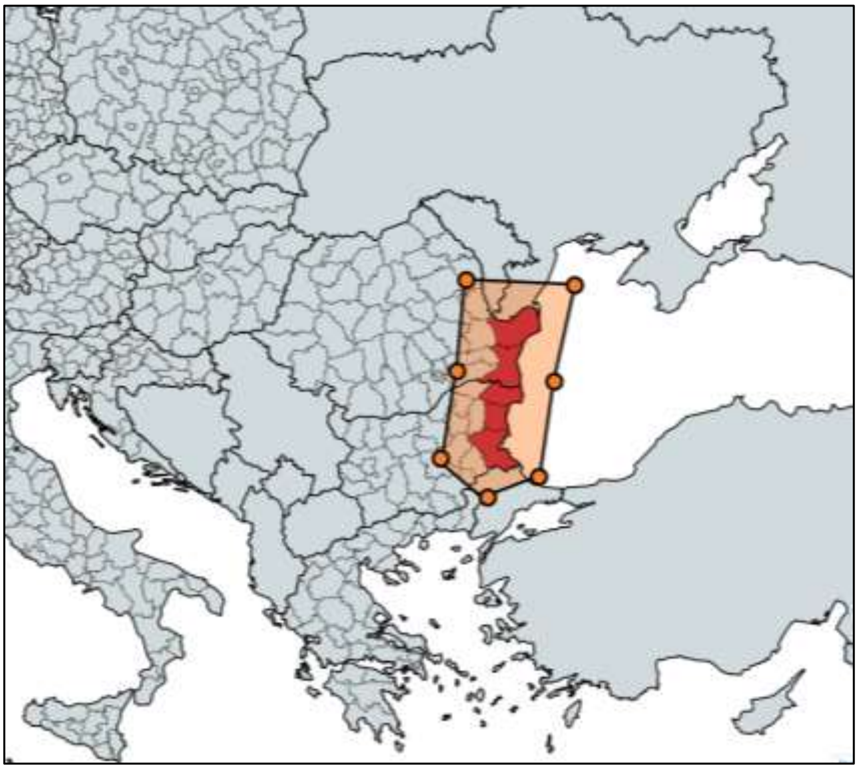


Figure 7.21: Closed Polygon example using points for determining sea region of Black Sea

By determining closed polygons coordinates, next step is checking whether the port's coordinates (latitude and longitude) belong inside the closed polygon region, or outside the closed polygon region. If the coordinates of the port belong inside the closed region, it is considered that the examined port is bordered by the examined Sea's closed polygon, otherwise it does not belong to it.

This check is occurring with the help of Python's following libraries:

- `turfpy` [18]: Turfpy is a Python library for performing geospatial data analysis
- `geojson` [19]: GeoJSON is a format for encoding a variety of geographic data structures. Point, Polygon, MultiPolygon, etc, are all geometry types supported by GeoJSON.

By importing these libraries in combination with "If-Else" conditional statements, a list containing the Sea region of each port is created. The "If-Else" flow diagram for specifying Sea region is shown in ***Figure 7.22***.

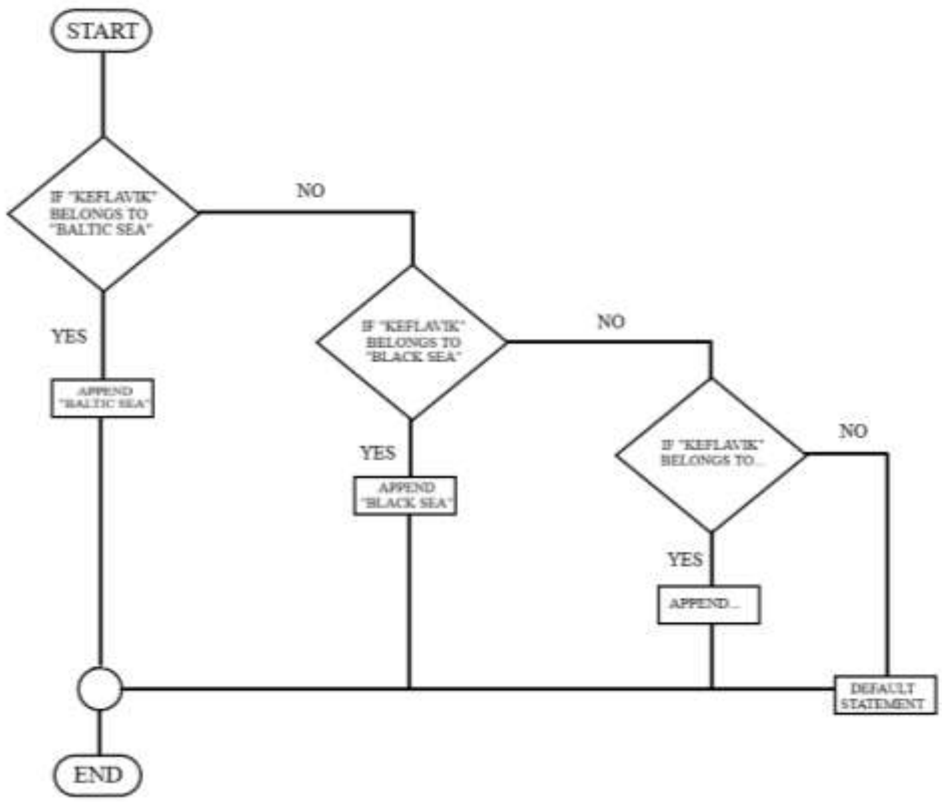


Figure 7.22: Flow chart for determining Sea region of each port

As seen in Flow chart in ***Figure 7.22***Figure 7.22, if the "If-Else" conditional statement is true, then the Sea region that satisfies the statement is inserted in the list. Differently, it goes to the next statement to check whether is true or false, repeating this procedure for all the ports that must be examined. The final result is a list that contains all the ports' Sea regions.

7.3.7.4. Total Energy in each port

The LDC, not only gives the minimum load present throughout the specified period, but also the area under the LDC represents the energy demand. For calculating the total energy under the LDCs, numerical methods and more particularly with the library of SciPy.

SciPy is a Python library that may be used for both scientific and technical computing. Optimization, linear algebra, integration, interpolation, special functions, FFT, signal and image processing, ODE solvers, and other modules used in science and engineering are all covered by SciPy [20].

SciPy is imported in the script of Python as follows:

```
import scipy
```

For the creation of the emissions figures and the tables of External costs of each port, it is important to calculate the area under the LDCs (basically the Total Energy Demand in a year). To calculate this area under each LDC of each ship type, in each port, module `scipy.integrate` will be utilized. Principally, `scipy.integrate.trapz` calculates the area under a Python array along the given axis using the composite trapezoidal rule.

For example, let f be a continuous function on $[a, b]$. The trapezoidal rule for approximating $\int_a^b f(x)dx$ for a domain discretized into N equally spaced panels:

$$\int_a^b f(x)dx = \frac{\Delta x}{2} \cdot (f(a) + 2f(x_1) + 2f(x_2) + \cdots + 2f(x_{N-2}) + 2f(x_{N-1}) + 2f(b))$$

Where:

$$\Delta x = \frac{b-a}{N}$$

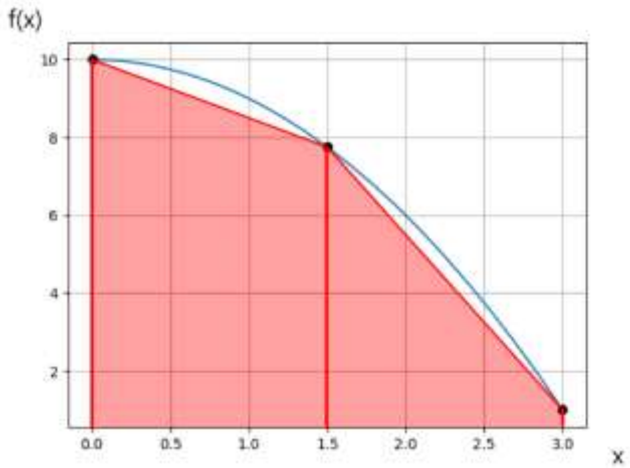


Figure 7.23: The Trapezoidal rule example. With red shaded color is the calculated integral with Trapezoidal rule

The calculated area is describing the total (yearly) energy demand of each ship type of each port, in $[kWh]$.

7.3.7.5. Calculating Emissions in each port

By computing the total energy demand in a year for all ship types and all ports, the upcoming operation is to find the annual emissions in these ports, for all the ship types. As discussed before, the emissions that will be calculated and are given more emphasis are the ones analysed before, which are NO_x, SO_2, $PM_{2.5}$ and also, CO_2.

Table 7.4 is representing the emission factors for the examined emissions.

Compound	**Symbol**	**Emission Factor f_i $[t/kWh]$**
Carbon Dioxide	CO_2	6.90×10^{-4}
Nitrogen Oxides	NO_x	1.39×10^{-5}
Sulphur Dioxide	SO_2	1.10×10^{-6}
Particulate Matter	$PM_{2.5}$	3.00×10^{-7}

Table 7.4: Emission Factors values

By correlating Emission Factor and Energy Demand of one ship type in a port, Mass of each emission released for the ships at berth can be calculated. Mass of the emission is given by the following formula:

$$M_i = f_i \times E$$

Where:

- i is the emission,
- M_i $[t]$ is the mass of the emission,
- f_i $[t/kWh]$ is the Emission Factor of the emission,
- E $[kWh]$ is the Energy, otherwise activity that will produce the analogous emission.

By having as known the Mass of each emission, the next procedure would be to create the emission figures. ***Figure 7.24*** shows a typical example of the bar diagrams created for the port of Piraeus, displaying emissions in logarithmic scale, categorized by ship type.

In addition, from ***Table 7.3*** can be quantified the External Cost, in [€], of each ship type, in each port by the following simple formula:

$$(External\ Cost) = (Cost\ Factor) \times M_i \times 10^{-3}$$

Where:

- M_i $[t]$ is the mass of the emission,
- $(Cost\ Factor)$ $[€/kg]$ which is taken from ***Table 7.3***.

Below, ***Figure 7.25*** demonstrates the External Costs in a table, for the port of Piraeus.

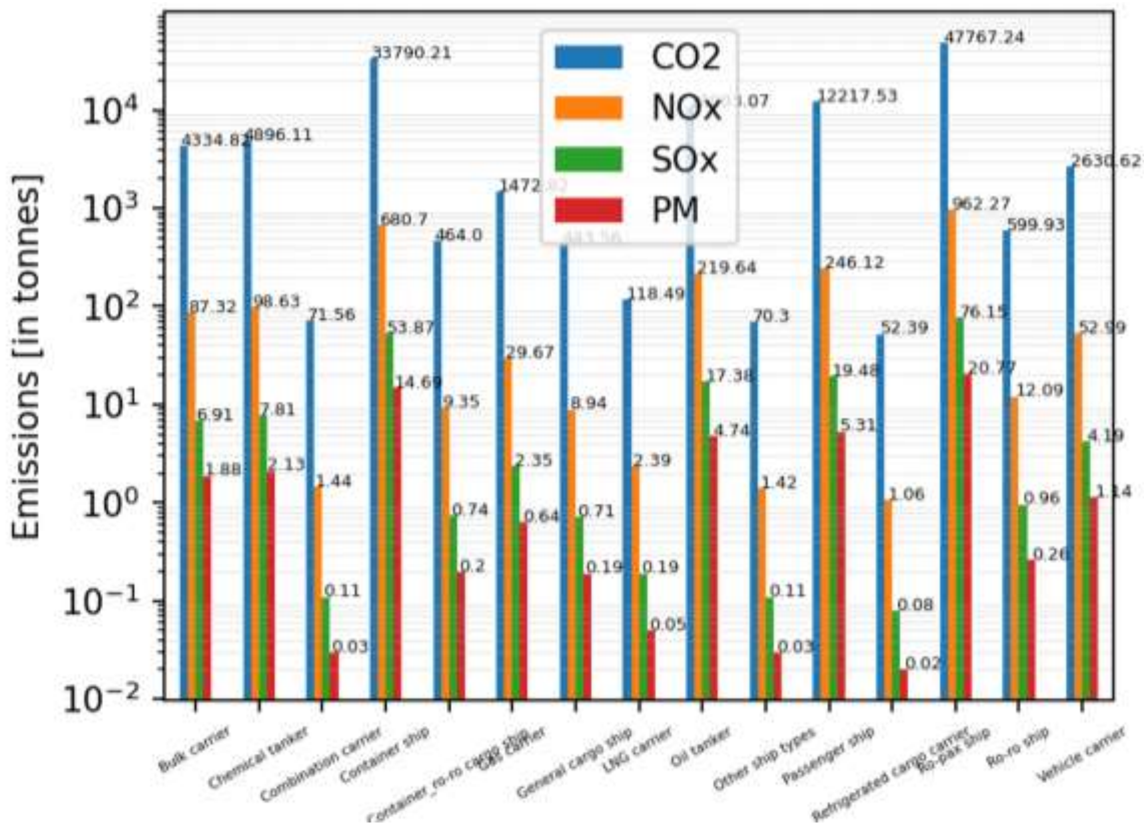


Figure 7.24: 6th Layer Bar Diagram presenting emissions in port of Piraeus

	SOx Cost [€]	NOx Cost [€]	PM Cost [€]	Total Cost [€]
Bulk carrier	[illegible]	[illegible]	[illegible]	[illegible]
Chemical tanker	[illegible]	[illegible]	[illegible]	[illegible]
Combination carrier	[illegible]	[illegible]	[illegible]	[illegible]
Container ship	[illegible]	[illegible]	[illegible]	[illegible]
Container ro-ro cargo ship	[illegible]	[illegible]	[illegible]	[illegible]
Gas carrier	[illegible]	[illegible]	[illegible]	[illegible]
General cargo ship	[illegible]	[illegible]	[illegible]	[illegible]
LNG carrier	[illegible]	[illegible]	[illegible]	[illegible]
Oil tanker	[illegible]	[illegible]	[illegible]	[illegible]
Other ship types	[illegible]	[illegible]	[illegible]	[illegible]
Passenger ship	[illegible]	[illegible]	[illegible]	[illegible]
Refrigerated cargo carrier	[illegible]	[illegible]	[illegible]	[illegible]
Ro-pax ship	[illegible]	[illegible]	[illegible]	[illegible]
Ro-ro ship	[illegible]	[illegible]	[illegible]	[illegible]
Vehicle carrier	[illegible]	[illegible]	[illegible]	[illegible]

Figure 7.25: External Costs, in [€], for each emission and ship type separately

Except the two aforesaid figures, the 6th Layer contains information for two economical investments estimations:

1. Estimated Cost for investment in port for Cold Ironing,
2. Estimated Cost for power increase.

7.3.7.5.1. Estimated Cost for investment in port for Cold Ironing

In accordance with EU Regulations (see ***Chapter 5.2***), all Container and Passenger ships will need to use OPS (or otherwise Cold Ironing) or zero-emission technologies in TEN-T network ports, to cover their required energy.

Such an investment will be crucial for ports and communities, not only from the scope of reducing emissions in these, usually inhabited areas, but also from the scope of minimising noise that is produced by ships.

The cost of an OPS investment depends mainly on the Maximum Power Demand of each port. Approximately, the cost of an OPS funding will be:

$$(OPS\ investment) = (Maximum\ Power\ Demand) \times 750{,}000 \left[\frac{€}{kWh}\right]$$

Where:

- $(OPS\ investment)$ [€] is the required amount of capital to develop OPS,
- $(Maximum\ Power\ Demand)$ $[kWh]$ is the Maximum Power Demand of each Total LDC.

7.3.7.5.2. Estimated Cost for power increase.

An estimated power increase of the local electrical grid in ports of EEA and UK is essential for supporting OPS methods to provide ships with energy that does not produce in the port region CO_2, SO_x, and other emissions, harmful for human health and for the environment.

The estimation of power increase of the local electrical grid of the port can split into two (2) different occasions:

a) When Maximum Power Demand in a port is less than 20 $[MVA]$, then the cost will be **€3,000,000**,
b) When Maximum Power Demand in port is greater or equal than 20 $[MVA]$, then the cost will be **€20,000,000**.

For Maximum Power Demand in a port less than 20 $[MVA]$, cost can be broken down in the following, according to data given by **Hellenic Electricity Distribution Network Operator (HEDNO)** [21], **Independent Power Transmission Operator (IPTO)** [22] and **Agency for the Cooperation of Energy Regulators (ACER)** [23]:

- Increase of power from Medium Voltage with new line of average length of 10 $[km]$ per 10 $[MVA]$. Cost estimate for 10 $[MVA]$:

  $$90{,}000 \left[\frac{€}{km}\right] \times 10\ [km] = €900{,}000$$

  While for 10 $[km]$ per 20 $[MVA]$ the cost is about 1.5 times the previous one with double cable:

  $$135{,}000 \left[\frac{€}{km}\right] \times 10\ [km] = €1{,}350{,}000$$

  Approximately, the cost for power increase will be around **€1,500,000**,

- Additionally, reinforcement of the substation may be required distribution in the port area with the addition of a new transformer, with the corresponding cost estimated at **€1,500,000**,
- The total cost for power increasing up to 20 $[MVA]$, will be around **€3,000,000**.

For Maximum Power Demand in a port equal or greater than 20 $[MVA]$, according to **Independent Power Transmission Operator (IPTO)** [22] and **Agency for the Cooperation of Energy Regulators (ACER)** [23], the cost will be analysed as:

- Increase of power from High Voltage Network with new of average length of 10 km, cost estimate will be:

$$900{,}000\ \left[\frac{€}{km}\right] \times 10\ [km] = €9{,}000{,}000$$

  The cost for increase of power will be around **€9,000,000**.

- In addition, a new gas insulated substation may be required in the port area with the addition of a new transformer, an estimation cost of **€10,000,000**.
- The total cost is estimated at **€20,000,000**.

This can be simplified in ***Figure 7.26***, that is showing how the two (2) cases were placed programmatistically into the 6th Layer script.

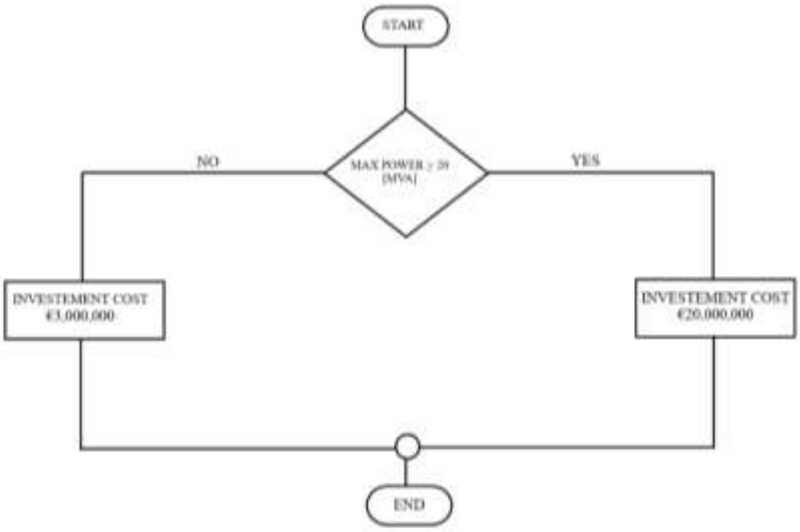


Figure 7.26: Flow chart of "If-Else" statement about estimated cost for power increase of the local electrical grid

7.3.7.6. 6th Layer of Interactive Map format

The 6th Layer of Interactive Map has a different look, in comparison with the Layers 1 to 5. This is due to the different figures that are implemented in the layer. Instead of LDCs, 6th Layer (and also 7th one) have the bar diagrams of emissions and table presenting External costs for each port. The 6th Layer, in its comprehensive presentation looks like ***Figure 7.27***, which is the port of Piraeus.

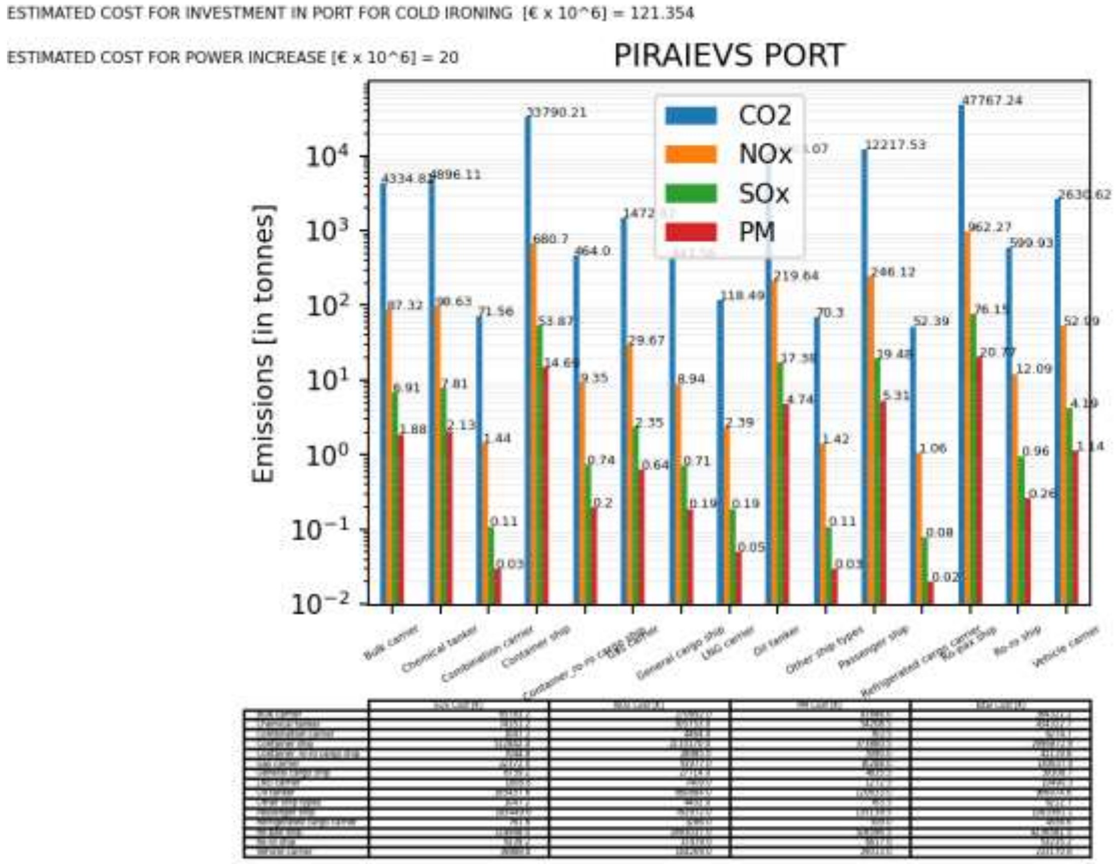


Figure 7.27: 6th Layer comprehensive format of the port of Piraeus

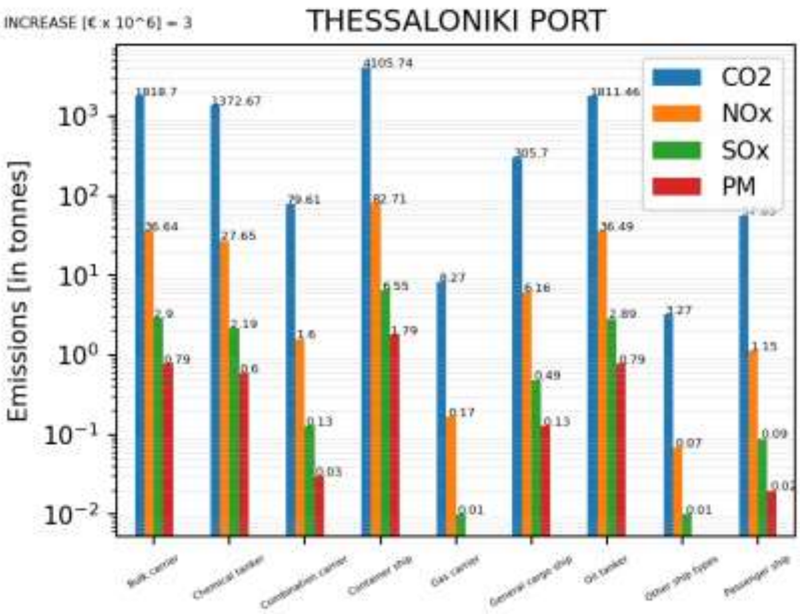
For the occasion of Piraeus' port, an estimated cost for Cold Ironing (or OPS) would be somewhere around €121,354,000, while an expenditure for power increase in the local electrical grid would cost around €20,000,000.

On the other hand, for the same port, the External costs are approximated around €10,600,000. A significant amount that should be taken into account whether it is beneficial of investing in the specific port.

Other cases of other ports of large ports of Greece are seen below and are compared in ***Table 7.5***.

ESTIMATED COST FOR INVESTMENT IN PORT FOR COLD IRONING [€ x 10^6] = 9.335

ESTIMATED COST FOR POWER INCREASE [€ x 10^6] = 3

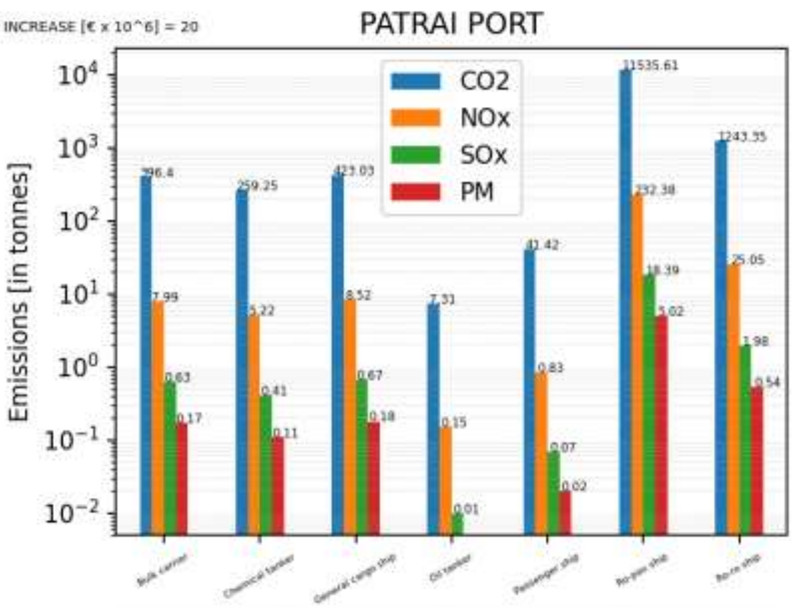


	SOx Cost [€]	NOx Cost [€]	PM Cost [€]	Total Cost [€]
Bulk carrier	27608.0	113584.0	20105.5	161297.5
Chemical tanker	[illegible]	[illegible]	[illegible]	[illegible]
Combination carrier	1117.6	[illegible]	765.5	[illegible]
Container ship	62356.0	[illegible]	[illegible]	[illegible]
Gas carrier	95.2	527.0	0.0	622.2
General cargo ship	[illegible]	[illegible]	[illegible]	[illegible]
Oil tanker	27512.0	113118.0	20105.5	[illegible]
Other ship types	95.2	217.0	0.0	312.2
Passenger ship	[illegible]	[illegible]	[illegible]	[illegible]

Figure 7.28: 6th Layer format presenting port of Thessaloniki

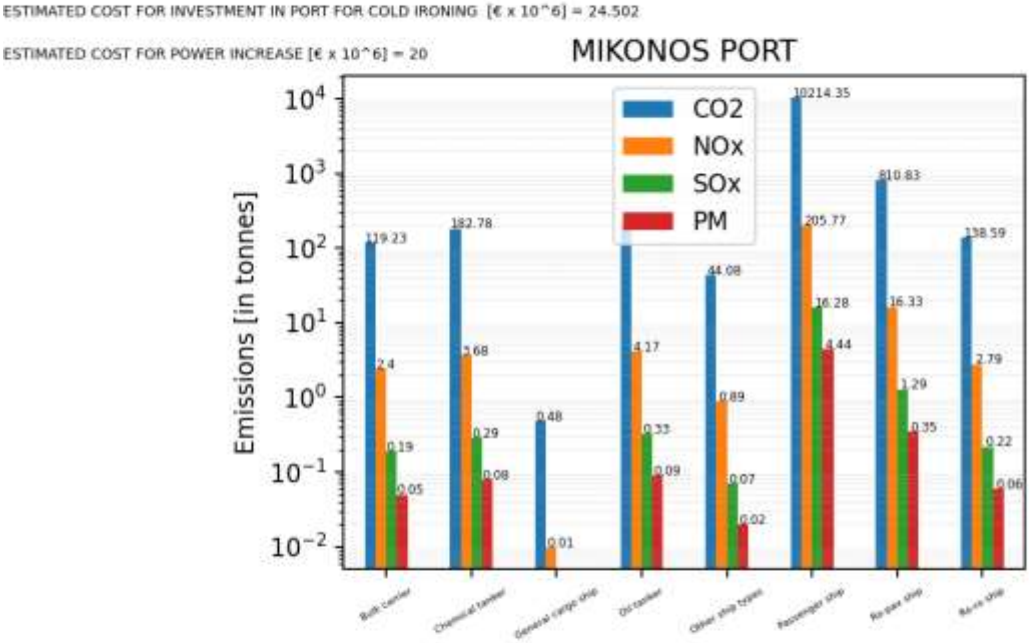
ESTIMATED COST FOR INVESTMENT IN PORT FOR COLD IRONING [€ x 10^6] = 19.069

ESTIMATED COST FOR POWER INCREASE [€ x 10^6] = 20



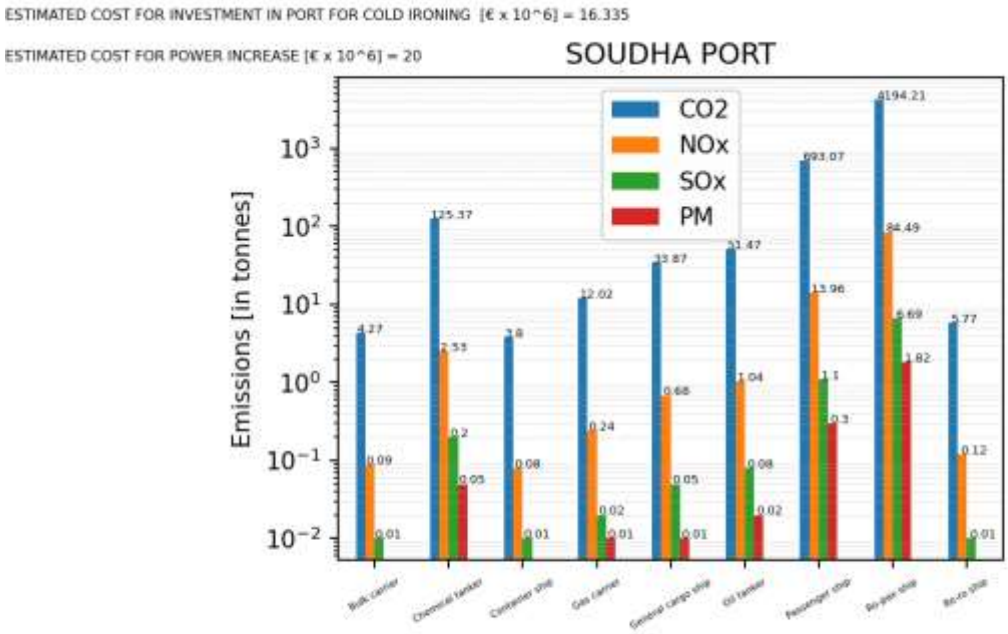
	SOx Cost [€]	NOx Cost [€]	PM Cost [€]	Total Cost [€]
Bulk carrier	5997.6	24769.0	4326.5	35093.1
Chemical tanker	3903.2	16182.0	2799.5	22884.7
General cargo ship	6378.4	26412.0	4581.0	37371.4
Oil tanker	95.2	465.0	0.0	560.2
Passenger ship	666.4	2573.0	509.0	3748.4
Ro-pax ship	175072.8	720378.0	127759.0	1023209.8
Ro-ro ship	18849.6	77655.0	13743.0	110247.6

Figure 7.29: 6th Layer format presenting port of Patra



	SOx Cost [€]	NOx Cost [€]	PM Cost [€]	Total Cost [€]
Bulk carrier	1808.8	7440.0	1272.5	10521.3
Chemical tanker	2760.8	11408.0	2036.0	16204.8
General cargo ship	0.0	31.0	0.0	31.0
Oil tanker	3141.6	12927.0	2290.5	18359.1
Other ship types	666.4	2759.0	509.0	3934.4
Passenger ship	154985.6	637887.0	112998.0	905870.6
Ro-pax ship	12280.8	50623.0	8907.5	71811.3
Ro-ro ship	2094.4	8649.0	1527.0	12270.4

Figure 7.30: 6th Layer format presenting port of Mykonos



	[illegible]	[illegible]	[illegible]	[illegible]
Bulk carrier	[illegible]	[illegible]	[illegible]	[illegible]
Chemical tanker	[illegible]	[illegible]	[illegible]	[illegible]
Container ship	[illegible]	[illegible]	[illegible]	[illegible]
Gas carrier	[illegible]	[illegible]	[illegible]	[illegible]
General cargo ship	[illegible]	[illegible]	[illegible]	[illegible]
Oil tanker	[illegible]	[illegible]	[illegible]	[illegible]
Passenger ship	[illegible]	[illegible]	[illegible]	[illegible]
Ro-pax ship	[illegible]	[illegible]	[illegible]	[illegible]
Ro-ro ship	[illegible]	[illegible]	[illegible]	[illegible]

Figure 7.31: 6th Layer format presenting port of Suda

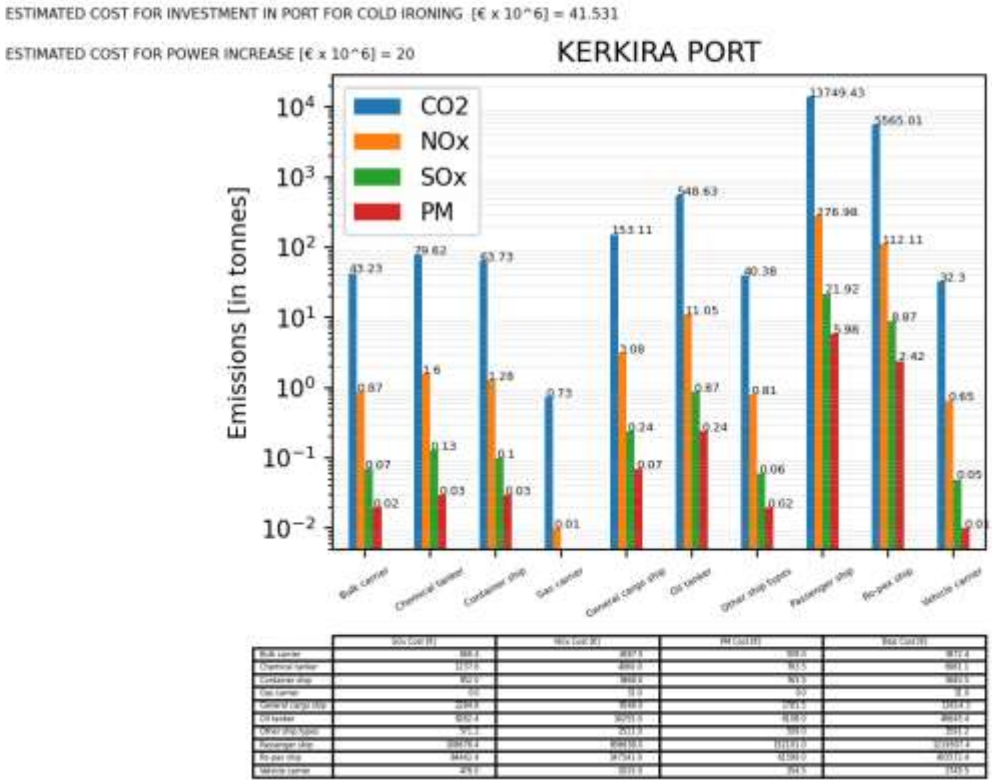


Figure 7.32: 6th Layer format presenting port of Kerkyra

Port	SO_x cost [€]	NO_x cost [€]	PM cost [€]	Total Cost [€]	OPS Cost [€]	Power Increase Cost [€]
Piraeus	1,818,700.2	7,483,493.0	1,325,236.0	10,627,429.2	121,354,000	20,000,000
Thessaloniki	145,275.2	597,184.0	105,617.5	848,076.7	9,355,000	3,000,000
Patra	211,963.2	868,434.0	153,718.0	1,234,115.2	19,069,000	20,000,000
Mykonos	178,738.4	731,724.0	129,540.5	1,040,002.9	24,502,000	20,000,000
Suda	78,048.4	320,013.0	56,244.5	454,305.9	16,355,000	20,000,000
Kerkyra	307,591.2	1,266,164.0	224,469.0	1,795,478.7	41,531,000	20,000,000

Table 7.5: SO_x, NO_x, PM, OPS and Power Increase Cost [€]

Obviously, from ***Figure 7.27*** and ***Table 7.5*** ,the most costly investment for OPS is for the Port of Piraeus, which the estimated cost of investment will exceed 100 million euros, but it is also the port that will have the greatest financial benefits from such an investment, in the case of Greece’s ports.

From ***Figure 7.33***, it is apparent that the costliest emission for 2018, for the ones that were studied in this postgraduate thesis, was the NO_x. In fact, in the External cost of NO_x of Piraeus port was evaluated €7,483,493.0, around €2,100,000 more than the Total External cost of all emissions of the other five (5) ports (Thessaloniki, Patra, Mykonos, Suda, Kerkyra), that are presented in ***Table 7.5*** and had a cost of €5,371,979.4.

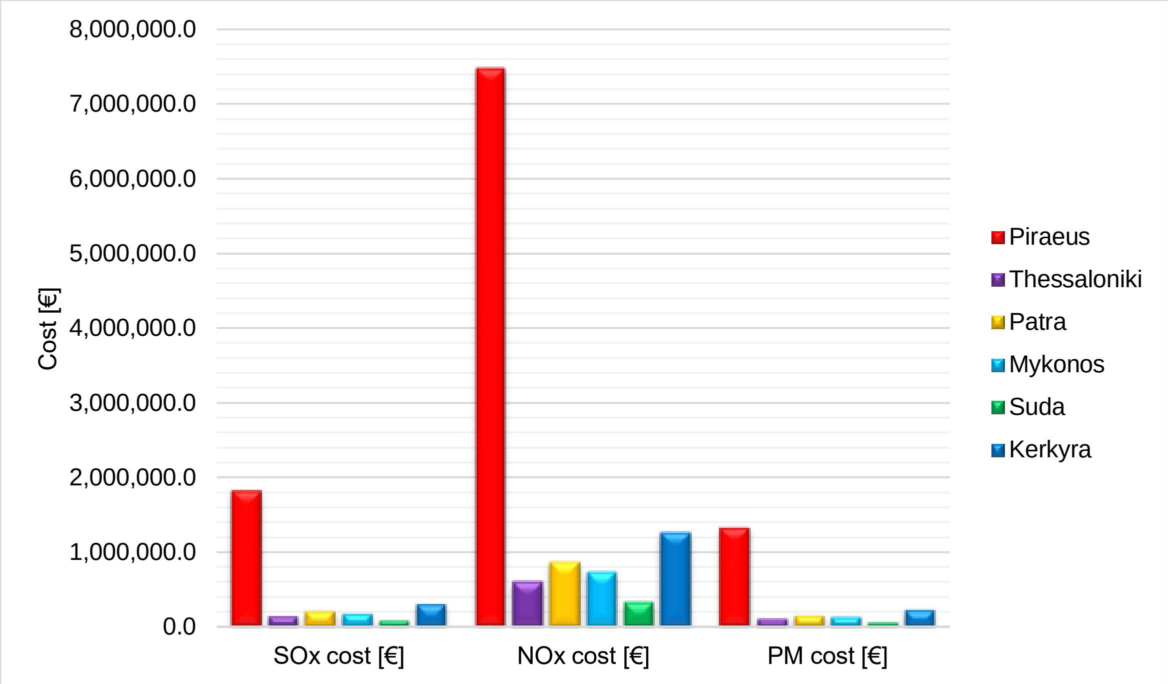


Figure 7.33: Bar Diagram for 6th Layer showing costs of SO_x, NO_x and PM, in [€], for 2018

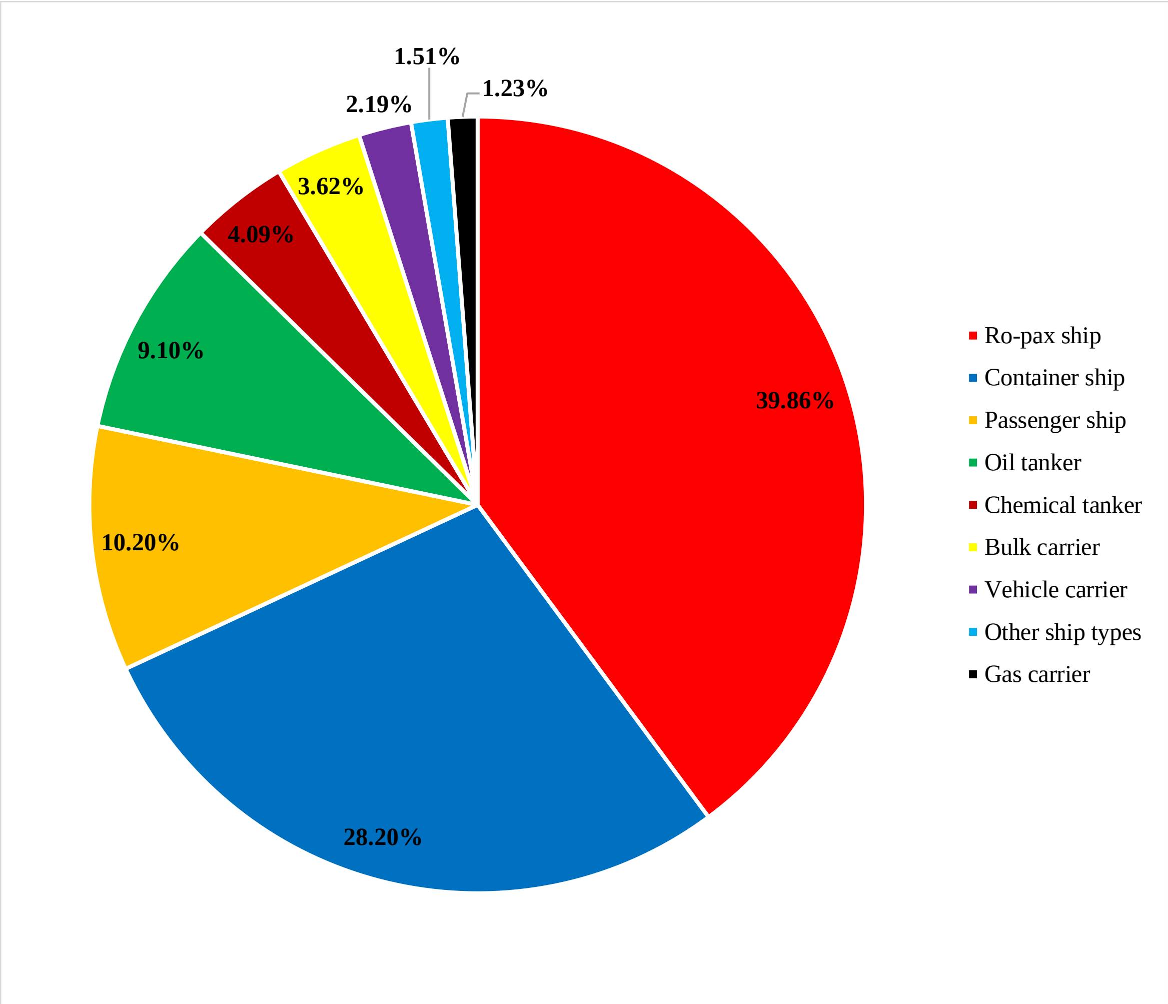


Figure 7.34: Pie diagram showing External costs of Piraeus, as a percentage of the Total External costs

From ***Figure 7.34*** it is clear that Ro-pax ships hold around 40%, Container ships own about 28% and the rest of the ships in the port of Piraeus possess a portion of 32% of the Total External costs. Note that in Piraeus port Passenger ships constitute a percentage of approximately 10%.

7.3.8. 7th Layer of Interactive Map

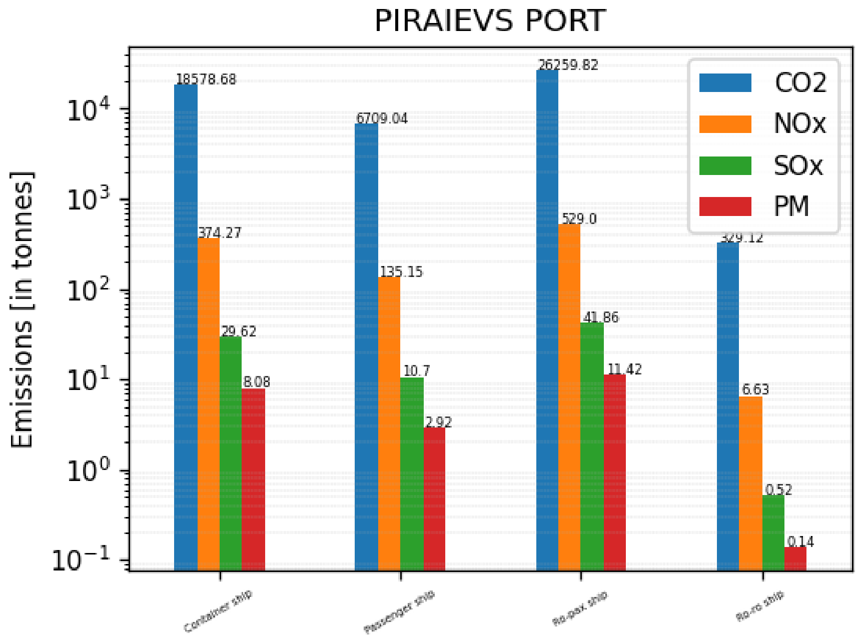
In this section will be described the last Layer of the Interactive Map, named "***Total Emission and External Costs for Container and Passenger ships***", which is a subcategory of the former 6th Layer. As the title indicates, it presents the emissions and External costs of each port, but this time only for the categories of Container and Passenger ships.

Basically, this layer gives a more realistic view of how beneficial will be an investment for developing an OPS system or increasing the local electrical grid of the port, since a lot of ship activity consists exclusively of Passenger and Container ships.

Again, similar methodology and libraries were used as ***Chapter 7.3.7***, in an attempt to again compute the area under the LDCs (and consequently annual energy demand of a port), the emissions that would be released in the case that auxiliary engines were operating at berth and the External costs of the port, sorted by ship type. Anew, in this layer aims at Container and Passenger ships.

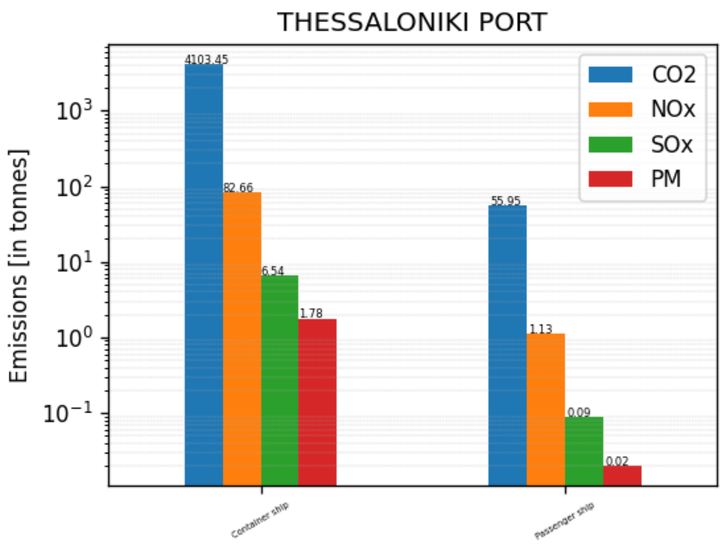
For the port of Piraeus, the 7th Layer looks like the one displayed underneath in ***Figure 7.35***.

Also, other ports from Greece in 7th Layer are given below, displaying emissions in bar diagrams and External costs in tables.



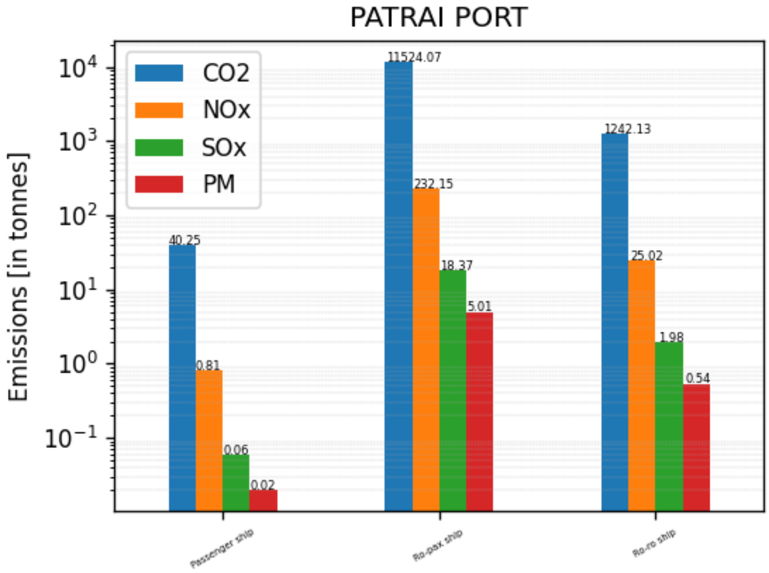
	SOx Cost [€]	NOx Cost [€]	PM Cost [€]	Total Cost [€]
Container ship	349516.0	1440939.5	254843.2	2045298.7
Passenger ship	126260.0	520327.5	92096.8	738684.3
Ro-pax ship	493948.0	2036650.0	360186.8	2890784.8
Ro-ro ship	6136.0	25525.5	4415.6	36077.1

Figure 7.35: 7th Layer figure and table for the port Piraeus, accounting only for Container and Passenger ships



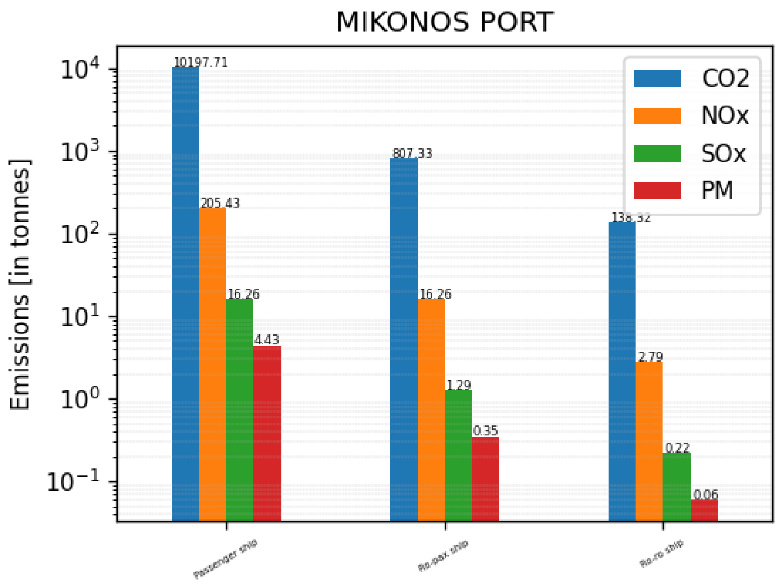
	SOx Cost [€]	NOx Cost [€]	PM Cost [€]	Total Cost [€]
Container ship	77172.0	318241.0	56141.2	451554.2
Passenger ship	1062.0	4350.5	630.8	6043.3

Figure 7.36: 7th Layer format presenting port of Thessaloniki



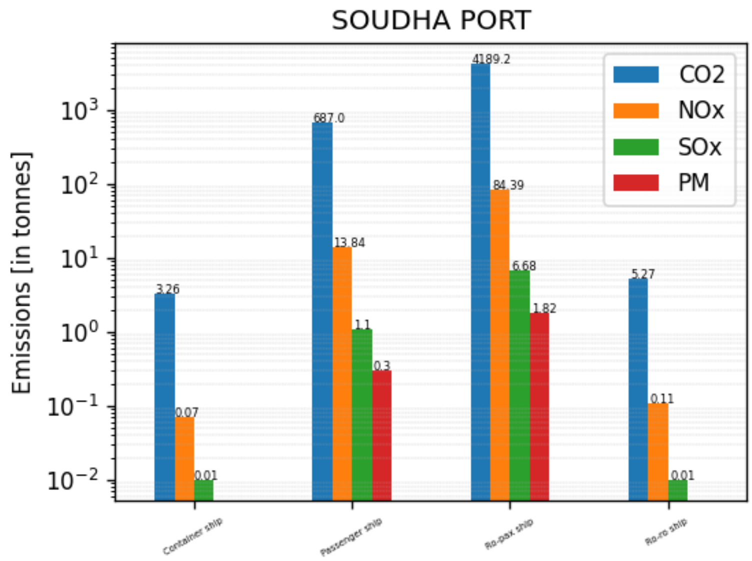
	SOx Cost [€]	NOx Cost [€]	PM Cost [€]	Total Cost [€]
Passenger ship	708.0	3118.5	630.8	4457.3
Ro-pax ship	216766.0	893777.5	158015.4	1268558.9
Ro-ro ship	23364.0	96327.0	17031.6	136722.6

Figure 7.37: 7th Layer format presenting port of Patra



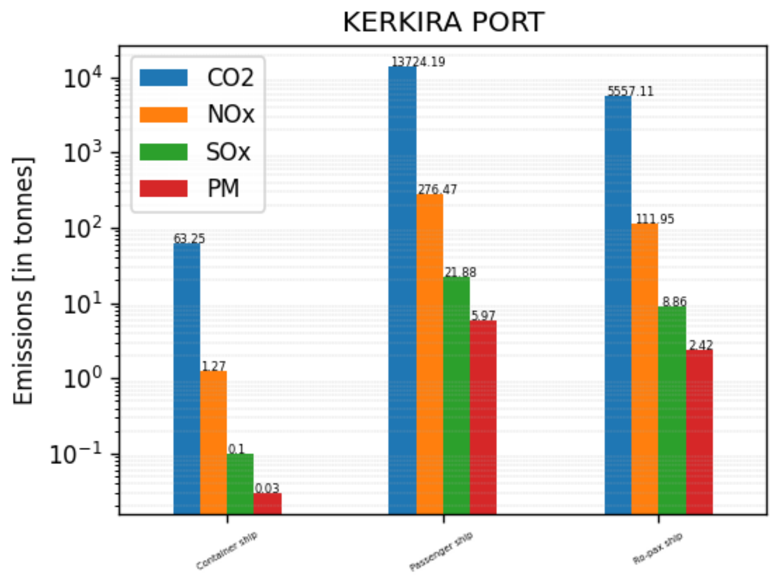
	SOx Cost [€]	NOx Cost [€]	PM Cost [€]	Total Cost [€]
Passenger ship	191868.0	790905.5	139722.2	1122495.7
Ro-pax ship	15222.0	62601.0	11039.0	88862.0
Ro-ro ship	2596.0	10741.5	1892.4	15229.9

Figure 7.38: 7th Layer format presenting port of Mykonos



	SOx Cost [€]	NOx Cost [€]	PM Cost [€]	Total Cost [€]
Container ship	118.0	269.5	0.0	387.5
Passenger ship	12980.0	53284.0	9462.0	75726.0
Ro-pax ship	78824.0	324901.5	57402.8	461128.3
Ro-ro ship	118.0	423.5	0.0	541.5

Figure 7.39: 7th Layer format presenting port of Suda



	SOx Cost [€]	NOx Cost [€]	PM Cost [€]	Total Cost [€]
Container ship	1180.0	4889.5	946.2	7015.7
Passenger ship	258184.0	1064409.5	188293.8	1510887.3
Ro-pax ship	104548.0	431007.5	76326.8	611882.3

Figure 7.40: 7th Layer format presenting port of Kerkyra

Below, in ***Table 7.6*** are given External costs that are related to the Passenger and Container ships. Again, the costs are given in [€] for 2018 prices, for the main emissions and the cost per port.

Port	**SO_x cost [€]**	**NO_x cost [€]**	**PM cost [€]**	**Total $Cost_{P\&C}$ [€]**	**(Total $Cost_{P\&C}$)/(Total $Cost_{all}$)**
Piraeus	1,432,379.20	5,893,658.0	1,044,213.50	8,370,250.70	78.8%
Thessaloniki	63,212.80	259,966.00	46,064.50	369,243.30	43.5%
Patra	194,588.80	800,606.00	142,011.00	1,137,205.80	91.8%
Mykonos	169,360.80	697,159.00	123,432.50	989,952.30	94.8%
Suda	74,621.20	305,815.00	53,954.00	434,390.20	95.6%
Kerkyra	294,072.80	1,210,147.00	214,543.50	1,718,763.30	95.6%

Table 7.6: SO_x, NO_x, PM Cost [€]

Here, it is important to mention the Passenger (Ro-Ro and Ro-Pax ships are included) and Container ships' External costs as a percentage of the all the ship types' External costs of the port. Clearly, ports that are highly dependent on tourism industry like Mykonos and Kerkyra, Total External costs for Passenger and Container ships is high, reaching about 95% of the Total External costs of all the ship types of the port (hence the power demand).

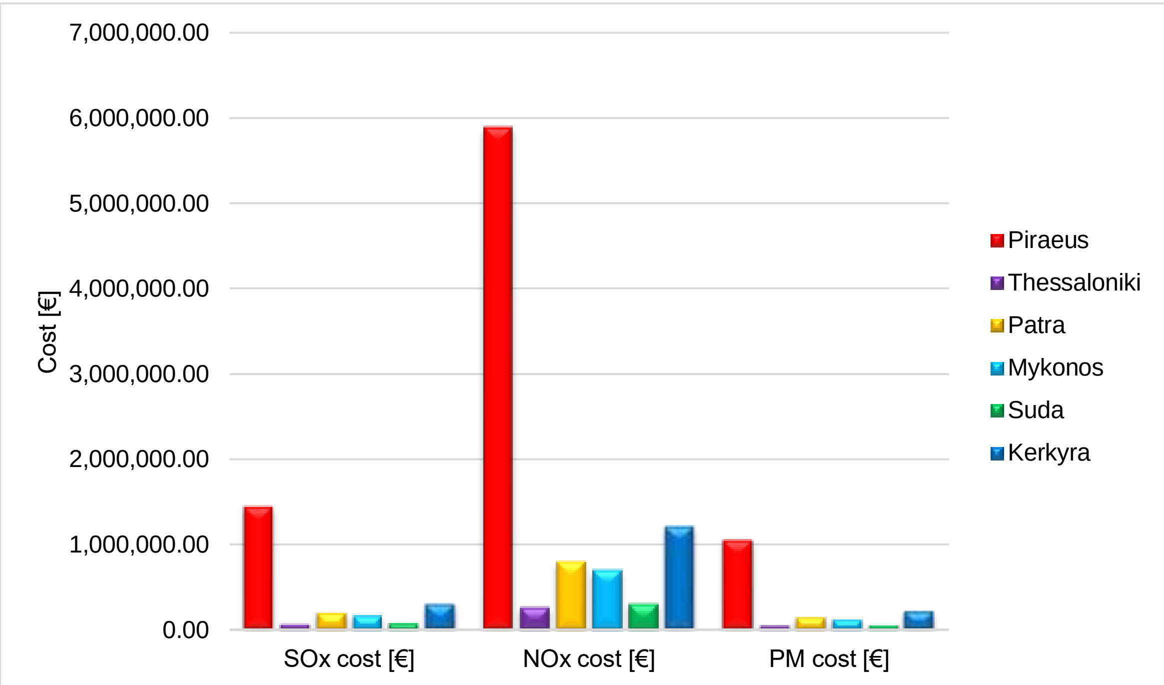


Figure 7.41: Bar Diagram for 7th Layer showing costs of SO_x, NO_x and PM, in [€], for 2018

In case of External costs of SO_x, NO_x, and PM for Passengers and Container ships (see ***Figure 7.41***), a significant amount of External costs should be taken into account if these ship types are selected for utilizing OPS systems at berthing.

In ***Figure 7.42***, which demonstrates the Total External costs of the ports of Greece, is showing the power needs only for Passenger and Container ships. It is worth mentioning that ports like Kerkyra, that there is a lot of activity of Passenger ships, had a Total External cost about €1,700,000, while ports like Thessaloniki instead, had a Total External cost of €370,000.

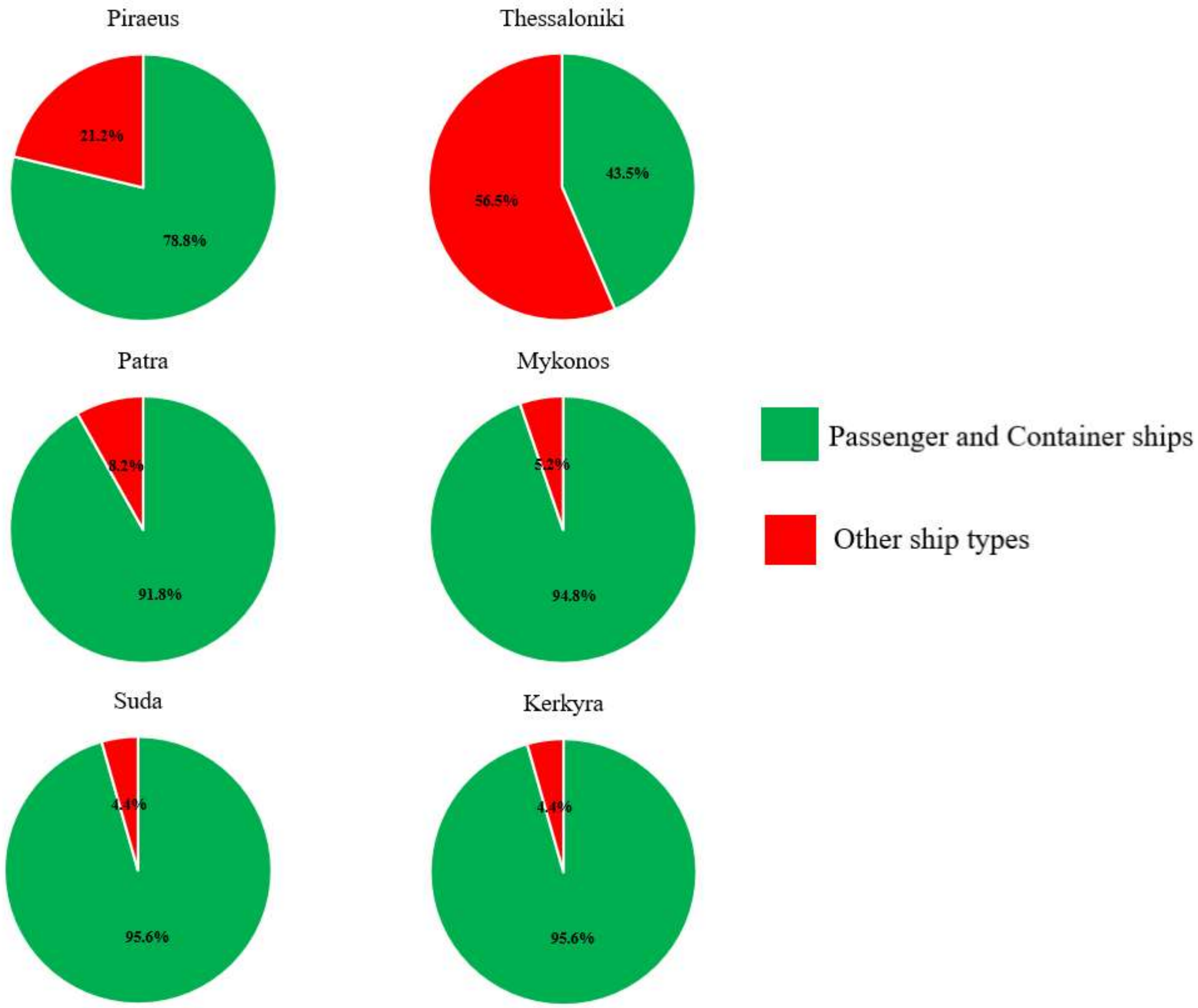


Figure 7.42: Pie Diagrams presenting costs as a percentage depending on ship type

7.3.9. Interactive Map Program

The Interactive Map Program is constructed in a Python script, which creates an HTML executable that is a Graphical User Interface (GUI). The Python script that creates the HTML executable is called "**Multilayer_Ports_Map**". In this script, three (3) libraries are used in order to achieve the expected result, are imported:

```
import csv

import folium

import pybase64
```

`folium` makes it easy to visualize data that's been manipulated in Python on an interactive leaflet map. It enables both the binding of data to a map for choropleth visualizations as well as passing rich vector/raster/HTML visualizations as markers on the map.

`folium` is the library used for creating the map. Firstly, the map is created with command `folium.Map`.

The figures of LDCs, Bar Diagrams and External costs tables are imported as pictures, which were made by the scripts of the Layers 1 to 7. To import a figure (picture with .png format) into the map, first it must open, code it in the language of the computer and then decode it so it can be displayed. The coding of the of the figure happens with assistance of `pybase64`. Also, pybase64 is responsible for embedding figures in HTML.

`folium` is charge of creating the following:

- Markers,
- "Pop-up" windows,
- Informational text about port,
- Layer selection menu.

Figure 7.43 is showing layer selection menu, while the basic elements of Multilayer Map like Markers are showed in ***Figure 7.44***.

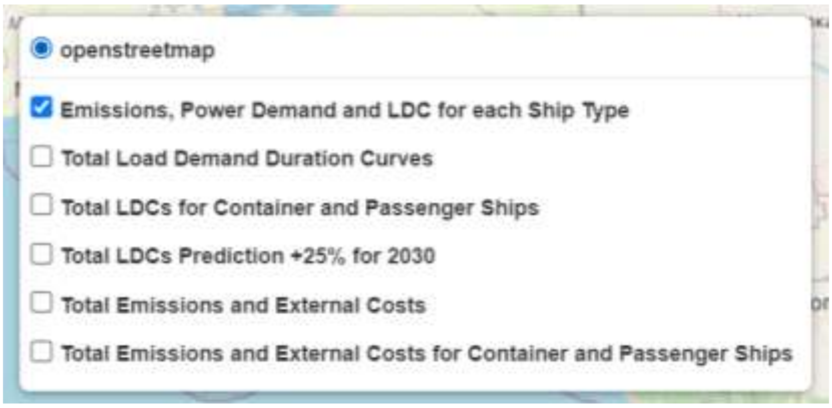


Figure 7.43: Layer selection menu of Multilayer Map

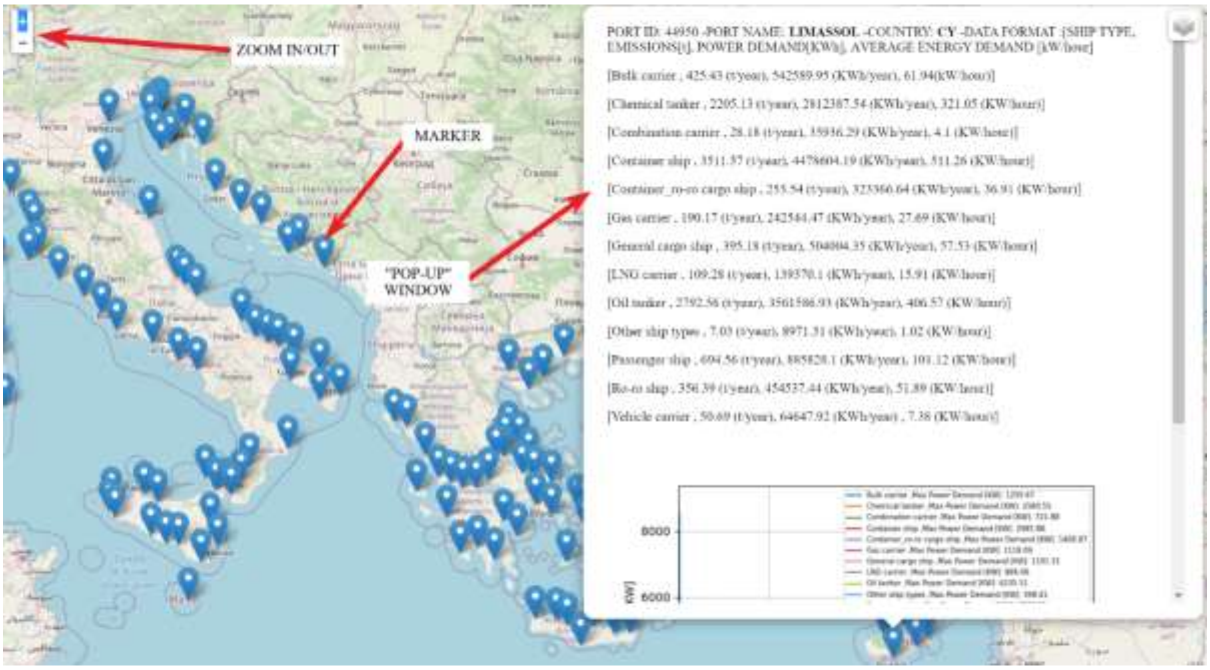


Figure 7.44: Multilayer Map composition of basic elements

The interaction of a user with the map program is similarly with Google Maps (see ***Figure 7.45***), where by dragging with the mouse can be navigated to difference regions and ports of EEA and UK.

Figure 7.45: Multilayer Map screen capture

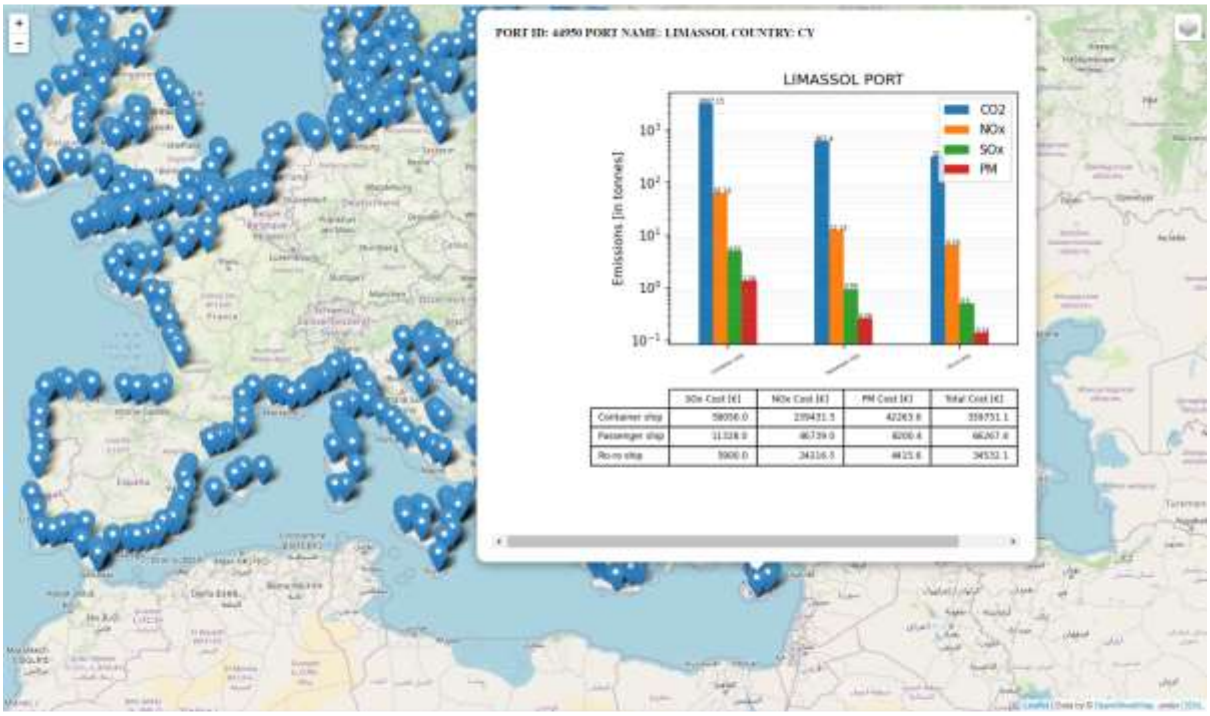


Figure 7.46: Screen capture of the Map displaying 7^{th} Layer for the port of Limassol, in Cyprus

By first selecting the desired layer (1 of the 7 mentioned in the previous chapters), the user can left-click to select the port where he wants the data to be displayed. Since the interactive environment is a map in the form of a Mercator projection, navigating to the desired area is easy to locate ports. ***Figure 7.46*** is displaying port of Limassol, the largest port in Cyprus.

8. Conclusions

As the well-known adage says "Rome wasn't built in a day", there must be somewhere in the back of our mind, that time and effort is needed to create better opportunities and times. This must be supported combinatorically in two weighty pillars: usage of technological means and desire for innovation. In closing, words of an American computer scientist will be referred (and not by chance), who is best known for his pioneering work on Object Oriented Programming (OOP) and Graphical User Interface (GUI) design. His name is Alan Kay and his words are quoted below:

"The best way to predict the future is to create it."

-Alan Kay (born 1940)

Alan Kay's basic approach is essentially encouraging. Nobody can predict the future, but people can invent it, fitting appropriately to the unconventional, but still innovative manners, that humanity should focus on improving the world for our descendants.

8.1. Conclusions on OPS methods in ports

As regarding OPS systems in ports, there are many variables that should be taken into account. Some of these variables are:

- Geographical location of the port,
- Number of ships that are served in the port,
- Ship types and sizes of the port,
- LDCs and Maximum Power Demand of a port,
- The Member State where the port is under jurisdiction,
- The legal context of the area where the port is located,
- The number of habitants and population density in the area,
- Other factors such as soil morphology, or whether it is a seismic area.

There are many reasons to implement an OPS system in a port, which are:

- OPS systems are the most appealing option, in terms of alternative ways to comply with the regulations, not only at the local level, but also at an international one,
- In the communities surrounding the port, OPS systems will surely provide healthier, cleaner and more noiseless environments,
- OPS may also provide financial rewards (economical or psychological) with the correct investment strategy,
- OPS research is relatively new methodology, as in the last 20 years it has started to be implemented in ports,
- In the next few years, with enactment of laws, such as EU "Fit for 55" package and IMO different indexes for reducing GHGs and pollutants, a growth trend will be observed in ports for evolvement of topical electrical grid and OPS systems

8.2. Conclusions on Interactive Map Program

With reference to Interactive Map Program, this technological aid can contribute to:

- In the recent years, extensive research is happening in many aspects of maritime, that requires information and recording of data on the issue of reducing emissions. This is a catalytic factor in reducing the greenhouse effect,
- It could help feasibility studies occurred for developments in ports, either for power increment of the local electrical grid, or for forming an OPS station,
- Correlation with the latest EU directives is important in terms of speeding up the implementation of laws related to the electrification of ships by land in ports,
- Take into account the benefits to the communities, by reducing CO_2, NO_x, SO_2 and PM,
- Compare emissions produced from different types of ships, in order to give priority to the ship types that are more "polluting". This will help diminishing air emissions from major ship categories, such as Container and Passenger ships.

Further futuristic innovations that can be made for the Interactive Map Program are:

- Enlarging the network of ports by adding more ports, but also with more port's information and further classification, as far concerns Deadweight, itineraries, and many more,
- Developing a more accurate way for the costing of OPS systems or increment in the local electrical grid, with novel methods like Machine Learning,
- Creating layers that will cover other ship needs and info,
- Constituting other ways of meeting the energy needs for ships at berth, like running with hydrogen or fuel cells. This can be done by creating a layer in relation to these methodologies.

9. Bibliography for Appendix I

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