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“Techno-economic feasibility study on the electrification of the port of Rafina”

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Abstract

Marine transportation is considered a major source of airborne emissions which directly affects the environment and human health in several ways. Air pollution and greenhouse gases produced by the shipping sector have been linked to degradation of local air quality especially around port cities as well as to various health problems related to the human respiratory system. Over the last decades there has been a significant effort by the global community on the mitigation of such emissions with the introduction of environmental regulations and the implementation of technological developments and emission reduction methods.

In this study, the possibility of implementing an Onshore Power Supply facility in the port of Rafina, Attica in Greece is investigated for the purposes of regulating and reducing the airborne emissions which are generated by the berthing passenger vessels. An initial assessment of the port's power demands in electricity is made by presenting each vessel's electrical load during berthing at the port of Rafina. Based on this analysis, a preliminary yet thorough design approach for a Cold Ironing facility is provided which includes dimensioning of the main equipment and detailed planning of the shore-side installations. The design methodology which is followed in this study is in accordance with specific standards that are issued by the International Electrotechnical Commission (IEC).

The proposed Onshore Power Supply facility is also examined by a cost and benefit perspective. Firstly, an initial estimation of the installation and maintenance costs that shall be absorbed by the port authority as well as additional costs which are required for the vessels' retrofitting procedures and will burden the ship operators are presented. Considering that Cold Ironing is a rather expensive method of reducing emissions, the indirect economic benefits that are associated with the environment and human health have been calculated. In order to achieve this, emissions that are produced by the vessels' auxiliary engines as well as through onshore power plants have been quantified, followed by an initial comparison which shows that such an investment offers major environmental advantages.

The final part of the study deals with the economic profitability of the investment which includes various scenarios and possibilities and takes under account the differences between onshore and onboard electricity production prices. Finally, the feasibility of integrating renewable energy sources is investigated and included in the economic analysis as part of an overall effort to transform ports globally into a new green era and engage more efficient energy transactions.

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1 Introduction

1.1 Background of study

Climate change is one of the most defining issues of our time. It is now more certain than ever that humanity is affecting and changing the earth's climate while the average surface air temperature has increased by about 1°C since the 1900s with much of this increase taking place since the mid 1970s. Greenhouse gases (GHG) such as carbon dioxide, methane and nitrous oxide are increasing as a consequence of human activities and are affecting the Earth's energy balance. Electricity production and transportation which require significant combustion of fossil fuels are two of the primary sources that are responsible for the substantial increase of GHG around the world.

Maritime transport is considered as the most environmentally friendly and efficient type of transportation. However, air pollution and GHG generated from ship emissions have been increasing in an alarming way mainly due to the increase of maritime traffic. Vessels emit substantial quantities of pollutants into the air which affect human health and the environment. For a long time shipping companies and port authorities operated with limited environmental oversight but this approach has changed over the last few decades where strict regulations as well as technical measures have been applied aiming at the mitigation of ship emissions.

It is estimated that nearly 70% of ship emissions occur within 400km of land (Endresen et al., 2003)[1] thus ships have the potential to contribute significantly to air quality degradation in coastal areas and harbour ports. Although emissions in ports account for only a few percent of the global emissions related to shipping, their impact is significant mainly due to their close proximity to urban areas and also as a result of the vessels' diesel-powered activities at berth such as lighting, cooling, heating and sanitation. Exposure to air pollution can lead to asthma, respiratory and cardiovascular diseases, lung cancer and premature deaths according to the World Health Organization (WHO, 2006)[6]. Shipping-related particulate matter emissions are responsible for approximately 60,000 cardiopulmonary and lung cancer deaths annually, with most deaths occurring in coastal regions within Europe as well as eastern and southern parts of Asia (Corbett et al., 2007)[6].

Based on the above, it is more than clear that the shipping sector shall limit its emissions by transforming into an even more energy efficient mode of transport in order to finally achieve sustainable growth.

Cold Ironing or Alternative Maritime Power (AMP) or alternatively Onshore Power Supply (OPS) is an initiative aiming at the elimination of ship emissions produced during berthing times while at the same time providing air pollution free maritime transportation for coastal areas as well as paving the way for greener and energy efficient port electrical grids.

With the implementation of Cold Ironing, ships are able to "switch off" their diesel-operated auxiliary engines and plug into shore power, which is provided from the electrical grid, thus reducing significantly all emissions along with a substantial mitigation on noise levels and vibrations.

Unlike other emission reduction methods such as the installation of exhaust gas scrubbers or fuel switching which do not address nitrogen oxides (NO_X) or carbon dioxides (CO_2), cold ironing minimizes these types of oxides. However the sulfur oxides are substantially reduced but not minimized since vessels' onboard steamed boilers are required for several operations during berth. Moreover it has been found that since the auxiliary engines of a vessel are not running while at berth, their operating costs which are absorbed by the ship owners are significantly reduced. In addition, one of the main advantages of onshore power supply technology is the environmental profile of onshore produced electricity through power plants as opposed to that of the onboard generated electricity from the vessel's diesel-operated auxiliary engines. Onshore generated electricity is considered far more efficient and in general is produced in remote areas thus its impact does not affect densely populated zones.

Overall the use of onshore power supply is widely considered as a viable way in order to reduce ship-based local polluting emissions. Furthermore, the use of renewable energy sources within the port area or in close proximity where the produced electricity can be consumed from the system's operation can create a smarter, stronger and greener port grid.

1.2 Scope and objective

The purpose of this thesis is to present a comprehensive and sustainable solution that will address the challenges that are created by the air emissions of all berthing ships within the port of Rafina, Attica in Greece. The port is located within the suburban town of Rafina thus the ship emissions have a direct impact to the residents' human health and the environment.

The possibility of implementing an onshore power supply facility within the port's surroundings that will provide electricity to the berthing vessels is investigated. For this reason several aspects are evaluated in order to proceed to the appropriate design choices for the Cold Ironing installation. Additionally, compliance with international regulations is also taken under account and relevant standards are applied to the proposed electrical shore grid. Furthermore, social and economic benefits for the residents from the limitation of ship emissions are considered whereas the financial sustainability of the facility is also examined. Lastly, the feasibility on the use of renewable energy that will provide additional benefits is studied.

1.3 Structure of study

Chapter 2

Chapter 2 provides an overview of the current conditions occurring within the maritime industry as well as an outline of the ship emissions and the various environmental and human health challenges. Lastly, the relevant regulatory framework aiming at the emission reduction is also briefly presented.

Chapter 3

The Cold Ironing technology and its characteristics are presented within this chapter. An extensive description of international regulations, relevant standards and connection systems is provided. Moreover, the essential shore side and ship-port interface equipment and a brief summary of the existing installations worldwide are also included.

Chapter 4

The fourth chapter of this study presents the results of the implementation of the onshore power supply technology and its methodology in the case study of the passenger port of Rafina. Firstly, an analysis of the port's daily and weekly power demands is presented based on each vessel's electrical requirements during berth. Secondly, the preliminary design and electrical topologies of the Cold Ironing installation are provided including all technical aspects that have been considered.

Chapter 5

An initial estimation of the installation and maintenance costs for the onshore power supply facility are presented in this chapter. In addition, a cost and benefit analysis is implemented which calculates the indirect economic benefits associated with human health and the environment. This is achieved through the quantification and comparison between ship and onshore emissions. Furthermore, the possibility of the implementation of a solar car park within the port's premises is also examined. Lastly, taking under account all the above as well as the differences between onshore and onboard electricity generation costs, an economic analysis for three separate investment scenarios is performed and presented in this study.

Chapter 6

Final conclusions of this study as well as recommendation for future work are included in this chapter.

2 World fleet and ship emissions

2.1 World merchant fleet and international trade

According to Equasis the world merchant fleet accounted for 116,857 ships in total for the year 2018 and an overall gross tonnage of 1,361,920[3]. Equasis is an online database and system information that collates existing safety-related information on ships from both public and private sources and has been developed by the European Commission and the French Maritime Administration. Within the large and very large categories which represent ships with a gross tonnage of 25,000 and above, bulk carriers (42.8%), oil and chemical tankers (25%) and container ships (16.3%) stand for approximately 83% of the fleet in these ship size categories.

Table 1: World fleet - Number of ships by type and size[3]

Ship Type	Small(1)	Medium(2)	Large(3)	Very Large(4)	Total	
General Cargo Ships	4,346	11,659	245		16,250	13.9%
Specialized Cargo Ships	8	227	61	5	301	0.3%
Container Ships	19	2,213	1,538	1,441	5,211	4.5%
Ro-Ro Cargo Ships	30	629	565	247	1,471	1.3%
Bulk Carriers	316	3,788	6,119	1,706	11,929	10.2%
Oil and Chemical Tankers	1,931	7,241	2,642	1,943	13,757	11.8%
Gas Tankers	36	1,116	362	481	1,995	1.7%
Other Tankers	396	698	12		1,106	0.9%
Passenger Ships	4,094	2,793	277	184	7,348	6.3%
Offshore Vessels	2,727	5,297	149	294	8,467	7.2%
Service Ships	2,744	2,750	27	6	5,527	4.7%
Tugs	17,848	1,041			18,889	16.2%
Fishing Vessels	19,359	5,244	3		24,606	21.1%
Total	**53,854**	**44,696**	**12,000**	**6,307**	**116,857**	**100.0%**

Table 2: World fleet – Gross Tonnage by type and size[3]

Ship Type	Small(1)	Medium(2)	Large(3)	Very Large(4)	Total	
General Cargo Ships	1,474	49,643	8,089		59,206	4.3%
Specialized Cargo Ships	3	1,767	2,323	371	4,464	0.3%
Container Ships	8	25,754	58,096	156,077	239,935	17.6%
Ro-Ro Cargo Ships	10	6,265	26,898	16,605	49,778	3.7%
Bulk Carriers	125	56,675	227,640	173,208	457,648	33.6%
Oil and Chemical Tankers	622	43,923	94,293	206,707	345,545	25.4%
Gas Tankers	14	7,098	15,671	53,896	76,679	5.6%
Other Tankers	118	2,022	355		2,495	0.2%
Passenger Ships	1,053	11,357	9,965	19,458	41,833	3.1%
Offshore Vessels	765	15,274	6,710	33,412	56,161	4.1%
Service Ships	671	8,888	994	891	11,444	0.8%
Tugs	4,296	1,024			5,320	0.4%
Fishing Vessels	4,228	7,070	114		11,412	0.8%
Total	**13,387**	**236,760**	**451,148**	**660,625**	**1,361,920**	**100.0%**

(1)GT<500 – (2)500≤GT≤25,000 – (3)25,000<GT≤60,000 – (4)GT≥60,000

Maritime transport remains the backbone of globalized trade and the manufacturing supply chain, as more than four fifths of the world merchandise trade by volume is carried by sea. However, according to a publication by the United Nations, growth in international maritime trade fell slightly in 2018, owing to softer economic indicators amid heightened uncertainty and the build-up of wide-ranging downside risks[4]. This decline reflects developments in the world economy and trade activity. Volumes increased at 2.7% below the historical average of 3.0% during the years 1970-2017 and 4.1% in 2017. Nonetheless, total volumes reached a milestone in 2018, when an all-time high of eleven (11) billion tons was achieved.

Based on the above numbers it is easily noticed that during the last five decades there has been a clear trend of increases in total trade volume. The world's population and economy is expected to continue to grow and shipping will need to respond to the demand for its services[5]. According to predictions made by the United Nations Conference of Trade and Development (UNCTAD) international maritime trade is set to expand at an average annual growth rate of 3.5% over the 2019-2024 period driven in particular by growth in containerized, dry bulk and gas cargoes. Projected growth estimated by UNCTAD is consistent with historical trends and is based on the estimated income elasticity of maritime trade over the 2006-2018 period.

2.2 Ship emissions and environmental challenges

Air emissions from ships is an important concern that has a major impact on human health and the environment. Vessels emit large quantities of several pollutants into the air atmosphere principally in the form of sulphur, nitrogen and carbon oxides, particular matter and volative organic compounds which have been steadily growing and increasing in an alarming rate. The shipping industry is accountable for generating almost 3% of the world's total greenhouse gas emissions such as carbon dioxide thus contributing to global warming and extreme weather conditions[7]. Although international shipping is already by far, the most carbon efficient mode of commercial transport and continues to improve in terms of fuel efficiency, the emissions that are generated from vessels are comparable to those of a major national economy[5]. Ship emissions will continue to increase in both absolute terms as well as in shipping's share of global greenhouse gases without further actions. Thus the implementation of new regulations and environmental measures is imperative for the sea transportation in order to stabilize or even further decrease the overall produced air emissions and therefore maintain a stable "fair share" of global CO_2 emissions.

As mentioned already in above paragraph, although maritime shipping has been the most energy efficient mode of transport and represents almost 90% of the international trade, it has been criticized and found itself subject of global discredit for failing to reduce its global greenhouse gas emissions. However, according to the third greenhouse study published by the IMO (International Maritime Organization) in 2014[8] prior to the economic crisis and specifically in 2007 the global CO_2 emissions that were generated from the shipping industry reached 885 million tons whereas in 2012 same emissions accounted for 765 million tons. On the other hand, in a study published by the UNCTAD, during the same time period (2007-2012) the amount of goods that were transported through sea was increased by 1163 million tons[9]. It is obvious that despite the growth of international trade even during the world economic crisis, CO_2 emissions produced by sea transport were substantially reduced.

The mitigation of the CO_2 emissions that occurred between years 2007 and 2012 was justified mainly by the environmental regulations as well as technological and operational developments aiming at the reduction of GHG (greenhouse gas) emissions. However, it shall also be stated that during the economic crisis the practice of slow steaming was implemented by many shipping companies for the purposes of reducing fuel costs and thus operational economic costs.

Predictions, primarily of the future amount of CO_2 emissions, are considered difficult due to the fact that they are highly dependent on international shipping demand. Additional factors that contribute to this uncertainty are the technological developments and the increase of alternative fuels usage and their profitability. Forecasts made by the IMO and presented in the third GHG study[8] estimate that CO_2 emissions from shipping will be 50% to 250% higher in 2050 than in 2012 despite fleet average efficiency improvements of about 40% and considering dramatic increase in future transport demand. Additionally it is estimated that by 2050, GHG emissions from shipping will contribute to approximately 10% to 14% of the global GHG emissions under several different scenarios given that mandatory regulatory measures are not implemented to the fullest extent. However since the third GHG study by IMO in 2014, shipping traffic has fallen and as of today it is generally expected that international trade will continue to decrease slightly. New technologies and present nationalistic trends are further decreasing international trade. On the other hand, population and global economic growth are factors that lead to greater maritime shipping transport.

During berthing in ports, vessels require electric power for accommodation needs such as heating, lighting, air conditioning and cooking among other but also for the proper operation of various machinery auxiliaries used during cargo loading and unloading conditions such as cranes and pumps. The amount of energy that is required for all the above mentioned activities is produced by one or two of the vessel's auxiliary diesel generators at port and ranges from hundreds of kilowatts for passenger and cargo ships such as bulk carriers to several megawatts for big cruise ships[9]. It is estimated that 190 grams to 250 grams of fuel are necessary for the production of one kWh of electricity and approximately 600 grams of carbon dioxide are generated[9]. Considering the amount of time that one ship stays at port on a daily basis and consequently during a year it is obvious that the quantity of emissions produced by each vessel is substantial.

Taking under consideration the above and although the majority of the emissions take place at sea, the most directly noticeable part of shipping emissions affects port areas as well as cities that are in close proximity to major ports due to the fact that they have a significant impact in human health as well as visible effects on the atmospheric ecosystem of these areas. Emissions produced by the maritime industry in ports are substantial and account for approximately 5% of the total amount of emissions caused by shipping (Dalsoren et al. 2008). The largest part of emissions in ports is generally attributed to the shipping activity and it is estimated that between 70% and 100% of emissions in ports of developed countries is caused by ships. Shipping emissions in port can represent a significant share of the overall emissions of one city depending on the size of each port and the industrialization rate of the area. Following table represents the ports with the ten largest absolute carbon dioxide and sulphur oxide emissions worldwide.

Table 3: Ports with the largest absolute emissions[2]

Top 10 ports (CO_2 emissions)	Share of total CO_2 emissions produced by shipping in ports	Top 10 ports (SO_x emissions)	Share of total SO_x emissions produced by shipping in ports
Singapore	5.9%	Singapore	6.5%
Hong Kong	2.2%	Hong Kong	2.3%
Rotterdam	2.0%	Port Klang	2.2%
Port Klang	1.9%	Tianjin	2.1%
Tianjin	1.8%	Shanghai	2.0%
Shanghai	1.7%	Fujairah	2.0%
Fujairah	1.7%	Busan	1.7%
Busan	1.4%	Kaohsiung	1.6%
Kaohsiung	1.4%	Ulsan	1.0%
Antwerp	1.2%	Beilun	0.9%
Total	**19.0%**	Total	**22.3%**

Above depicted table is included in the International Forum's discussion papers of the OCDE (Organization for Economic Co-operation and Development) regarding shipping emissions in ports. OCDE is an intergovernmental economic organization consisting of 54 member countries founded in 1961 for the purposes of stimulating economic progress and international trade ensuring environmental protection and preservation of human life.

Particular attention shall be given to the overall share of total emissions (CO_2 and SO_x respectively) for these ten ports as it is more than clear that these emissions represent almost a fifth of the total shipping emissions in ports. These numbers illustrate the highly skewed nature of shipping emissions generated in port areas. Most of the shipping emissions in ports are concentrated in Asia and Europe which is more than reasonable as these two continents represent almost 70% of the total port calls[2]. However ports in Asia and Europe are considered relatively time efficient and therefore, especially regarding Europe ports, present much less emissions than their share of port calls would suggest which can be explained mainly due to the implementation of air emissions policies such as shore power facilities and incentives for fuel switching. On the other hand, ports in Africa, the Middle East, Latin America and to a slightly lesser extent in North America, present higher emissions relative to their port traffic and efficiency times.

Prior to analyzing the various air emissions that are caused by maritime transport and addressing the main impacts and negative effects that each category causes to human health and the environment it is important to establish the difference between air pollutants and those components that lead to climate change due to alteration of the earth's atmospheric properties[10].

- Air pollutants are generally considered to be harmful substances for human beings as their impact on populated urban areas decreases as the distance from their release point increases. Nitrogen oxides, sulphur oxides and particulate matters are some of the main air pollutants.

- Emissions that alter the constituents of the earth's atmosphere through changes to their atmospheric concentrations are considered as a separate category where greenhouse gases (GHG) and ozone depleting substances (ODS) are typical elements included in this group of emissions.

The impact of GHG affects the environment in a global scale whereas air pollutants described further above are considered emissions with significant local effects.

The main exhaust emissions from marine diesel engines can be categorized as following:

- Nitrogen oxides (NO_X)
- Sulphur Oxides (SO_X)
- Carbon dioxides (CO_2) and water vapor
- Carbon monoxides (CO)
- Volative Organic Compounds (VOC)
- Particulate Matter (PM)

Nitrogen oxides (NO_X), sulphur oxides (SO_X) and particulate matter (PM) are among the most common categories of air pollutants while carbon oxides (CO_2 and CO) and volative organic compounds (VOC) are considered as greenhouse gases.

Free nitrogen (N_2) and oxygen (O_2) are two of the main components of both the air intake and the exhaust emissions from a marine engine. The formation of the nitrogen oxide (NO) and nitrogen dioxide (NO_2) occurs during the combustion process where a small quantity of nitrogen is oxidized to form various nitrogen oxides. The quantity of NO_X produced by a marine diesel engine is primarily a function of combustion temperature and it presents the amount of organic nitrogen found in the fuel (NO_X Technical Code, 2008). NO_X are considered reactive gases at the presence of sunlight which means that they have very low chemical reactivity. These byproducts have detrimental effects on the environment and human health. More specifically, they are said to cause various health problems in the respiratory system whereas their presence contributes to the global warming and acid rain phenomenon. In addition, photochemical smog produced when ultraviolet light from the sun reacts with nitrogen oxides is a major issue especially in densely populated warm cities and has many adverse effects. When combined with hydrocarbons, the chemical contained within smog forms molecules that cause eye irritation as well as respiratory ailments such as asthma, chronic bronchitis and lung cancer.

The oxides of sulphur (SO_X) are derived directly from the sulphur content of the fuels that are used. In the combustion chamber, the sulphur is oxidized principally forming sulphur dioxide (SO_2) and to a lesser degree sulphur trioxide (SO_3)[7]. It shall be noted that the amount of produced sulphur oxides by the shipping industry has increased over the last decades unlike those that are emitted from road transport and various land based industries which have been reduced. Sulphur oxides are the main cause of acid rain as well as soil and ocean acidification. Similar to nitrogen oxides (NO_X), sulphur oxides (SO_X) are harmful to the human respiratory system and can cause breathing problems especially to people with asthma that live close to ports. At high concentrations, SO_X can harm trees and plants by damaging foliage and decreasing growth.

Furthermore, sulphur oxides can react with other compounds in the atmosphere and form fine particles that reduce visibility especially within densely populated areas. Lastly, corrosion of metal structures as well as damage of stone and other materials are common outcomes of SO_X presence.

Carbon dioxide (CO_2) is the most significant emission in every internal combustion engine and the amount produced is highly dependent on the hydrocarbon composition of the fuel that is used during the combustion process. Maritime transport is among the leading industries emitting significant amounts of CO_2 since it was estimated that during 2012 the shipping industry contributed to approximately 2.2% of the global carbon dioxide emissions[9]. Although these types of emissions do not affect directly human health, they participate actively to the rapid global climate change.

Particulate matter (PM) is also considered a dangerous pollutant which affects in a substantial way the environment and human health. Particulate matter consists mainly of elements such as carbon, ash minerals, heavy metals and a variety of non or partially combusted hydrocarbon components of fuel and lubricating oils. Its effect on human health and the environment is determined mainly by the type and size of the compounds. Particle pollution includes inhalable particles with diameters of 10 micrometers and smaller (PM_{10}) and fine inhalable particles with diameters that are generally 2.5 micrometers and smaller ($PM_{2.5}$). Particles less than 2.5 micrometers in diameter pose the greatest risk to health affecting the lungs and causing greater problems by entering into the bloodstream.

Volative organic compounds (VOCs) are organic compounds composed primarily of carbon and hydrogen atoms and can easily vaporize into the atmosphere at room temperature. VOCs that are emitted outdoors are a concern not only for the potential to be carcinogenic but also because of their ability to create photochemical smog in the atmosphere. The VOC management plan which shall be applied for all crude oil carriers is ship specific and provides written procedures for minimizing VOC emissions during cargo loading and unloading according to MARPOL Annex VI, Resolution MEPC.185 (59).

2.2.1 Regulations and measures aiming at the reduction of shipping emissions

As already acknowledged by the Kyoto Protocol, emissions from international shipping cannot be attributed to any particular national economy due to their global impact. For this reason and since 1959, the International Maritime Organization (IMO) has proactively taken responsibility with respect to all issues related to pollution by the shipping industry by issuing and enforcing strict legislation aiming at the mitigation of such emissions.

The Marine Environment Protection Committee (MEPC) is an assembly that is responsible for addressing the environmental issues under IMO's remit and is supported by sub-committees that are frequently shared with the Maritime Safety Committee. One of these issues includes the control and prevention of ship-source pollution covered by the MARPOL (International Convention on the Prevention of Pollution by Ships) treaty which now contains technical regulations for the reduction of GHG emissions and has been enforced globally through a combination of flag and port state control by IMO Member States.

MARPOL Annex VI which was first adopted in 1997, limited the main air pollutants contained in ships exhaust gas, including sulphur oxides (SO_X) and nitrogen oxides (NO_X) and in addition prohibited deliberate emissions of ozone depleting substances. Furthermore, MARPOL Annex VI regulated shipboard incineration as well as the volatile organic compounds (VOC) produced by tankers[11]. In July 2005, the Marine Environment Protection Committee (MEPC) proceeded to the revision of MARPOL Annex VI with the aim of significantly strengthening the emission limits taking under consideration the recent technological improvements. More specifically, by enforcing the reduction of the global sulphur limit from 3.5% to 0.5% (effective January 2020). Stricter limitations which are effective since January 1st 2015, are applied to specific areas known as Emission Control Areas (ECAs). The limits applicable in ECAs for SO_X and particulate matter have been reduced to 0.1% since 2015. Progressive reductions in NO_X emissions from marine diesel engines installed on ships are also included with a "Tier II" emission limit for engines installed on a ship constructed on or after January 1st 2011 and a stricter "Tier III" emission limit for engines installed on a ship constructed on or after January 1st 2016 operating in ECAs. Compliance with "Tier I" emission limits is required for ships constructed between January 1st 1990 and January 1st 2020[11].

Further to all the above rules, Member States of the IMO agreed in July 2011 on a comprehensive package of technical regulations for reducing shipping's CO_2 emissions which entered into force in January 2013. The amendments to the MARPOL Annex VI include a system of Energy Efficiency Design Indexing (EEDI) which will lead to a 25-30% emission reduction by 2030. Additionally a template for a Ship Energy Efficiency Management Plan (SEEMP) for use by all ships is also included, which will assist companies to monitor and improve vessels' performance[5].

Additional measures such as the use of low sulphur fuel and natural gas as well as the installation of new scrubbers on board are three alternatives that shall be applied in compliance with new regulations. More efficient engines and propelling systems are the two main solutions enabling owners to comply with the stricter regulations[9]. Lastly, during berth, vessels can minimize the generated emissions by shutting down their auxiliary engines utilizing a procedure known as *Cold-Ironing* which will be presented in detail during the next chapter.

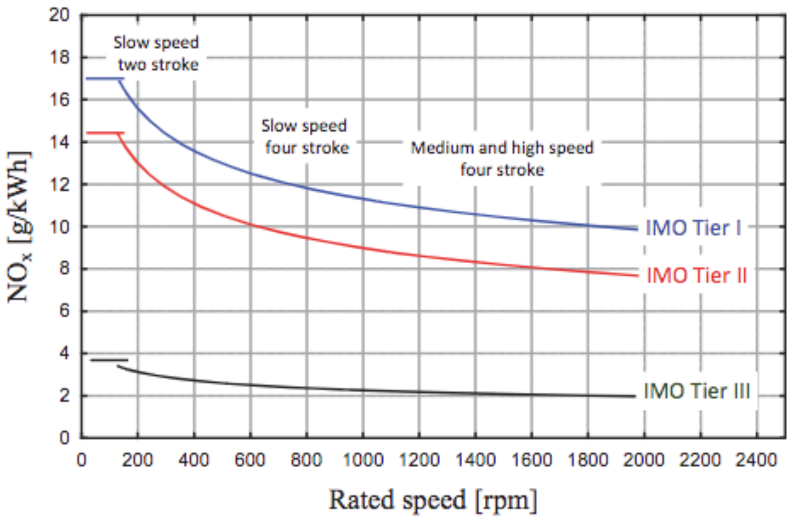

Figure 1: MARPOL Annex VI NO_X emission limits[22]

3 Cold Ironing

3.1 Cold ironing overview and background

The term "Cold Ironing" was initially used by the U.S. Navy and is dated a long time ago back when ships used to produce steam through boilers in order to generate the energy required for their propulsion systems. During berth the iron steam engines would stop operating thus allowing the iron to cool down.

Currently the term has a different meaning since most vessels run on marine diesel engines or diesel electric propulsion. During a ship's berthing time within a port, the auxiliary engines are operating in order to produce electricity covering in this way various hoteling needs which include lighting and ventilation, among others as well as for cargo loading and unloading. Taking under consideration the significant amount of fuel that is required during berth it is widely recognized that the produced emissions are substantial and constitute a major issue with serious consequences to human health and to the wellness of the environment in densely populated areas. The optimal solution to the above mentioned problem is the use of Cold Ironing which is also known as "Alternative Maritime Power" or "On Shore Power Supply" or alternatively "Shore-side Electricity".

Cold Ironing enables vessels to shut down their auxiliary engines while at berth and plug into an onshore power source through a main incoming station which is connected to the local power grid. Electrical power is transferred with the use of several underground and aerial cables to the vessel without any disruption to its onboard services. In this way emissions that are produced within the local surroundings by the vessels' auxiliary engines are eliminated whereas noise pollution and vibrations from auxiliary engines are significantly reduced. It is worth stating that the use of shore power does not minimize the overall emissions produced by a vessel during berthing time since steam that is produced through the onboard boilers is essential for operation of critical equipment.

It is argued that this transition of electricity source does not contribute to the mitigation of air pollution but rather shifts the emissions created to the onshore power generation facilities. However, taking under consideration the significant growth of renewable energy sources over the last decades from which electricity is produced as well as the higher efficiency of the power plants, the overall emissions reduction which is achieved is considered major[15]. Furthermore it shall also be noted that these stationary power plants are usually located remotely from densely populated areas whereas shipping emissions often occur within a city region thus having a direct negative impact to human health as well as the environment[16]. Additionally, another advantage of Cold Ironing is the benefit of lower operating costs for the ship owners due to the reduced time that the auxiliary engines are turned on and functioning[17] allowing also in this way a more holistic maintenance schedule to be followed.

Within this framework, Cold Ironing can transform many ports into energy hubs not only by decreasing the atmospheric pollution created by ships but also by contributing to each country's National Energy Policy plan[18].

3.2 Standardization of Cold Ironing and regulatory framework

There have been various implementation issues that have affected the standardization of the Cold Ironing and the creation of relevant regulatory framework that are justified mainly by the absence of a universal method in the design and construction of a ship's electrical power systems. More specifically, the auxiliary engines of a ship produce electrical current with a system frequency of either 60Hz or 50Hz. Ports in Europe, Asia and Africa are supplied with shore power frequency of 50Hz however in the USA shore power frequency is of 60Hz. Furthermore, system voltage of a ship can vary from 380 Volts to 6600 Volts depending on the type and size of a vessel. It is easily understood that the above differences and variations in a ship's system frequency and voltage are two of the main challenges in the process of creating several standards and configurations that should be followed for the implementation of an onshore power supply facility. For this reason, various voltage transformers and frequency converters are required in most cases which lead to a significant increase of the overall cost of a cold ironing installation in order to accommodate all vessels.

Two additional implementation challenges are, firstly the additional retrofit cost that shall be absorbed by the ship operators in case a ship is not properly equipped to receive shore power and secondly the possible upgrades of the national electrical grid system. Potential improvements include an extension of the nearby transmission lines closer to the cold ironing facility or an update of the local power grid substations.

3.2.1 The EU configuration

Since 2006, the European Union has presented a typical shore-side power supply configuration in the recommendation 2006/339/EC and is presented below whereas the advantages and disadvantages of this arrangement are extensively described within chapter five of this study. The configuration is considered a decentralized system configuration because a frequency converter is placed on each berth. The main equipment that is required for the supply and distribution of power to each vessel is presented in below figure and described extensively within the next page.

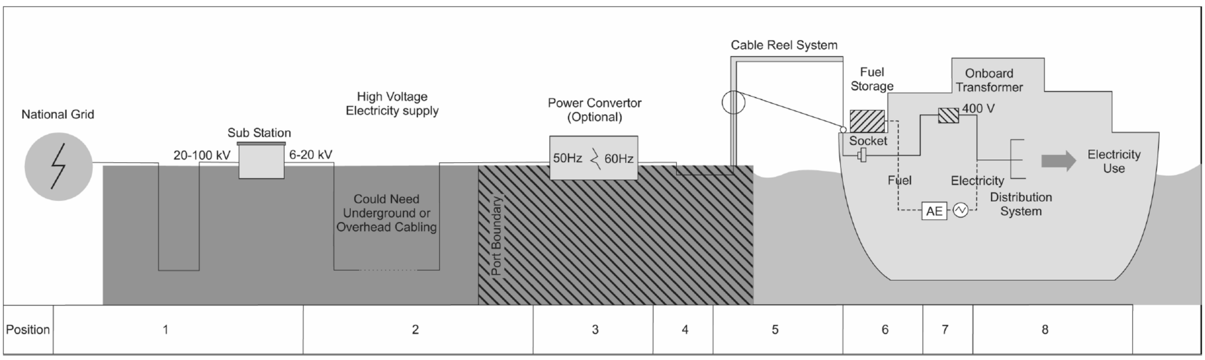

Figure 2: Electric supply system configuration according to EU regulation[35]

1. A connection to the national grid carrying 20-100kV electricity from a local substation where it is transformed to 6-20kV.
2. Cables to deliver the 6-20kV power from the substation to the port terminal.
3. Power conversion, where necessary. (Electricity supply in the Community has a frequency of 50 Hz. A ship designed for 60 Hz electricity might be able to use 50 Hz electricity for some equipment such as domestic lighting and heating but not for motor driven equipment such as pumps, winches and cranes. Therefore, a ship using 60 Hz electricity would require 50 Hz electricity to be converted to 60 Hz).
4. Cables to distribute electricity to the terminal. These might be installed underground within existing or new conduits.
5. A cabling reel system to avoid handling of high voltage cables. This might be built on the berth supporting a cable reel, davit and frame. The davit and frame could be used to raise and lower the cables to the vessel. The cable reel and frame could be electromechanically powered and controlled.
6. A socket onboard the vessel for the connecting cable.
7. A transformer onboard the vessel to transform the high voltage electricity to 400V.
8. The electricity is distributed around the ship and the auxiliary engines switched off.

3.2.2 Alternative shore-side configurations

Apart from the EU configuration which was presented further above, there have been several more architectural standards that can be categorized according to different criteria such as the presence or not of a frequency converter unit as well as the voltage level of the shore connection.

The shore supply systems which include a frequency converter unit can be further divided into those that use rotary frequency converters or those that incorporate static frequency converters. A decentralized solution includes a dedicated frequency converter to each shore connection point whereas the transformer at each berth serves the additional function of forming a sinusoidal curve shape together with the frequency converter. On the other hand a centralized configuration involves one frequency converter which is in most cases installed in a main central substation or alternatively several frequency converters in parallel. The converters supply a double busbar arrangement which can be used to selectively provide either 50Hz or 60Hz to each berth place. Each substation at berth can accommodate the isolation transformer and the appropriate low voltage switchgear which is connected through a breaker and a change-over switch that provides the ability to select which busbar shall be linked to the berth depending on the vessel[18]. In many cases where there is limited available space within the port promises and the centralized configuration is implemented, the shore-side transformers can be housed in groups of two or three within secondary substation buildings further away from the connection points.

The advantages and disadvantages of the abovementioned two solutions will be extensively presented and analyzed in chapter five prior to selecting the configuration that will be implemented for the port of Rafina.

As mentioned further above, depending on the voltage level of the shore connection there are two distinctive categories that shall be mentioned. Low Voltage System Connections (LVSC) with a system voltage of usually 440V are suitable for systems with power demand less than 1 MW while High Voltage System Connections (HVSC) with a system voltage of 6.6 or 11 kV usually are applicable for ships with higher power demand[18]. LVSC and HVSC systems are further described below.

3.2.3 Connection Systems

As mentioned above, there are two standards covering AC interconnection systems:

- The international standard IEC/ISO/IEEE 80005-1 which covers the AC High Voltage Shore Connection Systems and is applicable for ships with power requirements from 1MW and above or ships with HV main supply.
- The international standard IEC/ISO/IEEE 80005-3 which covers the AC Low Voltage Shore Connection Systems and is applicable for ships with power demands under 1MW.

The above mentioned standards aim to establish the requirements to ensure compatibility between ship and shore connection equipment, appropriate operating procedures and encourage compliance with the standard so that the maximum number of vessels can use shore connection equipment at as many ports possible. These standards provide simple connections eliminating the need for vessels to proceed to alternations regarding their equipment on board to different ports. Vessels that do not comply with the above standards may face difficulties to connect to shore supply facilities.

The standards cover among others: quality of the power supply, electrical, mechanical as well as environmental requirements, ship, safety and electrical equipment requirements, compatibility between shore connection and ship equipment, ship to shore connection and interface, plugs and sockets, verification and testing.

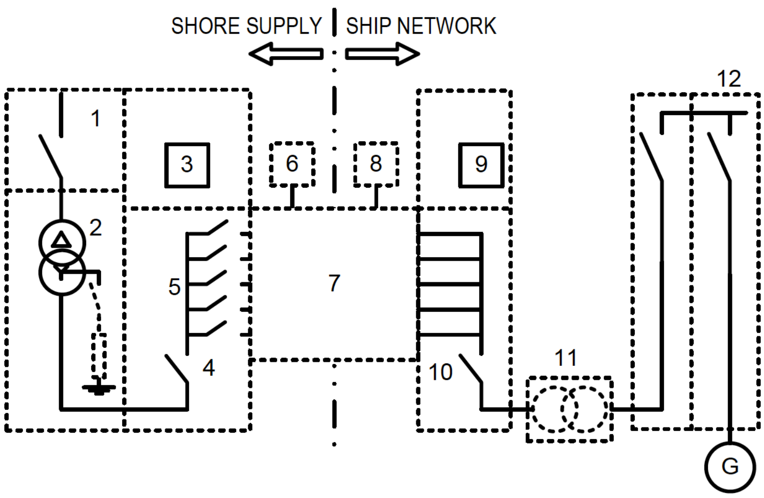

Figure 3: Port side configuration for a LVSC system (IEC/ISO/IEEE 80005-3)

Above mentioned standards propose similar configurations for both the HVSC and the LVSC systems. The main difference between the two configurations consists of the earthing equipment and its relevant interlocks used in the High Voltage systems to avoid residual charges. The above figure illustrates the port side configuration for a LVSC system as presented in IEC 80005-3. The main components of this configuration are presented below:

1. shore supply system
2. shore-side transformer and neutral resistor or/and IT system
3. shore-side protection relay
4. shore-side circuit breaker
5. shore-side feeders circuit breakers
6. shore-side control system
7. shore to ship connection and interface equipment
8. ship-side control system
9. ship protection relay
10. on-board shore connection switchboard
11. on-board transformer (where applicable)
12. on-board receiving switchboard

One thing that both systems have in common is the use of a dedicated isolated transformer as the last installation component prior to the interconnection between the vessel and the port. Hence, only one ship can utilize each transformer in order to satisfy galvanic isolation requirements. Therefore, the ship power system is protected from abnormalities that originate from the shore power system.

Many power system grounding problems and stray currents can affect the vessel's power – supply ground fault protection, unless the shore power system has its own grounding zone by providing a dedicated transformer with a neutral grounding resistor. The isolation transformer shall be of Dyn configuration. The neutral point of the isolation transformer shall be earthed through a neutral earthing resistor. The neutral earthing resistor may be omitted when shore LVSC utilizes IT system.

The continuity of the neutral earthing resistor shall be continuously monitored. In the event of loss of continuity the shore-side circuit breaker shall be tripped.

When frequency conversion of the shore supply shall be implemented, a secondary delta winding of the transformer, in combination with an earthing transformer with resistor on the primary side, suitable to compensate for possible circulating currents, are permitted provided that the other requirements of the standard are fulfilled.

Equipment earthing conductors terminated at the shore power outlet box receptacles shall be connected and connected to the vessel in order to create an equipotential bond between the shore and the ship. This may require bonding to the ship switchgear earthing bus and/or bonding to ship's hull.

Another important subject that the IEC/ISO/IEEE 80005-3 standard covers is the number of cables that shall be incorporated in an LVSC system. Table four indicates the number of feeding cables as a function of the maximum power demand and the voltage of the connection, while table five shows the maximum corresponding current per cable.

Table 4: Number of feeding cables

Power demand	**Connection Voltage**		
kVA	V		
	400 V	440 V	690 V
250	2	1	1
500	3	2	2
750	4	3	2
1000	5	4	3

Table 5: Maximum corresponding current per cable

Power demand	**Connection Voltage**		
kVA	V		
	400 V	440 V	690 V
250	180.4 A	328.0 A	209.2 A
500	240.6 A	328.0 A	209.2 A
750	270.6 A	328.0 A	313.8 A
1000	288.7 A	328.0 A	278.9 A

3.2.4 Smart grids and ports as energy hubs

Smart grid is considered an electrical grid which includes a variety of operation and energy measures such as renewable energy sources and energy efficient resources among other. The concept of smart grids engages more efficient energy transactions between energy producers and consumers. It has been under development in the last ten to fifteen years along with the energy deregulation as well as the deployment of smaller or larger scale electric energy production plants based mainly on renewable energy sources[18]. The European Commission has introduced the European Technology Platform for the Electricity Networks of the Future (SmartGrid) since 2006 which aims at boosting the competitive situation of the EU in the field of electricity networks with a particular focus on smart power grids.

In continuation to the above it shall also be noted that ports can be further developed as energy hubs. An energy hub is considered a unit where multiple energy carriers can be converted, conditioned and stored. The infrastructure of ports can be enhanced in a way that supports or includes the electrification of port-related activities, the selective-collective cooperation of energy storage units deployed in port as well as the possibility of supplying islanded networks with electric energy based on environmentally friendly fuels. In addition, the construction of hybrid electric driven shuttle ferries can be implemented that will be utilized for short distances and will be powered through a battery based energy unit [18].

3.3 Equipment and ship-port interface connections

3.3.1 Shore side electrical equipment

The main equipment that is required to be installed onshore has been briefly mentioned earlier during the presentation of the various configurations that can be implemented during a cold ironing facility and will be further described in this part of this study as well as in chapter five.

Considering a centralized configuration for a shore connection network, a main substation building that is usually located far away from the port's quays represents the core of the facility. All main components that belong to the shore-side power supply infrastructure are located inside the building. The facility's frequency converter with its matching transformers and double busbar switchgear with shifting devices and measuring transformers are all gathered in the building. Moreover, the main substation contains secondary equipment such as breakers, disconnectors, surge arrester and transformers in order to connect the shore-side facility to the national grid. The size of the building depends on the number of berths that are supplied with shore-side power as well as the overall power demand of the shore network[19].

Taking under account the frequency incompatibilities as already mentioned in previous pages of this study, frequency conversion is considered an essential part of an onshore power supply facility. One or several frequency converters which can be parallel coupled can be installed depending on the power demand values that are required. The frequency converters can be cooled by utilizing sea-water which is available in the port area with the presence of appropriate heat exchangers. Enabling connection of simultaneous 50Hz and 60Hz frequency can be achieved with the installation of a switchgear with double busbars. Lastly, the frequency converter is accompanied with step-up and step-down transformers with suitable input and output converter voltage [19].

Depending on the power demand that shall be accommodated in each port, the shore power facility is supplied with one or several shore side transformer stations which are usually located in close proximity to the port's quays. Each one of these substations contains one or multiple land side transformer(s) which is the last link between the electric grid at shore and the vessel's electric power system. Every single berth that will be shore-side power supplied corresponds to one shore-side transformer. As mentioned briefly earlier, the presence of such a transformer provides a galvanic separation between the electric grids and in addition reduces the effects of possible fault currents occurring on one vessel to the nearby berthed ships. Lastly, cable losses are reduced since a higher voltage is facilitated by the transformer from the electric grid to the berthing places. Connection between the step-up transformer inside the main substation building and the shore-side transformers is achieved with the use of underground cables carrying 20kV voltage preferably[19].

Each shore-side transformer station also contains a switchgear cell on its secondary side for the purposes of protecting the outgoing cables. The switchgear is supplied with a compartment with a withdrawable circuit breaker with appropriate protecting relaying. All outgoing cables to the shore-side connection boxes are fed through switch disconnector departments[19].

Multiple receptacle pits or alternatively connection boxes are considered as the last element of an onshore power supply facility and serve as the connection point between the shore side installation and the vessel's electric power system. They are usually placed every 65 to 70 meters thus providing flexibility. Alternatively one set of boxes near the bow and one near the stern of each ship's berthing position will accommodate a port or starboard berthed vessel considering that the connections are located near the ship's stern. However, a different approach was followed during the design for the port of Rafina with one receptacle pit for each berth taking under account the small size of the passenger ships.

Due to the fact that these connection boxes are placed closely to the port's quays they shall limit the accessibility to the vessels' various operations as little as possible. Essential equipment which is needed such as the presence of cranes for containerships during cargo loading or unloading shall not be obstructed by the interference of such receptacle pits. This is the main reasons as to why the placement of a connection box in an underground position fitted inside a container terminal has been chosen as the optimal solution as seen in below figure[19].

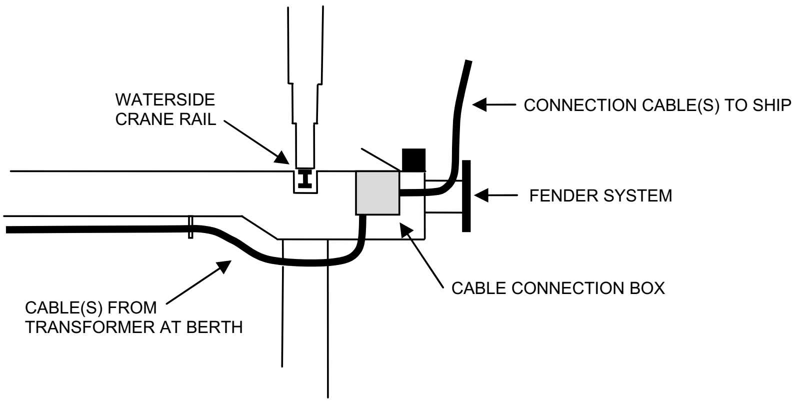

Figure 4: Shore-side connection arrangement between rail and quay[19]

These receptacle pits are key interlocked with the nearby switchgear. The receptacle key is removed when the incoming plug from the vessel is inserted which is then locked to the receptacle preventing it from being removed. The keys are then brought to the nearby switchgear which is usually powered continuously from the transformer switchgear and inserted into the locks at the breaker which in turn can be closed in order to hold the keys captive. Finally, the ship's onboard electrical power is then synchronized with the electric grid onshore. After the synchronization, the relevant circuit breaker on the vessel is closed in order to receive power enabling the auxiliary engines to shut down[20].

3.3.2 Cable management system

The overall interface equipment between the vessel and shore from the connection boxes which is utilized in order to control, record and handle the connection devices as well as the outgoing cables is called Cable Management System (CMS). The main two CMS categories are either those that are based onshore or those that are located onboard the vessel.

Available space is a limiting factor on any ocean-going vessel or even small passenger ships and usually allocation of such space poses a serious challenge for existing ships. For the abovementioned reason, several CMS provided from shore side have also been developed during the last recent years.

CMS that are based onshore can either be stationary, mobile or mounted on a movable barge. Stationary systems installed onshore are integrated on the port's quays and cannot be relocated further to their installation. On the other side, mobile systems are usually equipped with an electric unit which enables their transfer closer to the berthing vessel without obstructing the ship's various operations. The third option of a movable barge equipped with an appropriate cable reel system is suitable for smaller ships that are moored closely to the port's quays[21].

Systems that are based onboard the vessel are considered as the ideal option when the port's dock is occupied with multiple cranes and available space onshore is limited. Fixed systems are located on the vessel's upper deck containing the cable reel system and possibly an additional transformer. On the other hand, mobile systems are usually placed on a twenty or forty foot container (TEU or FEU) which can be transferred easily depending on the location where the connection is to be made[21].

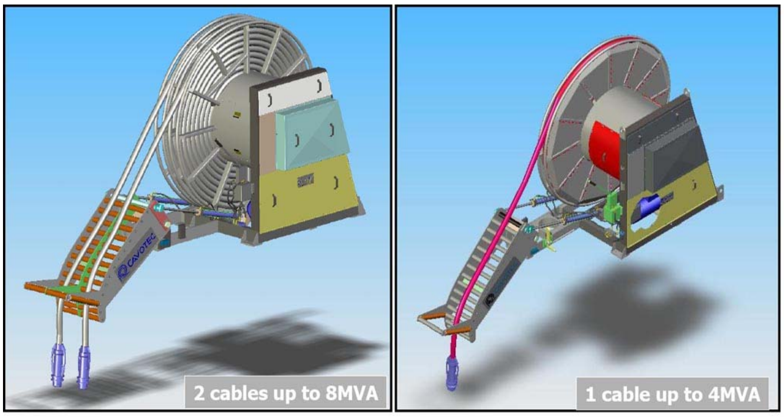

Figure 5: CMS with appropriate cable reel system based onboard (Cavotec)[20]

3.3.3 Onboard distribution and connection requirements

The connection cable(s) shall be supplied if possible by the vessel however as stated earlier in most cases this is not feasible. Additionally, in most cases a transformer onboard may be needed in order to allow an effective connection in a high voltage connection system. Power systems of many existing ships are of low voltage (440V) which is not ideal for providing shore power. In order to avoid issues such as voltage drop, power supply to the berthing place shall be at a higher voltage (6.6kV) and thus a step-down transformer located on berth or onboard shall provide current of low voltage[20]. Lastly, an upgrade of the vessel's existing synchronization equipment as well as the addition of a circuit breaker which is utilized when the vessel is synchronized and about to be coordinated to the onshore power supply facility shall also be taken under account[19].

3.4 Existing installations

As mentioned at the beginning of this chapter the use of shore power at ports is not new and has been introduced firstly by the U.S Navy where it has been successfully utilized in order to mitigate air pollution caused by ships. Roll-on/Roll-off ships where the first type of cargo ships to connect to power from an onshore power supply while at berth during the 1990s in Europe whereas more recently, shore power has been utilized to container cargo ships as well as cruise ships[15].

It is noticed that a growing number of cold ironing facilities are being implemented over the last decade around the world. The majority of the installations are found in northern Europe as well as along the east coast of the USA mainly because of the strict environmental regulations. On the contrary, the existing onshore power supply facilities in Asia are fewer where the cold ironing technology is still in stages of development[14].

During 2000, the port of Gothenburg in Sweden was the first to introduce a high voltage system connection (HVSC) within its cold ironing facility and since then many ports have reproduced this type of connection. The cold ironing installation provides shore power to Roll-on/Roll-off ships through a transformer substation of 6.6kV/10kV. Low voltage is provided as well and was the first to be introduced in 1989. However as of today, HV system connections are considered to be the most effective.

In 2004 the port of Los Angeles in cooperation with China Shipping Container Line became the first in the world to install a cold ironing facility specifically for cargo container vessels in its West Basin container terminal as an initiative under the "No Net Emission Increase program" (NNEI). The facility is supplied with power of 6.6kV voltage and frequency of 60 Hz whereas the transformer is placed on a barge that can be transferred towards the stern of the ship which is being cold-ironed. As of 2018, the port of Los Angeles has 75 Alternative Maritime Power (AMP) vaults which is considered the highest number among ports worldwide. In July 2012, The international standard IEC/ISO/IEEE 80005-1 which covers HV connection systems was introduced with the port of Los Angeles being an active participant in the development.

3.4.1 Electrification in the Eastern Mediterranean (Elemed project)

The electrification of the Eastern Mediterranean corridor is an initiative aiming at the cultivation of the cold ironing perspective in the Eastern Mediterranean region of Europe. It is coordinated by Lloyd's Register while several partners take part whereas Greece, Cyprus and Slovenia which are all EU member states are also included in the project. Elemed paves the way for the introduction of cold ironing as well as electric bunkering and hybrid ships across the Eastern Mediterranean sea area while attempting to study all technical regulatory, safety and financial issues related to the shore produced electricity and electric propulsion of ships[18].

In December 2018 the inauguration ceremony of the first cold ironing installation in Eastern Mediterranean took place at the port of Killini, Greece. The port of Killini is a four berth Roll-On Roll-Off ferry terminal and the cold ironing facility currently consists of one shore supply position which is constructed within the Elemed project framework with projections for other four electrification positions in the near future.

The shore-side substation includes among other, one static frequency converter for providing shore power with frequency of 50 Hz and 60 Hz as well as one isolation transformer which provides galvanic isolation from other connected ferries and consumers. The connection system is of low voltage (LVSC) since all berthing vessels have an electrical system of 380 to 440V voltage and their electrical power demands vary between 300kVA and 450kVA[18].

Below table depicts the majority of ports where cold ironing facilities have been installed in Europe and North America. It shall also be stated that newer installations are equipped with frequency converter units in order to provide shore power to all berthing vessels.

Table 6: Existing onshore power supply facilities in Europe and the USA[9], [14]

Port / Location	Country	Voltage	Frequency
Gothenburg	Sweden	440V/6.6kV/10kV	50 Hz
Stockholm	Sweden	400V/690V	50 Hz
Verko, Karlskrona	Sweden	-	50 Hz
Helsingborg	Sweden	400V/440V	50 Hz
Trelleborg	Sweden	10.5kV	50 Hz
Pitea	Sweden	6kV	50 Hz
Ystad	Sweden	11kV	50/60 Hz
Oslo	Norway	6.6kV	50/60 Hz
Bergen	Norway	440V/6.9kV	50/60 Hz
Antwerp	Belgium	6.6kV	50/60 Hz
Zeebrugge	Belgium	6.6kV	50 Hz
Rotterdam	Netherlands	11kV	60 Hz
Dunkirk	France	-	50/60 Hz
Marseille	France	11kV	50/60 Hz
Lubeck	Germany	6kV	50 Hz
Hamburg	Germany	6.6kV/11kV	50/60 Hz
Kotka	Finland	6.6kV	50 Hz
Oulu	Finland	6.6kV	50 Hz
Kemi	Finland	6.6kV	50 Hz
Livorno	Italy	6.6kV/11kV	50/60 Hz
Kyllini	Greece	400V	50/60 Hz
Los Angeles	USA	440V/6.6kV	60 Hz
Long Beach	USA	6.6kV	60 Hz
San Diego	USA	6.6kV/11kV	60 Hz
San Francisco	USA	6.6kV/11kV	60 Hz
Seattle	USA	6.6kV/11kV	60 Hz
Pittsburg	USA	440V	60 Hz
Juneau	USA	6.6kV/11kV	60 Hz
Vancouver	Canada	6.6kV/11kV	60 Hz
Prince Rupert	Canada	6.6kV	60 Hz

4 Power demand analysis

4.1 General information

The port of Rafina is almost exclusively a port that accommodates passenger and ferry ships. It is characterized as the second largest port in Greece after Piraeus in regards to passenger traffic. It serves approximately two (2) million passengers annually which accounts for 5.6% of the country's total passenger traffic. It serves as a link between the mainland and the Aegean islands. The port of Rafina accounts for 7.2% of all berthing ships, 15.8% of passengers and 2.5% of cargoes out of all ports in the country while the close proximity to Eleftherios Venizelos airport and high in demand tourist destinations such as the Cyclades and the island of Euboea have played a significant role in transforming the port of Rafina into one of the busiest ports of Greece.

Due to the port's proximity to the city of Rafina, where during the summer months its population climbs to thirty thousand residents, emissions that arise from berthing ships are a major issue in regards to the environment and public health. The port of Rafina as part of its strategy to become a zero-pollution port is already seeking expertise and support from European funding programs in order to achieve its goal. One option to this direction would be for ships to shut down their engines while at berth considering that the air pollution problem is caused mainly due to marine engine activity in ports.

4.2 Coastal shipping activities

Prior to deciding whether the port of Rafina is an ideal candidate for the implementation of a shore-side power installation facility, it is essential to gather as much information as possible regarding the type, number, particulars, capacity, characteristics of installed auxiliary engines as well as the electrical consumption of ships during their berth. One additional important parameter is the time (in hours) that each ship stays at port as this factor will define, in relation to the above aforementioned data, the size (in kVA) of the frequency converter that is required for the cold ironing installation. Below table shows the main characteristics of the ships that use Rafina port as their main hub.

Table 7: Passenger ships berthing at Rafina port

Vessel	D.G. Number	D.G. Output (kW/gen)	Length (m)	Gross Tonnage
Superferry	2	1250	121	10047
	1	937.5		
Superferry II	3	650	121.7	4986
	1	625		
HSC Superrunner	3	425	100.1	4724
Fast Ferries Andros	3	1025	115	4682
	1	975		
Theologos P	3	750	118.1	4140
Ekaterini P	3	600	116.5	3250
Paros Jet	2	812.5	105	3560
Tera Jet	4	1187.5	145.8	11374

During the summer months, the port of Rafina faces a significant rise in port calls from passenger ships that travel mainly to the Cyclades whereas during the winter only two to three ferry ships use this port as their main hub. Taking into account the fact that in the near future, demand in power needs will most likely increase due to a number of reasons, the worst case scenario shall be considered for the configuration of the on shore power supply installation. Below table shows the daily as well as the weekly turnaround time that each ship spends at the port of Rafina. This information allows us to better assess the current load that the port of Rafina is accommodating.

Table 8: Turnaround time (min) of ships that use Rafina as their main hub

Timetable 2018 (June - September)		
Vessel Name	Weekly turnaround time (min)	Daily average turnaround time (min)
Superferry	1670	239
Superferry II	2210	316
HSC Superrunner	4200	600
Fast Ferries Andros	4890	699
Theologos P	2010	287
Ekaterini P	4665	666
Paros Jet	775	111
Tera Jet	5980	854

As one can see, ships that berth for only a short time daily have been excluded from this study as it is considered that air emissions caused during such a short period are insignificant compared to a ship that keeps its auxiliary engines turned on during the night at least once a week.

In addition, small passenger only catamarans and hydrofoils have been excluded from this study due to the fact that they spend little time at port and/or have limited general power demand. For this reason their environmental footprint is insufficient compared to vessels with much higher power demands that spend eight (8) to ten (10) hours at berth. The same applies for aging ships, as their cost for retrofitting would be much more expensive and ship owners will probably be unwilling to retrofit them.

Based on data that was collected from various sources, including shipping companies which are managing many of the ships that use the port of Rafina as their main hub we successfully managed to gather the necessary information in regards to the power demand as known as hoteling load for all ships in kW. Load factor, which is the result of dividing the hoteling load with the power output of the auxiliary generators, varies from around 15% to 45%. A load factor of 1.0 means that the totally installed auxiliary generator capacity is utilized onboard a vessel. Additional results from the power demand study are addressed below:

1. Total power demand for ships that berth at the same time at the port of Rafina and have a system frequency of 60Hz varies from around 500kVA to 2200kVA and for those with a frequency of 50Hz from around 250kVA to 1600kVA.
2. The maximum number of simultaneously berthed vessels with a system frequency of 60Hz is four (4) during summer months and three (3) for vessels with a system frequency of 50Hz. The total number of vessels that berth simultaneously is six (6) during peak season.
3. Half of the berthing vessels operate with a system frequency of 50Hz and the rest operate with a system frequency of 60Hz. This factor will allow us to determine the load capacity that the frequency converter can withstand. The presence of a frequency converter is vital to the installation in order to enable the facility to supply vessels with 50Hz or 60Hz.
4. Primary voltage varies from 380V to 450V for all passenger ships which is considered as low system voltage. With the use of appropriate transformers localized at berth, voltage on shore will be adapted to system voltage onboard. In general, voltage as well as frequency of the vessels varies depending mainly at the place they were built.

Results of this study are also shown in below table and charts:

Table 9: Hoteling Load estimation for passenger ships that use Rafina as their main hub

No.	Vessel	D.G. Number	D.G. Output (kW/gen)	Frequency (Hz)	Voltage (V)	Maximum Hotelling Load (kW)	Maximum Hotelling Load (kVA)	Load Factor
1	Superferry	2	1250	50	440	500	625	0.20
		1	937.5	50	440			
2	Superferry II	3	650	50	440	500	625	0.26
		1	625	50	440			
3	HSC Superrunner	3	425	50	400	300	375	0.44
4	Fast Ferries Andros	3	1025	60	440	700	875	0.23
		1	975	60	440			
5	Theologos P	3	750	60	450	400	500	0.27
6	Ekaterini P	3	600	60	440	300	375	0.25
7	Paros Jet	2	812.5	50	380	200	250	0.25
8	Tera Jet	4	1187.5	60	440	350	440	0.15

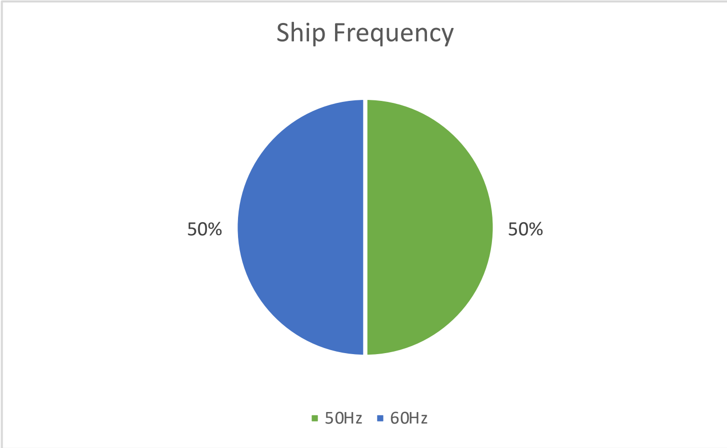

Figure 6: Electrical system frequency distribution

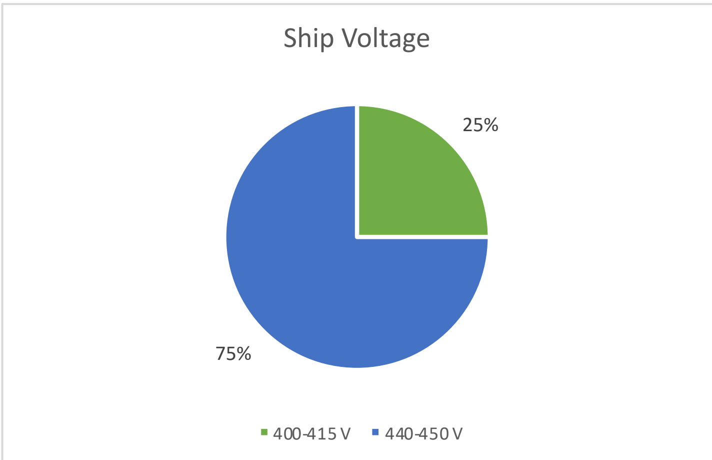

Figure 7: Electrical system voltage distribution

5 Technical Design

The main objective of this thesis is to present a preliminary design for a future shore-side electrical installation, therefore enabling vessels that berth at port to utilize land-based electricity instead of using their auxiliary diesel engines to provide power to their electrical equipment on board.

5.1 Technical design for the port of Rafina.

The provided electricity at the port of Rafina is of medium voltage at 20kV/50Hz hence a frequency converter shall be installed in order to accommodate vessels with a system frequency of 60Hz. Selecting the appropriate frequency converter will be based in accordance with the power demand study that has been already presented within the previous chapter.

As described more in detail in chapter three, the European union has presented its proposal (2006/339/EEC) on the promotion of shore-side electricity for use by ships in ports during berth. This configuration is a form of decentralized topology as the frequency converters are located very close to vessels' berthing places. As a result, during the stage of dimensioning the frequency converters, one has to consider that the aforementioned should be capable of accommodating the vessel with the highest power demands and electrical needs. Therefore, when a vessel with lower power demands calls at berth the above configuration will not be able to utilize the overcapacity of the frequency converters. Assuming that this arrangement was to be applied on our case, every frequency converter would be required to have a nominal output power of 1000 kVA in order to be able to provide shore-side electricity to the vessel with the highest power demand.

In addition, one more disadvantage of this configuration is the lack of galvanic isolation. Galvanic isolation is a design technique that separates electrical circuits in order to eliminate stray currents. Signals can pass between galvanically isolated circuits but stray currents such as differences in ground potential or currents induced by AC power are blocked. By implementing the proposed configuration of the European commission, vessels that have the same voltage on board as on the harbour lack a galvanic protection due to the fact that they are not supplied with a transformer on board. One can say that vessels that are equipped with a transformer, can achieve a galvanic protection at some degree.

The approach that will be followed, alternatively, for the design of the cold ironing implementation at the port of Rafina is based on a centrally placed installation for the frequency converter with matching switchgears with double busbars. This configuration was introduced by Patrik Ericsson and Ismir Fazlagic in their Master thesis of Science. More specifically, the centrally placed frequency converter is placed between two transformers (step-down and step-up transformer before and prior respectively) and is connected to one of the two busbars. In order to provide simultaneously power to vessels with 60Hz and 50Hz a second busbar is integrated and directly linked to the national grid through a transformer. In this way, each vessel that berths and is connected to the main facility has the advantage to be supplied with current of the desired frequency through a breaker and a change-over switch.

Lastly, a shore-side transformer is placed as the last link between the facility and the vessel in order to reduce the voltage to 6600 V or 440V depending on the type of connection made which is described in detail further below.

The presence of a transformer as the last component of this arrangement provides the necessary galvanic isolation by reducing the fault current that occurs on the vessel and preventing the possibility of a fault spread.

The above configuration has multiple advantages, one of them is that the frequency converter is used for what it is needed for that is, converting current of 50Hz frequency into 60Hz. For vessels using 50Hz current the frequency converter can be bypassed and consequently those vessels can achieve a direct connection to the second bypass providing 50 Hz current. Therefore, a higher efficiency can be achieved this way due to the fact that the frequency converter is not burdened by the 50Hz vessels. This configuration also provides a better distribution of available space inside the terminal due to the fact that most of the required equipment is placed centrally. Lastly, there is always the capability of placing an additional frequency converter in a parallel connection to the existing one in case there is an increase of power demand in the future.

However there are some drawbacks to this design. The most critical is that if a fault occurs in the centrally placed frequency converter, then the 60Hz frequency current will not be available to neither berths. This disadvantage causes the installation to be more vulnerable in case of a failure at the frequency converter. In addition, this design is considered more expensive as a consequence of the switchgear equipment that has to be installed since a double busbar is exploited with breakers and disconnectors.

Considering all the above and as already stated previously, the basic design concept that will be implemented for the port of Rafina will be based on a centrally placed frequency converter. The frequency converter that will be utilized will be dimensioned in accordance with the worst case scenario of power demand for the port of Rafina.

Since port's electrical grid is of medium voltage at 20kV and of system frequency at 50Hz, half of the vessels that berth (table 9) will need a frequency converter. One voltage transformer or multiple are required to be installed so that the 20kV current is stepped down to the frequency converter's voltage depending on how many frequency converters will be installed in parallel. Then additional voltage transformers are utilized again in order to step-up the 60Hz current to 20kV. In order to secure that current of 50Hz as well as 60Hz is provided in every berth place, a switchgear with double busbars shall be installed that will be connected with 20kV/50Hz current from the national grid on one side and 20kV/60Hz current from the frequency converters on the other side. Lastly, as mentioned previously every single berth that will be shore-side power supplied will be equipped with a shore-side transformer station as close to the berth as possible. The presence of a transformer ensures that current voltage is reduced from 20kV to 0.44kV and furthermore a galvanic separation is achieved between the grids. Transformers at berth facilitate even a higher voltage in the distribution grid to the berths, hence reducing cable losses. The connection point for communication between the vessels and the shore-side power supply infrastructure is established through a connection box that is watertight and constitutes to the vessels power connector cables.

5.2 Preliminary configuration of shore – side installation for passenger port of Rafina

Taking into account the limited space availability at the port of Rafina, five (5) berthing places for shore-side electrical distribution are considered adequate, further to the assessment that has been made previously of the current situation.

As shown in chapter four of this study, the number of simultaneously berthed vessels is six (6) during peak season while during winter this number drops significantly, whereas the overall load forecast for passenger ships with system frequency of 60Hz can fluctuate between 500kVA and 2200kVA and between 250kVA to 1600kVA for passenger ships with system frequency of 50Hz in a weekly basis. Given that only one ship has power demands around 900kVA we suggest one berthing place to be dimensioned for 1MVA with the possibility of an increase of electrical load in the near future. The remaining berthing places that will be proposed will be dimensioned for the ships with the higher power demands due to the fact that the shore-side electricity equipment will be used by more than one ship during the day as vessels berth in different times. Below table shows the number of berthing places and the highest load capacity that each one of them shall be able to accommodate:

Table 10: Maximum hoteling load for each berthing place

Vessel number	Berthing places	Hoteling Load kVA
4	1	875
1, 2	2	625
5	3	500
8	4	440
3, 6	5	375

As indicated on above table, power demand for all ships is lower than 1MVA, therefore the shore connection system and cable management from the shore-side transformers to the vessels shall be of low voltage and in accordance with the standard ISO/IEE/IEEC 80005-3. Hence the shore-side transformers at each quay shall be stepping-down the current voltage to 0.44kV and not 6.6kV. An onboard transformer is required in case vessel's voltage is not compatible with the system's voltage.

The shore-side transformers of each berthing place will be determined by the hoteling loads in kVA as depicted in above table, and their values are standardized in accordance with the R10 series as IEC 60076-1 suggests. As a result, the following transformers are selected:

- The first berthing place will be equipped with a shore-side transformer with rated power of 1MVA in order to be able to accommodate the vessel with the highest power demands that berths at the port of Rafina and with a possibility of accommodating vessels with even higher power demands in the future.
- The second berthing place shall be able to handle vessels with peak hoteling loads at 625kVA as seen above, therefore the size of the transformer is selected at 800kVA. These vessels are two sister ships that berth alternating weekly during nights thus one berthing place is adequate.

- The transformer at the third connection place will have a rated power of 500kVA for accommodating the vessel with power demands around 500kVA that also berths separately during the day, therefore during night this place can be utilized by other vessels and possibly other vessels with similar hoteling loads that will berth in the next few years.
- The last two berthing places will be equipped with a transformer of rater power at 500kVA each. These values for both transformers are selected considering a possible increase in power demand in the next few years although hoteling loads for remaining vessels can be currently exploited by using transformers of smaller capacity.

The next step in designing the shore-side installation would be dimensioning the centrally placed frequency converter that will facilitate the connection of simultaneously 50Hz and 60Hz vessels at the different berths.

5.2.1 Frequency converter unit

The total power output for all shore-side transformers is calculated at 3.3MVA however not all vessels operate with 50Hz frequency current. More specifically, vessels one and two (table 10) can be excluded from the process of dimensioning the frequency converter since their frequency current is the same as the shore-system's which is 50Hz. Vessel no. 3 can be taken into consideration since it has similar power demands with vessel no. 6 that operates at 60Hz. As a result all berthing places apart from quay no. 2 that accommodates vessels one and two shall be able to accommodate vessels with a frequency current of 60Hz. Therefore, the frequency converter unit shall have a nominal capacity of about 2.5MVA.

The converter unit will be selected from a wide range of static frequency converters that ABB offers and are specifically designed in order to convert the grid electricity to the appropriate load frequency. There are two alternatives that will be proposed that include the selection of different types of ABB converters. The ideal size for our configuration would be a frequency converter of 3MVA nominal power. However ABB does not offer units with such capacity and therefore the first option is to install two frequency converters in parallel connection of 1MVA and 2MVA respectively achieving the required electrical needs. The second option which will be followed is to install the ABB PCS 6000 SFC-4000 frequency converter with a maximum power output of 4MVA. There are two advantages with this alternative, the first one is the less amount of available space that the installation of one unit will occupy compared to the significant footprint of two units. The second advantage is the higher power output that this unit can produce. Despite the fact that the capacity of this frequency converter will not be exploited currently at its entirety, taking into account the required hoteling loads, there is the possibility in the near future of accommodating bigger ships with higher power demands.

The selected converter unit has a voltage input of 1.725kV and a voltage output of 2.3kV. Hence, the step-down transformer that will be placed prior to the frequency converter shall have a nominal power output of 4MVA and reduce current voltage from 20kV to 1.725kV. Similarly the step-up transformer that will be installed after the converter unit shall be of the same nominal power output as the step-up transformer and increase the current voltage from 2.3kV to 20kV.

The increase of the current voltage at 20kV is recommended for the purpose of distributing the power output from the main substation to the berthing places in high voltage and as a result minimizing the electric current flowing through the cables which can be easily explained taking into account the below relation between power and current:

$$P = V \times I$$

Where, P is the true distributed power in kW, V is the current voltage and I is the electric current flowing through the cables' conductors. As it is easily noticed, same power rate can be achieved by increasing the current voltage and decreasing the electric current. Consequently, cables with smaller cross-section are required and overall cost is significantly reduced.

5.2.2 Main substation building

The main substation represents the heart of the system and contains the main components of the system. The dimensions of the frequency converter indoor cabinet that will be utilized and positioned inside the main substation building will be 2.5 x 4.9 x 1.2 (m). Taking into account the fact that voltage transformers, circuit breakers, busbars, switchgears and control and protection relays among others will be also installed inside the main substation, the area that is required is estimated around 250m^2.

After examining multiple locations inside the port of Rafina for the installation of the facility it is determined that the optimal location is as indicated in the schematic drawing of the port displayed in figure 8. The biggest benefit from choosing this position is the minimum possible cable length that will be exploited and therefore the reduction in cost which is essential as a result of the close distance of the building to the port's quays.

5.2.3 Shore-side transformer buildings

Taking into account the limited available space within the port of Rafina and more specifically around the terminal area, the five (5) shore-side transformers that will be utilized are proposed to be housed inside two (2) small buildings that will be located in near proximity to the terminal's parking space but not inside respective area. By implementing this arrangement, the terminal area is not affected in a significant way taking into account the fact that especially during the summer months the port of Rafina experiences heavy traffic due to Greece's tourism season. Based on similar studies a building that can accommodate two (2) shore-side transformers covers a footprint of around 28m^2 whereas in order to include three (3) transformers 38.5m^2 are required approximately. The first building will consist of the two transformers with power outputs of 1MVA and 800kVA each whereas the second building will accommodate the three transformers of smaller power output (500kVA).

5.2.4 Cable arrangement

Fifteen (15) single-core cables in total are required for the connection of the shore-side transformers with the main substation building carrying medium voltage 20kV. In addition, multiple underground and aerial cables carrying voltage up to 1kV are necessary in order to achieve a proper connection with each berthing vessel. In order to dimension the cross sectional area of each cable that will be utilized, the following equation is required for three-phase electric power in order to calculate the maximum electric allowable current flowing through the conductors' cables.

$$I = \frac{S}{\sqrt{3} \times V}$$

Where I (in Amps) is the maximum electric current flowing passing through the conductors' cables, S represents the apparent or true power (in MVA or kVA) and V is the current voltage in kV or V.

Overall fifteen (15) single-core cables of medium voltage are required that connect the shore-side transformers inside the two secondary buildings with the double busbar after the frequency converter unit. Each of these cables is necessary to transfer true power (S) which is equal to the nominal power of the transformer for each position at current voltage of 20kV. More specifically, three single-core cables are necessary for the connection of each position with the main substation. The cross sectional area of these cables will be determined by calculating the short circuit current with values that are provided by the Hellenic Electricity Distribution Network Operator for the transmission line from the medium voltage substation in Nea Makri (150/20kV).

$$I_{sc,nom} = \frac{S_{sc}}{\sqrt{3} \times V} = \frac{250MVA}{\sqrt{3} \times 20kV} = 7.2kA$$

Based on similar completed studies for the port of Piraeus and Killini and according to the resulted short circuit current, each of these fifteen (15) single-core cables will have a cross sectional area of 1x70mm^2. The cables will be routed underground in a trefoil arrangement as per table B.2 of IEC 60502-2 standard[24]. The maximum current for each cable is calculated below.

$$I_{max} = I_{nom} \times f_1 \times f_2 = 227 \times 0.66 \times 1.12 = 167.8A$$

Where I_{nom} is the nominal current which corresponds to the selected sectional area for single-way trefoil ducts, f_1 represents the correction factor used for grouping of cables since it is possible that all five (5) groups of these cables (each group consisting of three single-core cables) will be routed together (200mm spacing) and f_2 is a correction factor relevant with the soil thermal resistivity which is selected at 1Km/W (tables B.2, B.15 and B.21, IEC 60502-2 standard).

The number of underground cables that are required for the connection of each shore-side transformer to the respective quay which includes the connection socket will be determined according to table 4 as extracted from IEC 80005-3 standard. The same number of aerial cables that connect each connection socket with the vessel's connection point will be utilized. The number of cables (underground and aerial) that are necessary for each berthing place are presented in below table.

Table 11: Number of underground and aerial cables for each berthing place

Berthing places	Transformer output (kVA)	Number of underground cables	Number of aerial cables
1	1000	4	4
2	800	3	3
3	500	2	2
4	500	2	2
5	500	2	2

Concerning berthing place no.1 that is connected with the shore-side transformer with power output of 1000kVA the maximum current flowing through the underground cables is calculated below.

$$I_{max} = \frac{S}{\sqrt{3} \times V} = \frac{1000kVA}{\sqrt{3} \times 0.44kV} = 1312A$$

Dividing the maximum current by four (4) which is the number of underground cables needed for quay no.1 the maximum current flowing through each cable is calculated at 328A.

With regards to berthing place no.2 that is connected with the shore-side transformer with power output of 800kVA the maximum current flowing through the three (3) underground cables is calculated as follows.

$$I_{max} = \frac{S}{\sqrt{3} \times V} = \frac{800kVA}{\sqrt{3} \times 0.44kV} = 1050A$$

Dividing the maximum current by three (3) which is the number of underground cables needed for quay no.2 the maximum current flowing through each cable is calculated at 350A. Taking into consideration the two values of current for each cable and based on table B.52.5 of IEC 60364-5-52 a cross sectional area of 3x300mm^2 is required which corresponds to a nominal current of 365A for installation method D1. The final maximum current for each of the selected cables is presented below.

$$I_{max} = I_{nom} \times f_1 \times f_2 = 365 \times 0.76 \times 1.18 = 344.6A$$

Where f_1 and f_2 are the same correction factors as the ones utilized for the calculation of the maximum current of the medium voltage cables but with different values (tables B.52.16 for grouping of seven cables with spacing of 250mm and B.52.19, IEC 60364-5-52 standard).

Regarding berthing places no.3 to no.5 which are all connected with shore-side transformers of the same power output each, the maximum current flowing through the two (2) underground cables for each position is calculated within the next page.

$$I_{max} = \frac{S}{\sqrt{3} \times V} = \frac{500kVA}{\sqrt{3} \times 0.44kV} = 656A$$

Dividing the maximum current by two (2) which is the number of underground cables needed for each quay (no.3 to no.5) the maximum current flowing through each cable is calculated at 328A. According to table B.52.5 of IEC 60364-5-52 a cross sectional area of $3x300mm^2$ is required which corresponds to a nominal current of 365A for installation method D1. The final maximum current for each of the selected cable is presented below.

$$I_{max} = I_{nom} \times f_1 \times f_2 = 365 \times 0.66 \times 1.18 = 344.6A$$

Where f_1 and f_2 are correction factors as further explained above (table B.52.16 for grouping of six cables with spacing of 250mm and table B.52.19, IEC 60364-5-52 standard).

Each aerial cable will have a cross sectional area of $3x185mm^2$ according to Annex A.2 of IEC 80005-3 standard.

In conclusion, the main elements that consist of the shore – side power installation facility are the following:

- One delta-wye transformer with nominal power output of 4MVA that will reduce the current voltage from 20kV to 1.725kV which is the voltage input value of the frequency converter unit.
- One ABB PCS 6000 SFC-4000 frequency converter unit with a maximum power output of 4MVA that will enable power supply to vessels with a system frequency of 60Hz apart from 50Hz.
- One delta-wye transformer with nominal power output of 4MVA that will increase the current voltage from 2.3kV which is the output voltage value of the frequency converter unit to 20kV in order to minimize transfer losses.
- Fifteen (15) underground copper XLPE single-core cables with a cross sectional area of $1x70mm^2$ each and lengths of 525, 525, 180, 180 and 180 meters per position transferring current voltage of up to 20kV for the power supply to the shore-side transformers.
- Five (5) delta-wye 20kV/440V transformers with a neutral wire on the wye output side in order to provide galvanic isolation between the ship and the national grid as previously mentioned. Three of these transformers will have a nominal power output of 500kVA, one of 800kVA and one of 1MVA.
- Thirteen (13) underground copper XLPE three-core cables with a cross sectional area of $3x300m^2$ each and overall lengths of 180, 225, 210, 150 and 220 meters per position transferring current voltage up to 1kV that will be connecting the shore-side transformers with the aerial cables.
- Thirteen (13) aerial copper XLPE three-core cables with a cross sectional area of $185mm^2$ each and overall lengths of 200, 150, 100, 100 and 100 meters per position transferring current voltage up to 1kV that will be connecting each berthing vessel with the shore connection facility.

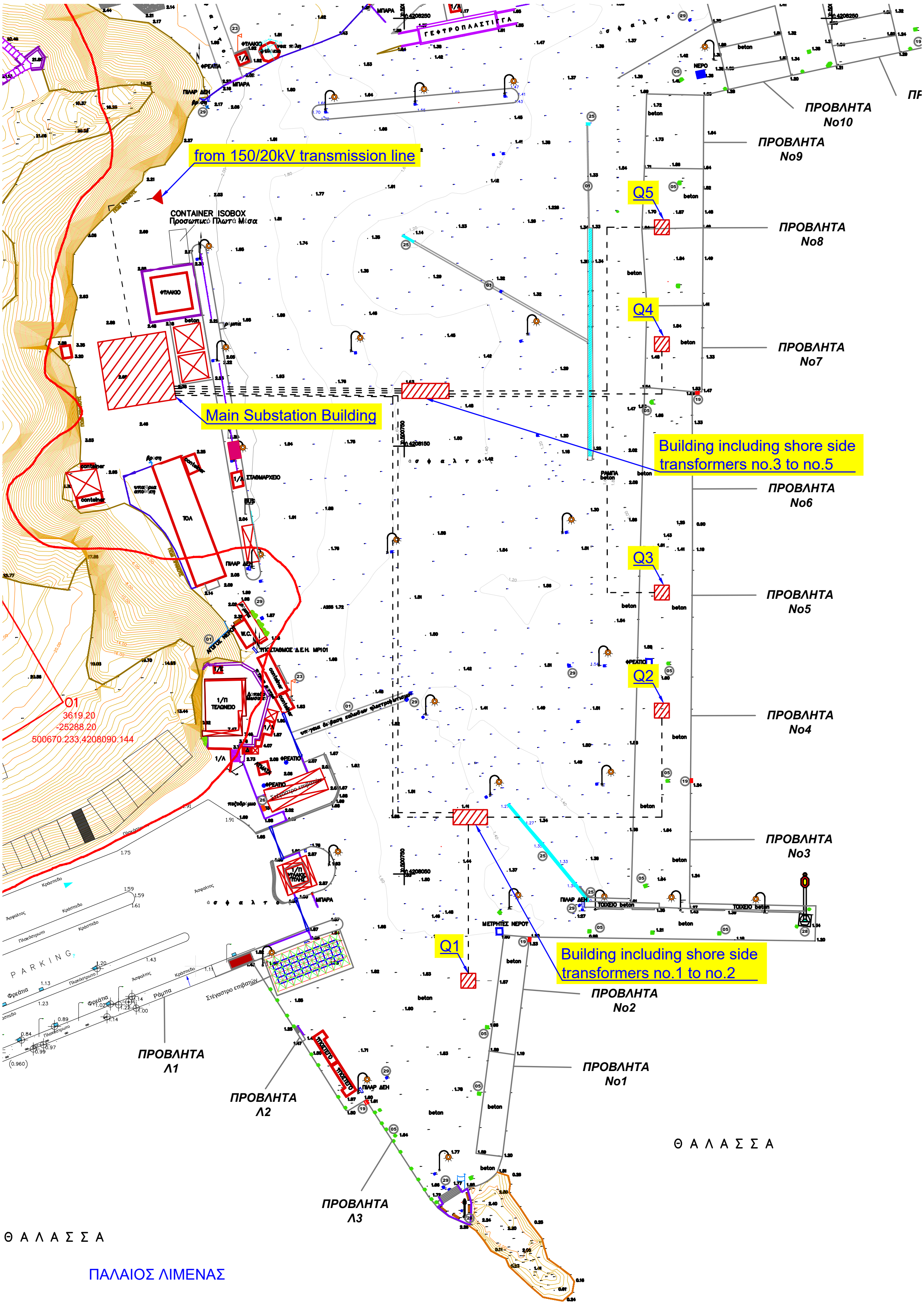

Figure 8: Topographic map of the port of Rafina incorporating the cold ironing network

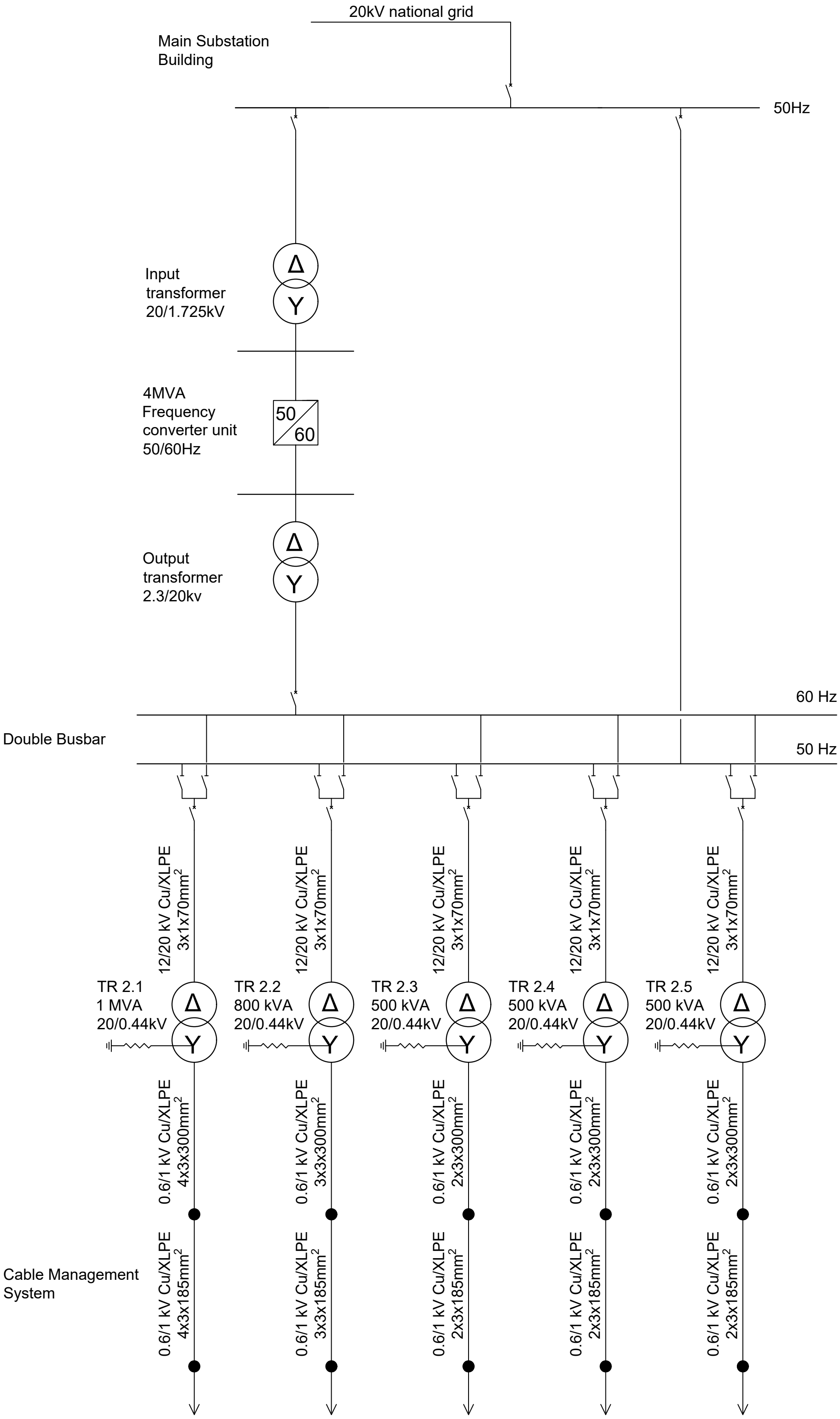

Figure 9: Schematic electrical drawing of the cold ironing facility at the port of Rafina

6 Cost and benefit analysis

In this chapter of the thesis, the financial and economic aspects of the shore to ship power facility will be presented. Taking into account the fact that actual prices of the equipment that will be utilized are not available online through the different makers' platforms, relevant results from multiple similar studies have been considered about the ports of Piraeus, Thessaloniki, Valetta, Rotterdam as well as the port of Gothenburg.

In addition, a cost and benefit analysis of the investment has also been performed in order to determine whether its benefits outweigh its costs. Furthermore, the health benefits for the residents of the town of Rafina are presented through the quantification of the ships' emissions.

At last, the option of creating a photovoltaic park inside the port area has been examined and is presented further below. Considering that the needs for electric power within the port will increase due to the newly installed cold ironing facility, one can assume that subsequently, the emissions created from the lignite that will be used for the increased electricity production will significantly rise. This is the basic argument and the reason that this optional investment is investigated. The increase in renewable sources for shore power generation (such as that of the creation of a photovoltaic park) will lead to even lower emissions within the area.

6.1 Cold ironing installation and maintenance costs

A general overview of the costs that are required during the installation process of the facility are presented below and are the results of similar studies as mentioned above. As it is noticed the cost of the frequency converter which shall be located inside the main substation building accounts for about 30% of the cost for the whole facility, while the cost of the convert's supply and output transformers, double busbars, shore-side transformers and connection boxes is also significant. The total installation cost for the passenger terminal of Rafina including five (5) berthing places is estimated around 2.4 million euros.

Maintenance and annual operating economic costs shall also be considered for the shore-side power facility. The need of one experienced and qualified electrical engineer is necessary in order to supervise and monitor the smooth operation of the facility. In addition, five (5) technicians are required for providing support during the connection and disconnection procedures of all berthing vessels at the on shore power facility.

Although the overall financial cost estimation for the construction and maintenance of the facility is considered high and thus can be reduced, the decision to proceed with the implementation of this investment shall not be evaluated only from an economic standpoint. The reduction in emissions with important positive impacts to the area's air quality and consequently to its residents health shall also be examined and assessed. A reduction in noise emissions incurred during the use of auxiliary engines can also be considered as a main external benefit. As a result, only by quantifying these external economic benefits can one determine whether this investment which is presented here, shall be implemented, taking into account the multiple environmental profits that will occur.

Table 12: Installation costs for the passenger terminal of the port of Rafina

Installation cost			
System size		4 MVA	
Main Substation			
		Cost in euro €	%
Building	250m^2	230,000	9.66
Frequency converter	1x4MVA	650,000	27.31
Converter's supply transformer	1x4MVA	75,000	3.15
Converter's output transformer	1x4MVA	75,000	3.15
Electrical grid extension works		300,000	12.60
Switchgear		250,000	10.50
Cooling, ventilation, fire detection, lighting, alarm		33,000	1.39
Power distribution			
1x70mm^2 / 20kV	1600m	45,000	1.89
3x300mm^2 / 1kV	1000m	100,000	4.20
3x185mm^2 / 1kV	650m	40,000	1.68
Shore side substations			
Buildings	66.5m^2	50,000	2.10
Transformers	1X1MVA	47,500	2.00
	1X800KVA	40,000	1.68
	3X500KVA	90,000	3.78
Connection boxes	5	225,000	9.45
Switchgears, circuit breakers, cables		130,000	5.46
Total estimated cost		**2,380,500**	**100.00**

The connection with the national grid will require additional costs due to the fact that an extension of the transmission line (150/20kV) from Nea Makri is required for the proper connection of the facility with the national grid. For this reason an approximate cost estimate has been considered however is shall be further specified by the Hellenic Electricity Distribution Network Operator.

In addition, depending on the type of the cable management system that will be utilized for the connection of the onshore power supply facility to each vessel, the economic cost for each solution differs significantly. Therefore it was decided not to include such cost estimates in this study in order to avoid deviations on the final cost projection. The different types of cable management system have been already described in chapter three of this thesis.

Table 13: Operational costs for the passenger terminal of the port of Rafina

Maintenance and operating costs		
	Number of employees	Annual wage / person €
Electrician - Engineers	1	24,000
Technicians	5	16,000
Total annual operating cost	104,000	
Maintenance cost	3% of the total installation cost	61,830
Total annual cost estimation	**€165,830**	

6.2 Benefits for the town of Rafina

6.2.1 Calculation of fuel consumption and emissions

In order to proceed with the calculation of emissions caused by berthing passenger ships within the area of Rafina an energy based approach will be followed. More specifically CO_2, SO_X, NO_X and PM emissions will be quantified by utilizing the power requirements of each berthing vessel. During berthing activities a vessel does not operate its auxiliary engines at their maximum power but only at a small percentage. As already mentioned during this work, the energy demand of each vessel during berth which is also known as hoteling load (in kW) has been presented (table 9) along with a suitable load factor. Vessels are assumed to be using approximately 20% to 40% of the engine power. The methodology that will be followed was proposed by the U.S. Environmental Protection Agency (ICF 2009) where the emissions can be determined using the equation below:

$$E = P \times LF \times A \times E_F$$

where:

E is the total emissions per engine in grams [g]
P is the maximum continuous rating power output in kilowatts [kW]
LF represents the load factor which is already known and is specific for each vessel according to table 9. Hoteling load is calculated by multiplying each vessel's load factor with the maximum rating power output of its auxiliary engines.
E_F is the emissions factor in grams per kilowatt-hour [g/kWh]

The calculation of fuel consumption on a monthly basis will be done by using the below equation which incorporates the specific fuel consumption in gr/kWh for passenger ships:

$$Fuel\ consumption\ \left(\frac{t}{month}\right) = \frac{SFOC\ \times Hoteling\ load \times t}{1000^2}$$

where:

SFOC represents the specific fuel oil consumption for each vessel in [g/kWh]
Hoteling load has been already explained above as the power demand each vessel requires during berth in kilowatts [kW]
t represents the total berthing time for each vessel per month in hours [h]

Since no specific data are available regarding the vessels' auxiliary engines manufacturers, specific fuel consumption values and emissions factors will be obtained from Entec UK Ltd final report on the quantification of ship's emissions between ports in the European community as presented at the European commission in 2002.

The general overview of the methodology which was followed in Entec's report was based on the published sources (mostly IVL and Lloyds Register Engineering Services data) where a new marine emission database (dataset "A") was compiled. By sorting and filtering the data, emission factors for five (5) different engine types and three (3) different fuel types, where possible, were derived. This was repeated for three (3) different activities of the ships, at sea, during maneuvering, or in port. In order to present universal emission factors, which represent a given vessel category, information regarding the typical engine types used for this category was necessary. Thus Entec UK Ltd examined the LMIS database for the ships entering the EU study area and provided such data (dataset "B"). Finally by combining the two underlying datasets A and B, weighted emissions factors for each specific vessel type can be derived for each of the three activities.

The ships that berth at the port of Rafina can be categorized as passenger/Ro-Ro cargo ships and the abovementioned values can be found further below. Specific fuel consumption numbers and emission factors are obtained from ships' "in port" activities.

Table 14: Emission factors for "in port" operation of passenger/Ro-Ro ships in gr/kWh

In Port	NO_x (gr/kWh)	SO_2 (gr/kWh)	CO_2 (gr/kWh)	VOC (gr/kWh)	PM (gr/kWh)	SFOC (gr/kWh)
Passenger/Roro cargo	11.3	11.2	746	1.0	1.8	235

Table 15: Emission factors for "in port" operation of passenger/Ro-Ro ships in kg/tonne fuel

In Port	NO_x (kg/tonne fuel)	SO_2 (kg/tonne fuel)	CO_2 (kg/tonne fuel)	VOC (kg/tonne fuel)	PM (kg/tonne fuel)
Passenger/Roro cargo	49	48	3179	4.4	7.6

According to Entec UK Ltd report in addition to the actual above values assigned as emission factors, it is of equal importance to assess the level of uncertainty associated with the factors. The uncertainty arises primarily from:

- the number and representatively the measurements used in deriving the emission factors in comparison to the total numbers and types of marine engines in use
- measurement uncertainties within the emission factor data set which vary for different measurement techniques and thus pollutants, and even activities
- assumptions made in assigning the factors for a given activity, e.g. main engine operation in port and lastly,
- the applicability of a universal factor for a given ship category

Considering the above, Entec UK Ltd attempted to determine and quantify uncertainty levels for the presented emission factors. Following guidelines presented in Eurochem 2000, uncertainty is expressed as a relative percent of the emission factors at the 95% confidence interval. These uncertainty levels are presented below for the three (3) different examined activities of the ships.

Table 16: Estimated uncertainties

	at sea	maneuvering	in port
NO_x	± 20%	± 40%	± 30%
SO_2	± 10%	± 30%	± 20%
CO_2	± 10%	± 30%	± 20%
VOC	± 25%	± 50%	± 40%
PM	± 25%	± 50%	± 40%
SFOC	± 10%	± 30%	± 20%

Table 17: Prediction of fuel consumption in a monthly basis

Vessel's name	Hoteling load (kW)	SFOC (gr/kWh)	Monthly berth time (h)	Fuel consumption (kg/h)	Fuel consumption (t/month)
SUPERFERRY	500	235	119	117.50	14.02
SUPERFERRY II	500	235	158	117.50	18.55
SUPERUNNER	300	235	300	70.50	21.15
FAST FERRIES ANDROS	700	235	349	164.50	57.46
THEOLOGOS P	400	235	144	94.00	13.50
EKATERINI P	300	235	333	70.50	23.49
PAROS JET	200	235	55	47.00	2.60
TERA JET	350	235	427	82.25	35.13
Total				**763.75**	**185.89**

Table 18: Prediction of emissions in a monthly basis

Vessel's name	Hoteling load (kW)	Monthly berth time (h)	NO_x (t/month)	SO_2 (t/month)	CO_2 (t/month)	VOC (t/month)	PM (t/month)
SUPERFERRY	500	119	0.67	0.67	44.49	0.06	0.11
SUPERFERRY II	500	158	0.89	0.88	58.88	0.08	0.14
SUPERUNNER	300	300	1.02	1.01	67.14	0.09	0.16
FAST FERRIES ANDROS	700	349	2.76	2.74	182.40	0.24	0.44
THEOLOGOS P	400	144	0.65	0.64	42.84	0.06	0.10
EKATERINI P	300	333	1.13	1.12	74.57	0.10	0.18
PAROS JET	200	55	0.13	0.12	8.26	0.01	0.02
TERA JET	350	427	1.69	1.67	111.53	0.15	0.27
Total			**8.94**	**8.86**	**590.11**	**0.79**	**1.42**

Table 19: Prediction of average fuel consumption and emissions of coastal shipping in Rafina port for one year

Fuel consumption (t/year)	NO_x (t/year)	SO_2 (t/year)	CO_2 (t/year)	VOC (t/year)	PM (t/year)
2230.72	107.26	106.32	7081.35	9.49	17.09

Table 20: Prediction of fuel consumption and emissions lows of coastal shipping in Rafina port for one year

Fuel consumption (t/year)	NO_x (t/year)	SO_2 (t/year)	CO_2 (t/year)	VOC (t/year)	PM (t/year)
1784.58	75.09	85.05	5665.08	5.70	10.25

Table 21: Prediction of fuel consumption and emissions highs of coastal shipping in Rafina port for one year

Fuel consumption (t/year)	NO_x (t/year)	SO_2 (t/year)	CO_2 (t/year)	VOC (t/year)	PM (t/year)
2676.86	139.44	127.58	8497.62	13.29	23.92

As one can see, by annualizing NO_x, SO_2, CO_2, HC and PM emissions caused by berthing ships, the environmental and health impacts on the town of Rafina are significant. Taking into account the worst case scenario, around 8500 tonnes of CO_2 emissions are released into the atmosphere with additional 130 and 140 tonnes of NO_x, and SO_2 produced. In addition, the quantity of VOC and PM should not be overlooked with almost 14 and 24 tonnes released yearly respectively. Taking into consideration that the calculation of fuel consumption and emissions is done only for eight (8) of the passenger ships that visit the port in a daily basis, it is evident that the air pollution that is created in reality is even greater. In addition, given the annual growth in shipping movements that is estimated in the future years, it is considered crucial to take measures in favor of the environment and the health of the residents of the town of Rafina.

It is to be added that other methods to reduce emissions from vessels are available whereas the technology varies between ships. Some of these measures which are outlined below allow only for a reduction of specific emissions but not necessary all of the emissions targeted through the use of on shore power supply. The most appropriate solution of eliminating all emissions while at berth remains that of supplying all ships with electrical power from shore thus enabling vessels to switch of their auxiliary engines. Some other methods include:

- Sea water scrubbing whereby SO_X is transferred to seawater. This however has led to debate in terms of the impact of these emissions to the ocean.
- Catalytic reduction whereby a urea solution is injected into an exhaust gas stream in combination with a catalyst housing in the exhaust channel.
- Exhaust gas treatment systems (EGTS) which are being installed on vessels and are intended to reduce SO_X or NO_X emissions or both. However several drawbacks are accompanied with the addition of an EGTS to a vessel such as high installation costs, occupation of valuable space onboard, frequent maintenance as well as the issues associated with the disposal of residues from scrubbing and NO_X as these emissions which are removed into a liquid solution, solid waste or powder form need to be disposed in a safely manner.

6.2.2 Estimation of emissions produced during shore electricity generation

During the last decades, Greece has been using lignite as a base fuel for its electrical power generation. However, the Greek power system is currently in a state where transition is bound to take place. During recent years, after the liberalization of market, natural gas has emerged and thus taking significant market share from lignite. Electricity is also generated through hydroelectric production and a smaller percentage comes from renewable sources of energy. Main electricity production takes place in western Macedonia with almost 50% of electricity coming from lignite extracted from that particular area.

Based on information which is available in the monthly energy balance reports from the Independent Power Transmission Operator (IPTO), during the time period from January to November of 2019 the total energy production in the electricity sector reached the number of 47,657 GWh. Almost 32% of the total production came from the extraction of natural gas whereas about 20% originated from the country's lignite power plants. Electricity through power exchange from neighboring countries was estimated at around 9%. Lastly, electricity produced through various renewable sources such as hydroelectric, solar or wind power amounted to 20%. Abovementioned values are also presented in the following table:

Table 22: Electricity production in Greece (January to November 2019)[36]

Type	Usage	
	GWh	%
Natural gas	15,214	31.92
Lignite	9,412	19.75
Hydroelectric	3,069	6.44
Renewable energy	6,472	13.58
Exchange	8,787	18.44
Other	4,703	9.87
Total	47,657	100.00

It is noted that natural gas has come into the foreground and gained the first place in terms of the ways electricity is produced in Greece overtaking lignite which was the main source of power production for many decades.

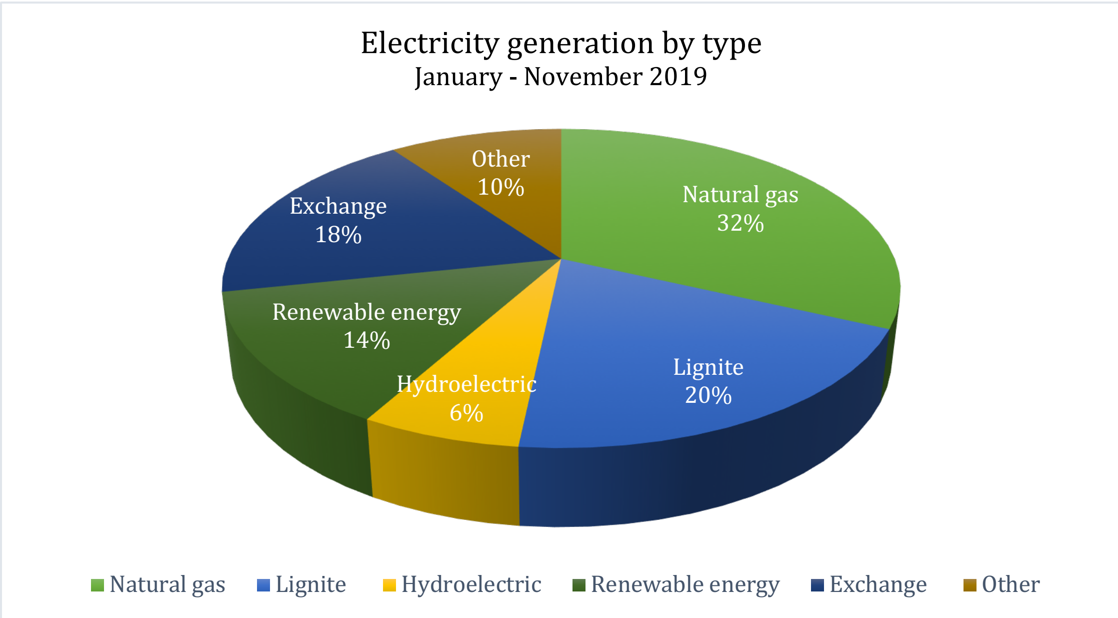

Figure 10: Electricity production in Greece (January to November 2019)[36]

According to reports published by Greece's Public Power Corporation (PPC), CO_2, SO_X, NO_X and PM emissions that are produced by each method of electricity generation have been quantified in gr/kWh and presented for further examination. The largest carbon footprint is created from the lignite power plants where about 950 gr/kWh are released through the atmosphere. The future of the lignite though is uncertain because of the pressure certain factors have placed on EU and Greek legislation to start imposing the decommission of lignite units and investing into more environmentally friendly sources of energy. Taking into account the impact each method of electricity generation has on the production of emissions, it is calculated that overall about 370 gr of CO_2, 0.55 gr of SO_X, 0.55 gr of NO_X and 0.20 gr of PM are formed per each kWh.

6.2.3 Comparison between onboard and onshore produced emissions

Table 23: Generated emissions in relation to electricity production per kWh[32]

Type	Usage	CO_2	SO_X	NO_X	PM
	%	g/kWh			
Natural gas	31.92	548.84	0.02	0.30	0.03
Lignite	19.75	984.29	2.80	2.30	1.02
Hydroelectric	6.44	0.00	0.00	0.00	0.00
Renewable energy	13.58	0.00	0.00	0.00	0.00
Exchange	18.44	0.00	0.00	0.00	0.00
Other	9.87	0.00	0.00	0.00	0.00
Total	**100.00**	**369.60**	**0.55**	**0.55**	**0.20**

Table 24: Emission factors for "in port" operation of passenger/ro – ro ships in gr/kWh[31]

In Port	NO_x (gr/kWh)	SO_2 (gr/kWh)	CO_2 (gr/kWh)	VOC (gr/kWh)	PM (gr/kWh)	SFOC (gr/kWh)
Passenger/Roro cargo	11.3	11.2	746	1.0	1.8	235

Above table which is also presented in page 47, provides emission and specific fuel consumption factors which are categorized based on each type of vessel and are derived by sorting and filtering data from multiple sources. It is clear that when comparing the emissions that are released through shore electricity production with the ones that are produced through onboard electricity generation, the possibility of investing in on shore power supply leads to a significant reduction in emissions. Providing that the country in which the port is based is generating electricity through a cleaner energy mix such as through gas and renewable energy sources, the benefits from the reduction of emissions can be substantial. In our case, energy production in Greece as already mentioned previously, is currently into a state of transformation where electrical generation through natural gas has rapidly increased grasping the first spot in terms of the amount of gigawatts produced per hour over electricity generated through lignite power plants. In addition, Greece's Public Power Corporation's intention is to switch off its coal plants sooner than expected and expand its renewable capacity by 2024 to boost profits and cut the country's carbon emission footprint. Given the country's climate where sunshine and winds can boost electricity production through renewable sources, it is estimated that solar, wind and hydroelectric power will account for at least 35% of Greece's energy consumption by 2030 which is more than double of the current level.

Taking into consideration the current situation in Greece, it is obvious that cold ironing is by far a greener option. The following table and figures provide a better understanding by comparing the emission factors that are produced when using vessels' diesel generators with those that are estimated to be produced if the alternative of an on shore power supply facility is introduced on a yearly basis.

Table 25: Comparison of onboard and onshore annual produced emissions

Emissions produced through vessels' diesel generators					
Type of vessels	Fuel consumption (t/year)	NO_X (t/year)	SO_X /SO_2 (t/year)	CO_2 (t/year)	PM (t/year)
Passenger/Roro cargo	2230.72	107.26	106.32	7081.35	17.09
Emissions produced through shore power electricity					
Type of vessels	Fuel consumption (t/year)	NO_X (t/year)	SO_X /SO_2 (t/year)	CO_2 (t/year)	PM (t/year)
Passenger/Roro cargo	0	5.22	5.25	3508.43	1.91
Reduction	-2230.72	-102.04	-101.07	-3572.92	-15.17
Reduction %	**100.00%**	**95.13%**	**95.06%**	**50.46%**	**88.81%**

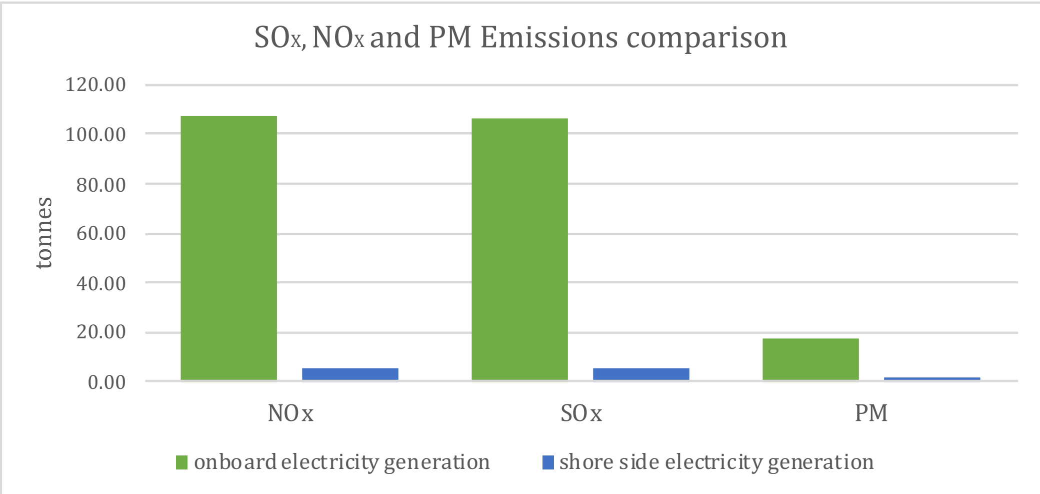

Figure 11: Comparison of onboard and onshore produced SO_X, NO_X and PM emissions

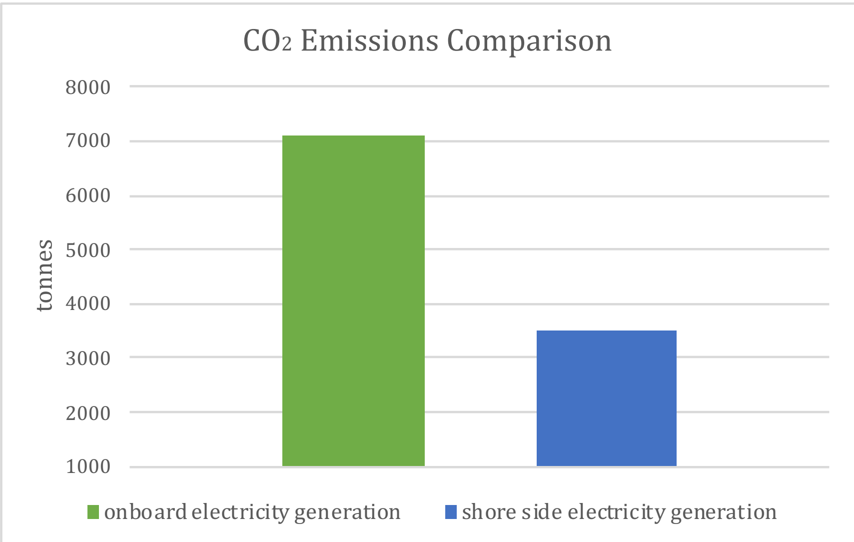

Figure 12: Comparison of onboard and onshore produced CO_2 emissions

As demonstrated in the above table and relevant figures, the reduction in SO_X, NO_X and PM emissions is considered substantial whereas the CO_2 emissions can also be decreased significantly by half of the amount that is currently released in the atmosphere through vessel's diesel generators while on berth. It is clear that by implementing an on shore power supply facility the air quality will improve dramatically since the emissions from shore-side electricity generation are much lower and occur further away from the town's populated area.

6.2.4 Economic benefits associated with the environment and human health

For the purposes of fully understanding the benefits that emerge by installing an onshore power facility, the shadow price or shadow cost approach shall be introduced for the emissions that burden the port of Rafina and have been mentioned in the previous chapters. This will allow us to explore the economic benefits that arise from the improvement of human health and the pollution mitigation in the wider area of Rafina. The study of these values will be presented, taking into account the fact that cold ironing as a process does not provide direct and immediate economic benefits to the port authority or the vessel operators.

Shadow prices are the values given to goods or production factors that are not traded in the market and inherently have no assigned monetary value to them. Therefore, shadow prices of emissions are the monetary values that are attributed in order to quantify the effect or the damage that the emissions cause to the human health and to the environment. More specifically, the shadow prices of the SO_2, NO_X, CO_2 and PM emissions will be calculated and presented in order to evaluate the economic effect of the onshore power supply plant. For this case, a report which was carried out by CE Delft and published in late 2018[34], presents estimated shadow prices of the aforementioned emissions and will be used as a reference point for this study. The updated CE Delft's report is extended and presents shadow prices, also mentioned as environmental prices, provided for air, soil and water pollution by over 400 environmentally hazardous substances as well as for noise and land use. It is worth noting that the environmental prices as extracted from CE Delft's report are average prices for the year 2015 per kilogram of emission from an average source and at an average location. Thus, these prices are rough-and-ready estimates and are not necessarily valid in specific situations. Upper pollutant levels have been taken into account and are depicted in the following table which are recommended for use in cost-benefit analyses.

Table 26: Environmental/shadow prices of emissions by CE Delft

Pollutant	Environmental price (€/kg)
CO_2	0.094
PM	50.25
NO_X	22.1
SO_2	17.9

The reduction in each of the above depicted ships' emissions in tonnes per year have already been calculated considering that all passenger ships that berth at the port of Rafina are retrofitted in order to receive power supply through a cold ironing facility. Therefore the indirect maximum economic benefit for human health and the environment is estimated for the wider area of the town of Rafina. Below calculated values apply only if all of the passenger vessels that have been studied in previous chapters of this thesis switch off their diesel generators during berth and receive shore power. This is considered as a very optimistic scenario since not all ship operators will be willing to switch to onshore power supply technology particularly due to the high cost of the required retrofits, the absence of direct economic benefits and the small number of ports providing shore power.

For this reason, the indirect economic benefits for human health and the environment have been calculated twice. Firstly, the calculated values are presented in table 27, where all berthing vessels are considered to be retrofitted and secondly calculations have been made when only half of the passenger ships are connected to shore power thus the reduction of emissions is lesser. For the purposes of calculating the emissions reduction in the second case, vessels with the longest berthing times and consequently higher power demands have been taken into account.

Table 27: Maximum indirect economic benefit through the use of shore power supply

	CO_2	PM	NO_X	SO_2	Total
Reduction in emissions (tonnes/year)	3,572.92	15.17	102.04	101.07	
Indirect economic benefit (€)	335,854.28	762,502.24	2,255,161.74	1,809,081.95	**5,162,600.21**

Table 28: Average indirect economic benefit through the use of shore power supply

	CO_2	PM	NO_X	SO_2	Total
Reduction in emissions (tonnes/year)	1,719.21	10.70	73.96	73.24	
Indirect economic benefit (€)	161,606.15	537,746.92	1,634,618.36	1,310,917.79	**3,644,889.22**

6.3 Cold ironing costs for berthing vessels

This part of the thesis will examine the additional costs that burden the ship owners and are required for the retrofitting of the vessels so that onshore power generation can be applied as well as maintenance costs such as the added cost of electricity during berthing time.

6.3.1 Retrofitting costs

According to ENTEC's 2005 study on shore-side electricity[35] which was conducted for the European Directorate Environment of European Commission, the total retrofitting cost that is required for an existing vessel is much higher than that of a newbuilding vessel. For the large majority of ships, as previously mentioned during this work, an onboard transformer will be needed in case they operate with a different system voltage. This is probably not the case for the port of Rafina since four out of the overall five shore-side transformers that will be utilized have an output voltage at 440V which is the same as the system voltage that most vessels operate at and use Rafina as their main hub. Nevertheless, the cost estimation for a transformer with a rated power that varies between 0.5 to 4 MW is in the range of 40,000 € and 107,000 € whereas the retrofitting installation cost is evaluated at 150% of the equipment cost (60,000 € to 160,500 €). Additionally, a transformer onboard that is located in an unsheltered position will need a suitable watertight enclosure with cable access via a watertight door in the topside which is estimated at 10% of the equipment cost (4,000 € to 10,700 €).

Furthermore, in order to avoid handling of high voltage cables, a cable reel system shall also be installed onboard in order to connect the high voltage electricity from the shore to each berthing vessel. The cable reel system which also includes the cable has an estimated cost of around 150,000 €. Average estimated costs are also depicted in below table and have been exploited from Entec's relevant report.

Table 29: Estimated retrofitting costs for the berthing vessels

Retrofitting costs		
	Newbuildings	Existing vessels
Onboard transformer	73,500	73,500
Installation	55,000	100,000
Cable reel system	150,000	150,000
Total Cost	278,500	323,500

6.3.2 Operating costs

6.3.2.1 Onboard electricity cost

Onboard electricity production cost in euros per hour for all berthing vessels that have been already studied will be measured taking into account the average bunker prices during the time period between August 2019 and February 2020 and also incorporating the fuel consumption factors in kg/h that have been previously calculated.

Fuel prices will be based on the average numbers in Piraeus port and in four additional ports globally, specifically the ports of Singapore, Rotterdam, Fujairah and Houston. These four ports represent approximately 25% of the global bunker volumes. Below figure presents the average MGO fuel prices in Piraeus port (in red color) and in four additional ports globally (in grey color).

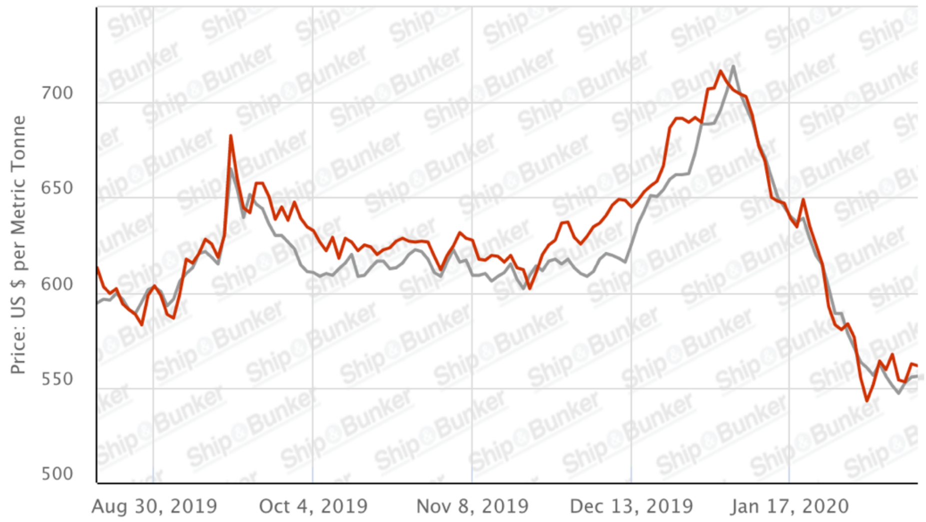

Figure 13: Average MGO fuel prices (source: www.shipbunker.com)

Table 30: Fuel prices in major ports globally, (source: www.shipbunker.com)

MGO fuel prices				
	Piraeus		Global four ports average	
	in $/mt	in €/mt	in $/mt	in €/mt
August	613.0	570.1	594.5	552.9
September	644.0	598.9	639.5	594.7
October	622.0	578.5	616.5	573.3
November	613.0	570.1	607.0	564.5
December	658.5	612.4	650.5	605.0
January	634.5	590.1	637.0	592.4
February	565.0	525.5	559.0	519.9
Average in $/mt	**618.14**			
Average in €/mt	**574.87**			

In order to calculate, for each vessel that berths at the port of Rafina, the cost of fuel in euros per hour and therefore in euros per each kWh, the fuel consumption numbers which have been presented in table 17 are necessary and in addition the average fuel oil price in euros per metric tonne which is depicted in above table will also be taken into consideration.

Table 31: Fuel costs for passenger ships while at berth

Vessel's name	Hoteling load (kW)	Fuel consumption (kg/h)	Average MGO fuel price (€/mt)	Fuel cost (€/h)
SUPERFERRY	500	117.50	574.87	67.55
SUPERFERRY II	500	117.50	574.87	67.55
SUPERUNNER	300	70.50	574.87	40.53
FAST FERRIES ANDROS	700	164.50	574.87	94.57
THEOLOGOS P	400	94.00	574.87	54.04
EKATERINI P	300	70.50	574.87	40.53
PAROS JET	200	47.00	574.87	27.02
TERA JET	350	82.25	574.87	47.28
Average				**54.88**

Since the MGO fuel price is considered the same for all the above mentioned berthing vessels, the fuel cost for each kWh is calculated at 0.1351 €/kWh.

6.3.2.2 Maintenance and operational costs

Additionally, maintenance costs for the auxiliary engines shall also be considered. Maintenance costs vary with engine type, for example two or four stroke, engine brand and size. Engine hours and running hours per year will also affect maintenance costs. Ships using shore-side electricity will still require a low level of routine maintenance for their auxiliary engines however this will be significantly lower compared to the ones that will are not be retrofitted in order to receive electricity from an onshore power facility. According to Entec's 2005 study, maintenance and operational costs for auxiliary engines are estimated at about 0.003€/kWh depending on the amount of energy (in kW) each vessel produces through its diesel generators.

Furthermore, the cost of lubricant oil consumption shall also be taken into account. Relevant costs are presented in similar study on the feasibility of installing a cold ironing facility in Piraeus port[9]. An estimated cost of 4000€/tonne of lubricant oil is assumed and marine diesel generators have an oil consumption of around 0.35 gr/kWh.

In view of all the above, total cost for the maintenance and operation of the auxiliary engines is calculated and presented in below table.

Table 32: Fuel and maintenance costs of a marine 4-stroke diesel generator

Fuel cost (€/kWh)	Maintenance cost (€/kWh)	Lube oil price (€/tonne)	Lube oil consumption (gr/kWh)	Lube oil cost (€/kWh)	Total cost (€/kWh)
0.1351	0.003	4000	0.35	0.0014	**0.1395**

6.3.2.3 Onshore electricity cost

Onshore electricity cost will be presented and analyzed in this paragraph in order to proper evaluate which type of electricity generation is more beneficial and therefore examine whether on shore power supply is more appealing to the ship owners compared to the resulting cost from the diesel generators. Required information regarding the electricity pricing and additional charges for large businesses and industries are available online through the Public Power Corporation's website. Considering that the electricity distributed through an on shore power supply facility will be required to be provided at all times, specifically every day, below table shows the costs and additional expenses that are implemented by the Public Power Corporation for the production and distribution of electricity. Different prices are applied depending on the time and day each consumer uses the provided power.

Table 33: Onshore electricity cost (source: www.dei.gr)

PPC cost (High Usage Factor)		
Time zone (24h)	Power fee (€/kW/month)	Energy cost (€/kWh)
07:00 - 23:00*	8.88	
07:00 - 23:00*		0.0647
23:00 - 07:00**		0.0620
Average energy cost (€/kWh)		0.05057

*Price rates apply during weekdays

**Price rates apply during weekdays, weekends and holidays

Additional expenses shall also be taken into account such as fees related to the services of general economic interest and others associated to the air emission reduction that support the growth of all renewable energy sources operating in Greece. Following table presents all aforementioned expenses.

Table 34: Additional onshore electricity expenses (source: www.dei.gr)

PPC additional expenses (High Usage Factor)						
Transmission system	Distribution network					
Power fee (€/kW/month)	Power fee (€/kW/month)	Energy cost (€/kWh)	Other expenses (€/kWh)	EREF fee (€/kWh)	SGEI fee (€/kWh)	CO_2 fee (€/kWh)
1.197	1.0970	0.0028	0.00007	0.00878	0.012405	0.00356

Table 35: Overall estimated power fee and energy cost (source: www.dei.gr)

PPC overall cost (High Usage Factor)		
	Power fee (€/kW/month)	Energy cost & other expenses (€/kWh)
Total cost	11.174	0.0782

As presented in the above table, the overall energy cost for onshore electricity generation is estimated at 0.0782 €/kWh which is slightly cheaper than the total cost that the diesel generators of a ship require for electricity production (0.1395 €/kWh including fuel and maintenance costs). However, one shall also consider the additional power fee which is substantial and will be a burden for the ship operators as well as the retrofitting cost for existing vessels which is also quite significant.

There are a number of options in order to further reduce the overall energy cost produced by the PPC so that the concept of on shore power supply to the vessels can appeal to the ship operators.

Firstly, a mutual agreement between the port authority and the Public Power Corporation could lead to a special reduced fee by introducing a tax reduction on the energy cost used through an on shore power facility for the hoteling loads of berthing vessels. In return, an increase in power demand can be achieved and therefore make cold ironing an attractive alternative for vessel operators.

Secondly, another solution that will be further assessed during the next chapter is the possibility of investing in renewable energy sources. More specifically, it is possible to obtain a significant percentage of electricity from these types of energy sources and this is the reason why the possibility of installing a photovoltaic park is examined. This would lead to an important reduction in the electricity cost and additionally, by decreasing the amount of electricity that is produced through land-based fossil fuels, an emission mitigation is also achieved in the areas where large power plants are typically located.

6.4 Photovoltaic Park

As already mentioned above, although cold ironing minimizes the emissions that are caused from the operation of the berthing vessels' diesel generators, it increases in an indirect way the emissions that are created from the generation of electricity through shore plants. This is the result of the greater demand for onshore electricity generation that is required to supply all berthing ships. In order to further mitigate the port's operation carbon footprint, it is possible to enchant the deployment of distributed renewable energy such as in ports of Rotterdam and South Louisiana. One feasible option is to exploit Greece's affluent and reliable supply of solar energy and introduce the possibility of facilitating a photovoltaic park inside the port's premises. Consequently, apart from the environmental benefit that originates from this alternative, a significant economic advantage can also be gained. More specifically, the port's authority can profit economically by selling the electricity which is produced through solar energy back to the grid to the Public Power Corporation with a number of ways that will be analyzed further below.

6.4.1 Photovoltaic technology and global energy transformation

Photovoltaic technology is one of the fastest growing renewable energy technologies and it is expected that it will play a major role in the future global electricity mix. Solar PV has been one of the pioneering renewable technologies over the decades. The total global capacity of installed and grid-connected solar PV power reached 480 GW (excluding concentrated solar power) by the end of 2018, representing 20% year-on-year growth compared to 2017 and a compound annual growth rate of nearly 43% since 2000. Solar PV power currently serves as the second-largest renewable electricity source after wind.

It is widely expected that by 2050 solar PV will be among the cheapest sources of power available, particularly in areas with excellent solar irradiation. Costs are estimated to vary between 0.011/kWh and 0.044/kWh and the total installed capacity is expected to reach the number of 8519 GW which means eighteen times higher than in 2018 according to the International Renewable Energy Agency report[38]. There are several reasons that contribute towards this direction with the most significant being the need to reduce energy-related CO_2 emissions globally by around 3.5% per year from now on until 2050 due to the fact that climate change has become a major concern of this century. Two additional secondary factors are the continuous rapid decline in renewable energy costs as well as the wider adoption of electricity for end-use applications in transport and heat.

Concluding, one can say that among all low-carbon technology options, solar PV contributes to a major emissions reduction potential by 2050. This is mainly due to the significant deployment of solar power replacing conventional power generation sources by utilizing the ample resource availability with the best technological solutions benefiting from drastic cost reductions, significant end-use electrification of transport and heat applications, shifting in this way energy demand to electricity.

6.4.2 Basic principle of a solar cell

The working principle of a solar cell is based on the photovoltaic effect, i.e. the generation of a potential difference at the junction of two different materials in response to electromagnetic radiation. The photovoltaic effect is closely related to the photoelectric effect, where electrons are emitted from a material that has absorbed light with a frequency above a material-dependent threshold frequency. This effect can be explained by assuming that the light consists of well-defined energy quanta, called photons. The energy of such photon is given by:

$$E = h \times \nu$$

where h is Planck's constant and ν is the frequency of the light.

There are three key steps for a working solar cell. First of all, there is the charge carrier generation (or light pumping). Electrons in the semiconductor absorber are pumped from the valence band to the conduction band in the presence of sunlight. Secondly, the charge carrier separation phenomenon occurs. Electrons in the conduction band and holes in the valence band have to move in different directions so that they are physically separated from each other in order to minimize direct recombination inside the device, which is often realized with selective contacts.

Finally, the charge carriers are extracted from the solar cells with electrical contacts so that they can perform work in an external circuit. The chemical energy of the electron-hole pairs is finally converted to electric energy.

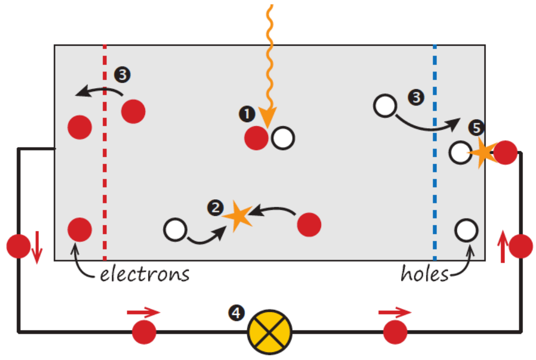

Figure 14: Working principle of a solar cell under sunlight illumination[39].

(1) Absorption of a photon leads to the generation of an electron-hole pair. (2) Usually, the electrons and holes will recombine. (3) With semipermeable membranes (selective contacts) the electrons and the holes can be separated. (4) The separated electrons can be used to drive an electric circuit. (5) After the electrons pass through the circuit, they recombine with holes[39].

6.4.3 Typologies of photovoltaic cells

Photovoltaic cell technologies are usually classified into three generations depending on the basic material used and the level of commercial maturity. First generation PV cells which are fully commercial, use the wafer-based crystalline silicon (c-Si) technology, either single crystalline or multi crystalline (mc-Si). The main advantage of the single crystalline PV cells is the efficiency which varies from 14% to 17% along with long operating lifespan. On the other hand, efficiency of the multi crystalline PV cells is lower compared to the single crystalline ones which comes with a reduced cost. However their lifetime is much longer compared to the single crystalline PV cells. Second generation PV cells are based on thin-film PV technologies and generally include three main families. Amorphous (a-Si) and micro morph silicon (a-Si/μc-Si), cadmium-telluride (CdTe) and lastly copper-indium-selenite (CIS) and copper-indium-gallium-selenite (CIGS). The market share of thin film technologies is still very limited (around 7%) but the solutions with the highest capacities in the medium-long term are being taken into consideration for a substantial price reduction. The two main advantages of this generation of PV cells are the reduced cost and the higher energy output with diffused radiation. Lastly, third generation PV cells include technologies such as concentrating PV (CPV) as well as organic cells that are still in a demonstrative phase but a gradual passage to the industrial production has been noticed in the last years[40],[42].

6.4.4 General overview and different typologies of a photovoltaic plant

The two main components of a solar plant are the photovoltaic generator and the DC/AC static converter or inverter. Secondary elements of a large scale PV plant include switchboards on the DC current side, a load generator and a battery storage system. The elementary component of a PV generator is the photovoltaic cell where the conversion of the solar radiation into electric current is carried out. A module consists of multiple cells, while several modules assembled together define one panel. An array is an assembly of panels connected in series and subsequently an assembly of arrays connected in parallel in order to obtain the required power form a photovoltaic generator[41].

The cell is constituted by a thin layer of semiconductor material, generally silicon which is properly treated and has a thickness of about 0.3mm and a surface which varies from 100 to 225 cm^3. The power conditioning and control system is constituted by an inverter that converts direct current to alternating current and also controls the quality of the output power that is to be delivered to the grid[41].

Stand-alone and grid-connected photovoltaic plants are the two main typologies that characterize a large scale PV plant. Stand-alone plants are not connected to the grid and consist of PV panels and of a storage system which guarantees electric energy supply also when lighting is poor or during dark periods. This kind of plants are advantageous from a technical and financial point of view whenever the electric network is not present or cannot be reached since they have the capability of replacing motor generator sets. On the other hand, permanently grid-connected plants draw power from the grid during periods that the PV generator is not able to produce the energy that is necessary to satisfy the consumer's needs. On the contrary, in case the PV system produces excess electric power, the surplus is then returned to the grid and therefore can operate as an energy storage device. Consequently there is no need to supply grid-connected systems with accumulator banks. This type of PV plants offers the advantage of distributed generation. The energy which is produced near the consumption area has a higher value than the energy produced in traditional large scale power plants due to the fact that the transmission losses are reduced[41].

6.4.5 Advantages and factors affecting the efficiency of a photovoltaic plant

There are multiple benefits that emerge with the installation and use of a photovoltaic plant. The most significant is the zero emissions they produce due to the fact that electricity generation through a PV plant does not involve the exploitation of fossil fuels and therefore can be considered as one of the greenest options. Additionally, operating and maintenance costs can be considered incredibly low while most PV plants can be characterized highly reliable for the reason that they do not have moving parts and their lifespan is estimated above twenty 20 years. However two major drawbacks are the low efficiency of 12-29% in their ability to convert sunlight to electrical power and the initial substantial cost during their development.

The performance of a photovoltaic power plant depends on many design parameters. An efficient design must optimize each parameter in order to achieve the greatest possible amount of energy. An overview of the most representative factors affecting the efficiency of a PV plant are presented further below.

The operating temperature plays an important role in the photovoltaic conversion process as PV current output is relatively stable at higher temperature. However the voltage is reduced leading to a reduction of solar or electrical conversion efficiency as the temperature is increased[43].

Another significant factor that is considered critical is the installing angles of the PV panels. The best tilt angle for any PV array is the one that produces the highest annual energy output for that particular location. The primary reference point is the latitude but other factors are involved as well. The arc of the sun varies depending on every period within a year so typically shallow tilt angles produce more energy in the summer months while during the winter months more energy is produced by steeper tilt angles[43].

Electrical current which is generated by photovoltaic devices is influenced by the spectral distribution (spectrum) of sunlight which varies during the day. However, the effect that the solar spectrum has on the PV performance is difficult to estimate since it depends on multiple factors such as local meteorological conditions, position of the sun, module mounting types as well as physical properties of the modules[43].

Module mismatch which is defined as the difference between the maximum power output of the total PV array and that of the individual modules (which is always higher) also effects the performance of a PV plant. This difference is a result of slight performance inconsistencies between neighboring modules and accounts for at least 2% loss in system power. Power is also lost to resistance in the system's wiring[43].

Soil and dirt can also play an important role on the efficiency of a PV array. Dirt and dust can accumulate on the solar module surface blocking some of the sunlight and as a result reducing output. Soiling may account for up to 10% of reduction during the annual energy production. Lastly, regarding northern locations during winter, snow reduces the amount of PV energy produced. The amount of snow received as well as how long it remains on the PV modules are key factors that affect the power output efficiency[43].

6.5 Size and location of the solar car park in Rafina, Greece

Solar radiation in Greece is considered, according to multiple known solar irradiation maps, as one of the highest in Europe. The sunshine duration in the south part of the country is about 3000h per year and the average annual solar radiation is around 1700 kWh/m^2 on the horizontal surface. This creates a favorable condition and has led to a huge growth of photovoltaic parks installations during the recent years. According to Georgios A. Vokas' paper[44] which examines the PV energy production in Greece, Attica is one of the three areas with the highest solar irradiation potential specifically calculated at 1802 kWh/m^2 using PVgis software[45]. Therefore it is obvious that Rafina town which is located within Attica region is an ideal candidate for the installation of a PV park.

The first step that has to be made, when examining the potential of installing a PV solar park inside the port's area, is to identify possible suitable spaces that will be appropriate for the deployment of the PV panels. After assessing the areas surrounding the port's premises, it was decided that the optional solution is to exploit the port's two open car park spaces by creating suitable carport canopies that can also integrate PV solar panels. Side benefit of this configuration is the ability of providing shade and pre-cooling to the vehicles which can effectively offset the latter's electricity consumption due to reduced air conditioning demand especially at start up. Furthermore, charging of electric cars through electricity that is generated from the PV solar panels, especially in the future can also be implemented and electrical charging infrastructure shall be included. Both areas are currently under port's jurisdiction and their size is estimated approximately to a total of 19,590m^2.

First area is located next to the city's coastline providing in this way parking availability for the people that visit the beach whereas second area is situated close to the port's terminal area. Abovementioned parking spaces are indicated and can be seen in the port's masterplan below.

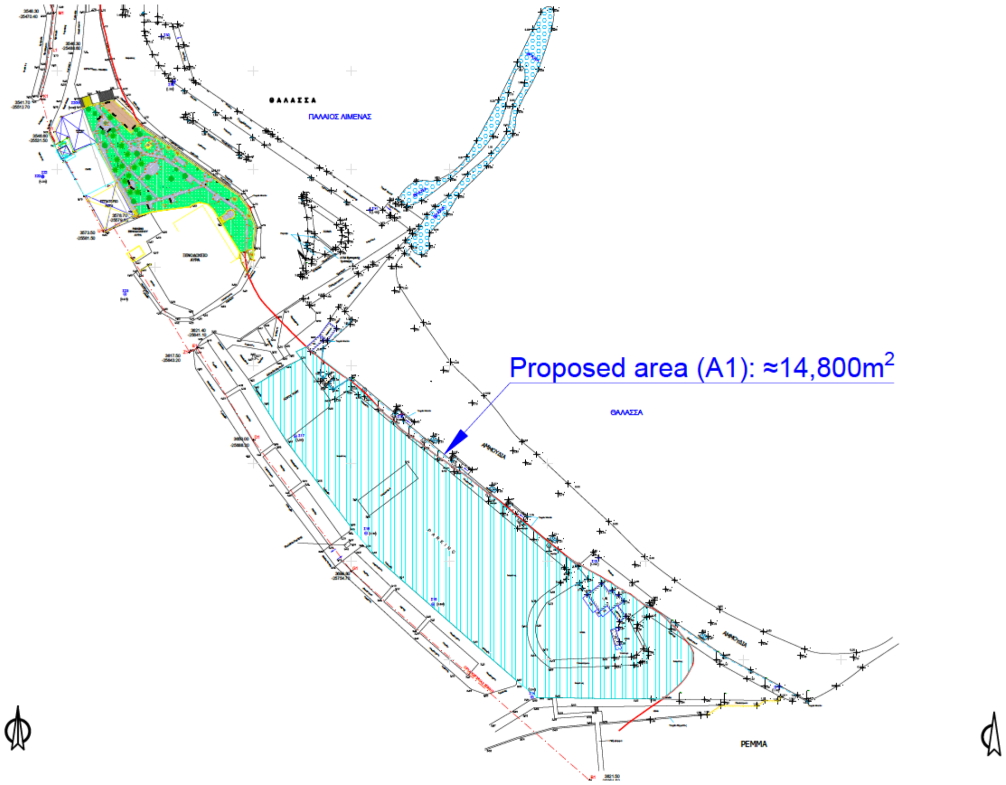

Figure 15: Proposed area no.1 of the PV park

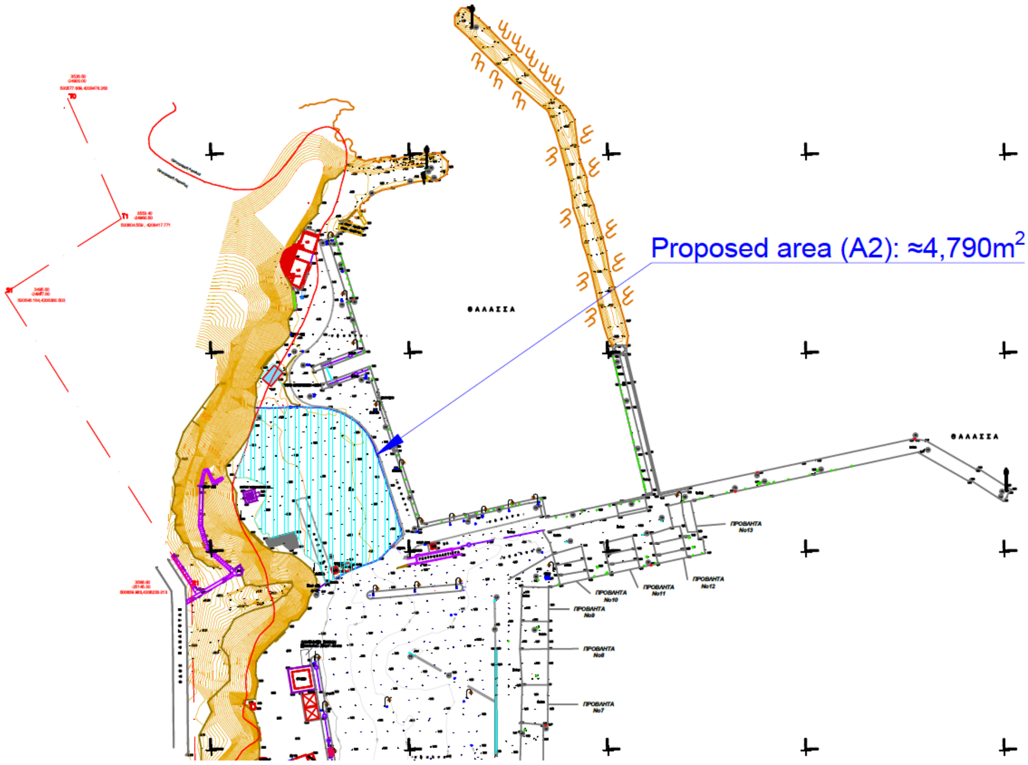

Figure 16: Proposed area no.2 of the PV park

Currently, above depicted proposed areas are not equipped with carport canopies thus significant modifications are required in order to transform these two open parking spaces into an advanced solar car park. During the next paragraphs, an estimation of the nominal power output of the PV solar park is presented as well as a general proposed arrangement that includes total number of parking bays and optimal inclination angle of the solar canopies. Additionally, throughout the following chapters the basic technical aspects of the proposed solar PV park are introduced and a brief cost analysis is also provided considering two different scenarios of how energy is produced and sold to Public Power Corporation (PPC).

6.6 Technical and design specifications of the solar car park

6.6.1 Potential PV deployment capacity

As mentioned previously, the overall estimated area of the two parking spaces which are proposed to be transformed into a solar park is approximately 19,600m^2. However the shading infrastructure where the solar canopies are to be installed, will not occupy the whole physical footprint of the dedicated parking spaces thus aforementioned area will be significantly reduced. An appropriate utilization factor of 40% can be assumed taking into account the fact that space is needed for the solar canopies' foundations, secondary equipment and more importantly for car access and maneuvering purposes[46]. According to similar studies (Alghamdi, Bahaj, Wu, 2017 and Jackson, MPhil, 2016), the size of ground space that a typical car port occupies varies between 12m^2 and 17m^2. Therefore an average space of 16m^2 is considered for this study.

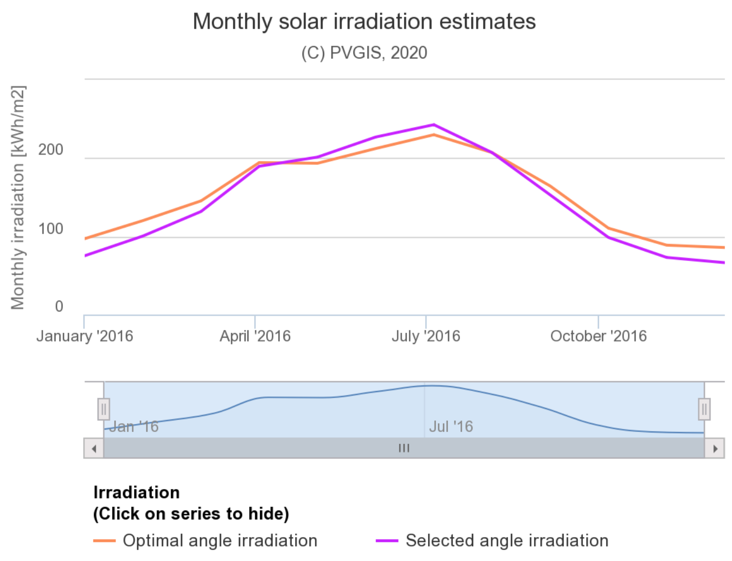

Figure 17: Monthly solar irradiation estimates[45]

The optimal inclination angle of the PV panels that provides the highest annual irradiation was calculated at 30° with the use of European Commission's photovoltaic geographical information system tool (PVGIS) during the year 2016[45]. However, eventually a tilt angle of 10° was decided for the purposes of integrating the dimensions of the PV modules from a specific manufacturer that are proposed further down into the total roof space for each solar carport. Additionally, most solar carports typically have a roof slope of 5°-10° which is considered as the optimum inclination angle range. Furthermore, these angles provide the best balance between support-structure cost and amount of solar production achieved. Solar roofs with bigger tilt angles can pose problems related with the visual appearance and user experience.

Above figure presents the monthly irradiation estimates at a selected angle of 10° as already stated for the year 2016. As easily noticed the selected angle irradiation curve offers nearly the same levels of monthly solar irradiation compared with the levels offered by the optimal angle irradiation and for that reason a 10° inclination angle was decided for the solar carports. Therefore, a total roof space of 16.2m^2 is required for each solar carport. Taking under consideration the fact that almost half of the overall proposed area will be exploited with solar carports which translates in approximately 7840m^2, it is expected that a total number of 483 car parking slots can be created.

In order to provide an accurate estimate of the PV capacity that can be deployed on the two proposed areas, specific details such as the nominal power and footprint of a crystalline PV module are required. This kind of information can usually be acquired through relevant datasheets that are produced from several solar energy manufacturers. Following a brief market research it was decided that a bifacial monocrystalline type PV module shall be selected for the purposes of achieving the maximum efficiency. Bifacial PV modules reabsorb sunlight from both sides whereas monocrystalline solar cells are cut from a single source of silicon resulting in an increased performance. The technical characteristics of the proposed PV modules can be found within the next page.

Table 36: Technical characteristics of the proposed PV modules[54]

Proposed equipment		Characteristics
PV module	Manufacturer	Jinko Solar Holding Co., Ltd.
	Model / Type	JKM465M-7RL3-BDVP
	Manufactured country	China
	Quantity	3,381
	Dimensions	2205x1032x30mm
	Module efficiency	20.43%
	Maximum power (STC)	465Wp (STC)
	Maximum power (NOCT)	346Wp (NOCT)
	Maximum system voltage	1500VDC (IEC)
	Certifications	IEC61215, IEC61730
	Product warranty	12 years
	Cell type	P type Mono-crystalline
	Number of cells per PV module	156 (2x78)

As depicted in above table the nominal power of a crystalline PV module under standard test conditions (STC) which occupies about 2.3m^2 is estimated at 465Wp with an efficiency of 20.43%. Consequently the area of one solar carport which is calculated at 16.2m^2 is sufficient to accommodate seven PV modules that are able to create a 3.255kWp solar PV array. As a result, it is estimated that a PV capacity of 1.57MWp can be deployed on the two proposed areas.

6.6.2 Inverters

Inverters are an essential part of a solar park installation for the following two reasons. Firstly, by optimizing the solar panel maximum power output through an internal device called a maximum point power tracker (MPPT) that adjusts the solar PV array operating voltage and current. Secondly by converting the electricity produced from the PV modules into alternating current (AC) that is then exported into the local electrical grid. The utilization of small string inverters that can fit inside specifically designed steel housings and mounted on the carports' frames spaced every 15 car parking bays is considered as the most appropriate solution. For this reason, the installation of a total number of 28, PVS-50/60-TL string inverters by ABB[56] is suggested that are suitable for commercial applications. Each one of these inverters has a rated (DC) input power 61,800W and a maximum (DC) input voltage of 1000V. These string inverters will supply one step-up medium voltage transformer of 2MVA (IEC 60072-1 standard) in order to convert the low voltage current that is produced by the solar modules into medium voltage so that it can then be delivered to the national grid.

6.6.3 Carport structures

Most carports will be installed with a back-to-back structure, i.e. two canopies joined together as indicated on below figure. As a result, duo pitch roofs will be utilized for the majority of the carport canopies and mono pitch roofs can be placed in areas where space is limited. It is widely considered that duo pitch systems provide the same annual energy yield regardless of their orientation.

The solar roofs will be supported by using V shaped frames which are one of the most common structural designs. V shaped frames with braced cantilevers have combinations of vertical beams and diagonal struts which can be positioned along the dividing markings of the car parking bays in order not to obstruct vehicles. This type of structure is the most cost-effective framing method for large scale car parks and provides sufficient space for the string inverters and additional electrical equipment that are usually mounted inside the V-frames.

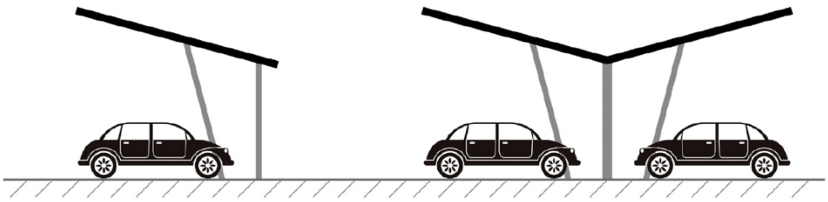

Figure 18: Mono pitch (left) and duo pitch (right) roofs[46]

Ground foundations make up a significant component of the overall costs that are required for the solar carports. Three of the most common foundation types are helical screws, concrete piles and concrete pads. The selection of one of the abovementioned foundation types is considered site-specific and depends mainly upon site ground conditions. The cheapest foundation solution is the one that includes helical screws. Carport structures that contain the foundations as well as the solar roof frames as mentioned previously can be constructed and supplied by Profilodomi which is a Greek company situated in Volos, Magnesia and is active since early 2000.

6.6.4 Cables

The cables that will be used on the DC side of the solar car park and connect the PV modules with the string inverters must be able to withstand severe environmental conditions in terms of high temperatures (which may reach approximately 70°C to 80°C), atmospheric precipitations and ultraviolet radiations. The conductors of these cables shall have double or reinforced isolation according to IEC 60364-7-712 standard in order to minimize the risk of earth faults and short-circuits. Considering all the above in most cases, single-core cables with rubber sheath and isolation are used, having a rated voltage of 0.6/1kV and operating at a maximum temperature of at least 90°C.

Cables on the AC side of the solar park connecting the string inverters with the step-up medium transformer are at an environmental temperature not higher than 30°C to 40°C. Thus these cables are not able to withstand UV rays and must be protected inside electrical conduits equipped with sheath protection.

6.6.5 Protection against overvoltage, overcurrent and indirect contact

The solar car park might be subject to overvoltage of atmospheric origin therefore it must be equipped with an appropriate lightning protection system which is constituted by detectors, ground electrodes and lighting conductors and is in accordance with IEC 60364-7-712. String inverters are equipped with internal protection against overvoltage but it is preferred that suitable surge protective devices (SPD) are added in order to improve protection. Additional protections against overcurrent on the supply (DC) side as well as on the load side of the inverter shall be taken under consideration. Lastly, the presence of the medium voltage step-up transformer shall provide galvanic isolation ensuring in this way that the solar park facility can be earthed properly.

6.6.6 Main Substation

One main substation building shall be constructed that will accommodate the required grid interface switchgear which consists of several circuit breakers and switch disconnectors for the proper isolation of the PV power plant. Additionally, the necessary metering equipment for measuring the energy that is produced shall also be placed inside the building.

6.7 Cost estimation of the solar car park

As mentioned in previous stages of this study the proposed solar car park will be connected to the grid. In general, there are two ways that produced energy from solar power plants is exported back to the national grid. The first option consists of the feed-in-tariff scheme which provides a guaranteed premium price to the renewable electricity producer that is usually guaranteed for a long period of time (approximately 15 to 30 years) and is set prior to the PV plant's operation. The biggest advantage of the feed-in-tariff plan is the long-term certainty of financial support which substantially lowers any risks related to the investment[48]. The second option includes the net metering electricity policy under which the excess electricity injected into the grid can be used at a later time to offset consumption during times when self-produced electricity from renewable energy source systems is either absent or not sufficient[49]. Net metering works utilizing a meter that is able to spin and record energy flow in both directions (i.e. spinning forward when the customers are using more energy than they are producing and spinning backwards when they are producing excess energy). At the end of every year, the customer is charged only for the net electricity used[48].

Greece has introduced net metering regulatory framework since late 2014 in order to regenerate the country's PV market as it offers significant advantages over the feed-in-tariff scheme. Renewable electricity producers that intend to benefit from abovementioned policy shall be aware that according to Greek legislation, only PV systems with a maximum peak power of 500kWp are eligible to be included in the net metering program. For this reason, the solar car park which is proposed in this study cannot utilize a net metering policy since its estimated peak power is calculated at 1.57MWp. However, and taking under account the fact that the suggested PV facility is located within the port's premises which is considered a public corporation, there is a slight possibility of the state granting an exception[14]. Considering all the above, below table presents a cost estimation for the installation and maintenance of the solar car park where all scenarios are included. More specifically cost calculations are provided for the scenario which includes the creation of a 1.57MWp PV facility with or without the use of a net metering program as well as for the scenario where a PV car park of smaller capacity (500kWp) is developed. The results of one similar study have been taken under consideration for the estimation of below project installation costs[14].

Table 37: Project costs for proposed PV facilities

Cost analysis		Solar car park capacity			
		1.57MWp		500KWp	
	Unit price (€)	Quantity	Total cost (€)	Quantity	Total cost (€)
PV modules JinkoSolar JKM465M-7RL3-BDVP	225	3,381	760,725	1,077	242,325
ABB string inverters PVS-50/60-TL	4,640	28	129,920	10	46,400
Solar carport structures	714	483	344,862	154	109,956
Secondary electrical equipment[1]	-	1	242,000	1	77,000
System installation	-	1	105,000	1	33,400
Grid integration	-	1	5,000	1	5,000
Main substation building	-	1	10,000	1	10,000
Total	-	1	1,597,507	1	524,081

[1] Secondary electrical equipment includes among other DC & AC surge arrestors, cables, one medium voltage distribution transformer, switchgear, MCCBs.

It is to be noted that costs in regards to earthing and protection against overcurrent and overvoltage will further increase the above presented overall project costs. Furthermore, the lifespan of the string inverters varies from ten to fifteen years consequently an additional cost for the replacement of these inverters must be considered. Apart from project costs during the installation of the PV plant, yearly operating and maintenance costs shall also be provided.

Table 38: Operating and maintenance yearly costs[53]

Annual costs in (€)	1.57MWp	500KWp
Scheduled maintenance/cleaning	11,304	3,600
Unscheduled maintenance	1,130	360
Insurance	8,478	2,700
Total	20,912	6,660

6.8 Economic analysis

As we approach the final stage of this study and since the technical and cost characteristics of the on shore power facility and solar car park have been presented, a comprehensive economic analysis shall be carried out with the use of an investment method. This financial analysis which will be based on three potential scenarios will allow us to further assess whether or not the investment project will be profitable for the port authority.

6.8.1 Different methods of investment analysis

Numerous investment methods are presented in financial textbooks and papers and are exploited in order to analyze different types of investment projects. In general, the most frequently used techniques and methods are Internal Rate of Return (IRR) and Net Present Value (NPV). Other methods such as Return on Investment (ROI) and Payback Period (PP) can also be considered as valuable financial techniques used for economic evaluation.

6.8.2 Net Present Value method

The Net Present Value method (NPV) nowadays has become the most commonly used tool in corporate economic and valuation analysis and it is widely accepted as the most preferred measure among the vast majority of analytical processes (Helfert, 2001). The Net Present Value method examines the project cash flows and through discounting resolves them to one equivalent cash flow or to an equivalent series of cash flows[50]. It can be defined as the present value of the expected cash flows minus the initial cost of the investment (Ross et al, 2005). Cash inflows are considered as positive cash flows while the initial investment cost as well as cash outflows are treated as negative cash flows[51]. The Net Present Value method is expressed by using the following formula[50]:

$$NPV = \sum_{t=0}^{T} \frac{CF_t}{(1+r)^t}$$

where r is the discount rate, CF_t is the cash flow in each period t and T is the horizon period (which is often the project lifetime). Similar to the above mentioned definitions NPV method is considered as the present monetary value of all project cash flows (including investment and salvage value) discounted at the appropriate discount rate.

6.8.3 Internal rate of return method

The most widely used rate of return methods is the internal rate of return (IRR). Rate of return methods measure the rate at which the invested capital will grow in case the project is pursued. Internal rate of return can be defined as the discount rate at which the Net Present Value equals zero and also corresponds to the yield to maturity on a bond. In this technique the present value of the capital assets in-flows are equal to the present value of the money out-flows (Milis et al, 2006). The Internal Rate of Return is expressed by using the following formula[50]:

$$\sum_{t=0}^{T} \frac{CF_t}{(1+IRR)^t} = 0$$

where IRR is the internal Rate of Return, CF_t is the cash flow in each period t and T is the horizon period (which is often the project lifetime). Internal Rate of Return is also defined as the marginal efficiency of capital or yield on an investment and in contrast to the NPV method it can be used to rank investments which have different initial costs (Kay – Edwards, 1994).

When comparing the two aforementioned financial methods, NPV is considered as the most appropriate investment criterion (Hardacer et al, 2004). It also tends to be somewhat easier in terms of the computational procedures required whereas the IRR model has the benefit of expressing the result as a compound rate of return which facilitates the process of comparing each project with multiple investment alternatives[51].

6.8.4 Economic analysis on the proposed onshore power supply (OPS) facility

In order to examine the feasibility of the cold ironing installation that is suggested in this study, the Net Present Value method will be utilized since it is generally considered as being theoretically superior to the IRR method[14].

For the purposes of applying the NPV model into our proposed investment project, a specific value shall be given to the discount rate r which is included in the NPV formula. Thus, the average calculated value of the annual inflation rates in Greece within the recent ten year period (2010-2020) will be utilized for this study as the discount rate r. These values have been extracted from comparisons of the overall consumer price index during the years 2001-2020 by the National Statistical Service of Greece and are also incorporated and presented in relevant figure within the next page. Taking all the above under consideration it is estimated that the average annual inflation rate in Greece during the last ten years is approximately 0.7%.

Apart from the above mentioned estimated values which will be utilized as a discount rate for the NPV method, two additional variables shall also be determined. More specifically, future prices of electricity and marine gas oil are necessary in order to create an investment analysis of the onshore power supply installation on account of the port authority.

Figure 19: Annual inflation rates in Greece (source: www.tradingeconomics.com)

Values for future price of marine gas oil will be based on prediction models that are presented in several reference case tables that are available through the U.S. Energy Information Administration's online platform[52]. The annual growth rate of distillate fuel oil price is estimated at 3.1% and has been calculated based on predictions that are made until the year 2050. According to the Annual Energy Outlook report[52] these growth rate values have resulted by utilizing three scenarios and more specifically one which considers a high oil price market, one including a low oil price market and one third which predicts annual growth rates by utilizing a reference case.

With respect to the annual growth rate electricity price value that shall also be considered, results will be utilized for this study from one paper that was published in 2013 and deals with the future price of electricity (Ozan Korkmaz, 2013[30]). Same paper has also been used as a reference point for similar studies[14]. It can be stated that in general, such long-term predictions can be considered challenging taking into account the fact that they heavily depend on several major parameters some of them being GDP growth and new power plant investments among others. Korkmaz's main aim is to explain in which ways the simulation model for the long-term electricity price assumption was developed. Additionally, assumptions on the future electricity price are presented specifically for Turkey and the annual growth rate is estimated at 2%. This number can be considered valid for Greece taking into account the similar climate and geographic conditions between the two countries[14]. However, and since Greece is currently facing a wide energy transformation and enhancing competition for energy production at all levels, the annual growth rate of electricity will be considered slightly lower at 1.5%.

6.8.5 Assumptions and scenarios on the NPV method

Several assumptions are necessary to be made prior to the development of an NPV model for the proposed onshore power supply facility. The majority of these assumptions have already been presented further above as well as in previous chapters, while some additional are introduced within the next page.

Starting date of the proposed investment can be considered the year 2020 whereas it shall be stated that the collection of data was conducted during the year 2018. Life of the investment is proposed for a time frame of thirty (30) years and it is considered that the lifetime for all elements and components of the OPS facility and solar car park is the same.

A. As already mentioned above, three economical predictions will be utilized. Annual inflation rate calculated at 0.7% will represent the discount rate *r* which is incorporated in the NPV formula. Additionally, annual growth rate of the price of distillate fuel oil is assumed at 3.1%. Lastly, growing rate of electricity price is evaluated at 1.5%.
B. Ships' calls, energy consumption as well as their produced emissions that are presented and calculated during this study for the year 2018 remain consistent for the required time frame of the investment (i.e. thirty years).
C. Cash flow calculations are required given that the system's capacity usage rate is 100%.
    - Overall onboard electricity cost (based on reference year 2018) is calculated at 1,324,147.48€.
    - Overall onshore electricity cost including additional tax charges (based on reference year 2018) is calculated at 1,110,600.96€.
    - Overall onshore electricity cost excluding additional tax charges (based on reference year 2018) is calculated at 875,568.43€.
    - Any cost difference that may arise between onboard and onshore electricity generation will be directed to the port authority in order to make cold ironing an attractive alternative for vessel operators.
D. Initial capital cost of the investment for the OPS facility and solar car park will also be incorporated into the NPV method.
    - The initial capital investment cost for the OPS facility has already been estimated at 2,380,500€.
    - The initial capital investment cost in case a solar car park with a PV capacity of 1.57MWp is installed is calculated at 1,597,507€ whereas this cost is reduced to 524,081€ for a 500KWp solar car park.
E. Annual costs for the OPS facility and the solar car park will be included in the economic analysis and are presented below.
    - Annual costs for the cold ironing installation are estimated at 165,830€ (based on reference year 2018).
    - Annual costs for the solar car park with an installed 1.57MWp PV capacity are estimated at 20,912€ whereas same costs for the 500KWp solar car park are proportionally calculated at 6,660€.
F. Two additional assumptions have been made. Firstly, PV panels' efficiency drops by 1% every year of the investment's time frame. Secondly, the Mediterranean still remains an area which is excluded from the ECAs.

The NPV model and the different possible scenarios that will be used will be based on a similar study that was conducted for the port of Thessaloniki, Greece (Kritikos, 2017). A brief explanation of the scenarios follows prior to the presentation of the economic results.

As already mentioned during the current chapter of the study, three main scenarios will be investigated as following:

1. First scenario will consider the OPS facility's capacity usage rate at 100% from the first year of operation.
2. Second scenario will consider the OPS facility's capacity usage rate at 15% during its first year of operation and an annual usage rate increase of 15% until system's full usage capacity is reached.
3. Third scenario will consider the OPS facility's capacity usage rate at 25% during its first year of operation and an annual usage rate increase of 20% until system's full usage capacity is reached.

For each and every abovementioned operational scenario four different funding opportunities have been examined:

1. The overall investment cost will be covered by the port's authority.
2. 70% of the overall investment cost will covered by the port's authority while the remaining 30% can be funded by the European Union.
3. 50% of the overall investment cost will covered by the port's authority while the additional 50% can be funded by the European Union.
4. 30% of the overall investment cost will covered by the port's authority while the remaining 70% can be funded by the European Union.

For every scenario and funding alternative two different NPV calculations will be made on the onshore electricity generation price:

1. NPV calculations on the onshore electricity price including the additional tax charges according to the following formula by the PPC:
$$Cost = 0.0782\frac{€}{kWh} + 11.174\frac{€}{kW}/month$$
2. NPV calculations on the onshore electricity price will also be calculated excluding the additional tax charges in accordance to the following formula by the PPC:
$$Cost = 0.0534\frac{€}{kWh} + 11.174\frac{€}{kW}/month$$

Lastly, five different NPVs will be calculated for all the above mentioned scenarios, funding alternatives and onshore electricity price calculation options as per below:

1. Installation will include only the OPS facility.
2. Installation will include the OPS facility and a solar car park of an installed PV capacity of 1.57MWp which will operate under a feed-in-tariff scheme and a fixed price of 45€/MWh.
3. Installation will include the OPS facility and a solar car park of an installed PV capacity of 1.57MWp which will operate under a Net Metering program on the condition that an exception will be granted.
4. Installation will include the OPS facility and a 500KWp solar car park taking into account the maximum allowable PV capacity limit that has been set by Greek legislation in regards to the Net Metering program.
5. Environmental benefits in monetary values that have already been calculated for the reference year 2018.

6.8.6 Economic results of the NPV method

6.8.6.1 Scenario 1: OPS facility's initial capacity usage rate at 100%.

Table 39: Scenario 1: OPS facility's initial capacity usage rate at 100%.

Scenario 1				
	Net Present Value results			
	Without EU funding	30 % EU funding	50 % EU funding	70 % EU funding
Additional tax charges included				
OPS facility only	12,618,287.62	13,332,437.62	13,808,537.62	14,284,637.62
1.57MWp solar car park	12,727,691.91	13,921,094.01	14,716,695.41	15,512,296.81
1.57MWp solar car park (NM)	13,661,261.68	14,854,663.78	15,650,265.18	16,445,866.58
500kWp solar car park (NM)	12,935,124.16	13,806,498.46	14,387,414.66	14,968,330.86
with environmental benefits	166,419,684.01	167,681,929.11	168,001,430.51	168,320,931.91
Additional tax charges excluded				
Installation of OPS facility only	20,489,982	21,204,132	21,680,232	22,156,332
1.57MWp solar car park	20,599,386	21,792,788	22,588,389	23,383,991
1.57MWp solar car park (NM)	21,532,956	22,726,358	23,521,959	24,317,561
500kWp solar car park (NM)	20,806,818	21,678,192	22,259,109	22,840,025
with environmental benefits	174,291,378	175,005,528	175,481,628	175,957,728

*NM: Net Metering

Above table presents the NPV results for every possible alternative, funding opportunity and onshore electricity cost option taking under consideration that all ships that berth at Rafina port switch their auxiliary engines and utilize the onshore power supply facility. However, considering the significant average age of these vessels one can say that the majority of them are not equipped properly in order to receive supply through onshore electricity. Therefore, this scenario can be characterized as ideal compared to the remaining two given the extensive electrical modifications and capital costs that are necessary for the retrofit of each vessel. Nevertheless, it is obvious as also noticed by the positive NPV values that even without the need of a funding program by the European Union, all installation options can be profitable in the long term for the port authority. Moreover, is shall be noted that the investment returns are increased further when calculating the onshore electricity price without the additional tax charges and especially when including the option of a 1.57MWp solar car park that operates under a net metering program. Lastly, the significant benefits from such an investment are also justified by the continuous increase of the price of distillate fuel. Concluding, it is more than clear that if scenario one can be implemented, the investment shall be materialized.

6.8.6.2 Scenario 2: OPS facility's initial capacity usage rate at 15% and an annual usage rate increase of 15%.

Table 40: OPS facility's initial capacity usage rate at 15% and an annual usage rate increase of 15%.

Scenario 2				
	Net Present Value results			
	Without EU funding	30 % EU funding	50 % EU funding	70 % EU funding
Additional tax charges included				
OPS facility only	-4,263,267	-3,549,117	-3,073,017	-2,596,917
1.57MWp solar car park	-4,153,863	-2,960,460	-2,164,859	-1,369,258
1.57MWp solar car park (NM)	-3,220,293	-2,026,891	-1,231,289	-435,688
500kWp solar car park (NM)	-3,946,430	-3,075,056	-2,494,140	-1,913,224
with environmental benefits	112,603,847	113,317,997	113,794,097	114,270,197
Additional tax charges excluded				
Installation of OPS facility only	736,355	1,450,505	1,926,605	2,402,705
1.57MWp solar car park	845,760	2,039,162	2,834,763	3,630,364
1.57MWp solar car park (NM)	1,779,329	2,972,731	3,768,333	4,563,934
500kWp solar car park (NM)	1,053,192	1,924,566	2,505,482	3,086,398
with environmental benefits	117,603,469	118,317,619	118,793,719	119,269,819

*NM: Net Metering

The second scenario includes a more realistic approach regarding the OPS facility's capacity usage rate. More specifically, it is considered that only 15% of the overall berthing vessels are retrofitted or equipped properly in order to receive onshore power supply during the first year of the facility's operation. System's usage rate is calculated to increase annually at 15% until it reaches its maximum capacity within fifteen (15) years. As depicted in above table there are no alternatives that result in a positive NPV value when additional tax charges are taken into account. It is more than clear that tax exceptions have to be applied for the second scenario, in order to provide a profitable investment option to the port authority. Additionally, similarly to the first scenario, a solar car park that will operate under a net metering program remains the optimum solution. Finally, worth mentioning is the slight decrease in the environmental benefit values compared to the ones that are calculated for the first scenario.

6.8.6.3 Scenario 3: OPS facility's initial capacity usage rate at 25% and an annual usage rate increase of 20%.

Table 41: OPS facility's initial capacity usage rate at 25% and an annual usage rate increase of 20%

Scenario 3				
	Net Present Value results			
	Without EU funding	30 % EU funding	50 % EU funding	70 % EU funding
Additional tax charges included				
OPS facility only	-1,207,577	-493,427	-17,327	458,773
1.57MWp solar car park	-1,098,173	95,229	890,831	1,686,432
1.57MWp solar car park (NM)	-164,603	1,028,799	1,824,401	2,620,002
500kWp solar car park (NM)	-890,740	-19,366	561,550	1,142,466
with environmental benefits	139,953,259	140,667,409	141,143,509	141,619,609
Additional tax charges excluded				
Installation of OPS facility only	5,092,385	5,806,535	6,282,635	6,758,735
1.57MWp solar car park	5,201,790	6,395,192	7,190,793	7,986,395
1.57MWp solar car park (NM)	6,135,360	7,328,762	8,124,363	8,919,964
500kWp solar car park (NM)	5,409,222	6,280,596	6,861,513	7,442,429
with environmental benefits	146,253,222	146,967,372	147,443,472	147,919,572

*NM: Net Metering

The economic NPV values for the third and final scenario which are depicted in above table have been calculated by taking under consideration a more optimistic initial usage rate for the OPS facility at 25% for the first year of its operation. Furthermore, an annual increase of 20% in terms of usage rate is also examined until the system reaches its maximum capacity within the first nine (9) years. It is easily noticed that seven options result in a net loss for the port authority and are all calculated without a tax deduction opportunity. More specifically, and as shown in above table, the investment does not provide any profits without a EU funding when tax charges are included. In the event, of a 30% EU funding, the two options which include, firstly the installation of the OPS facility only and secondly that of a 500kWp solar car park operating under net metering, also result in a net loss. Lastly, when the percentage of the EU funding is raised to half, the results indicate that the investment shall be implemented together with the installation of a solar car park which will operate under any of the three options described further above. The most profitable cases still remain those that offer a tax reduction on the electricity price and especially the option that involves the installation of a solar car park of the abovementioned power capacity (1.57MWp) operating however under a net metering program. The investment returns for these cases reach their maximum potential when the overall investment cost is covered by the EU at 70%. Lastly, the environmental benefit values are slightly increased compared to those calculated for the previous scenario.

The analytical calculations for the NPV values of the three main scenarios can be found in Appendix.

7 Summary and conclusions

The shipping industry contributes significantly to air pollution and to the world's climate change mainly due to its dependence on fossil fuel combustion and the fact that it is considered as one of the least regulated anthropogenic emission sources. Moreover, over the last few decades there has been a substantial growth in the international trade of goods and thus an increase in the world's merchant fleet which in return have led to a considerable escalation in the amount of generated airborne emissions. Air pollution by ships has a major impact on human health and is responsible for various respiratory and cardiovascular diseases especially in densely populated coastal areas and harbour ports. Furthermore, ship emissions present several environmental challenges contributing in this way to global warming.

Several international regulations as well as environmental measures and technologies have been implemented in recent years in order to transform the shipping sector into an even more energy efficient mode of transport. Onshore Power Supply (OPS) or alternatively Cold Ironing is considered as one of the abovementioned technologies aiming at the limitation of emissions which are produced during vessels' berth times at port when operating their auxiliary engines for various activities. Power supply is provided through an onshore electrical grid thus enabling ships to shut off their diesel operated engines and at the same time continue to function under the same conditions. Shore power is especially applicable to ships that operate on dedicated routes or vessels that consume large amounts of power and emit high levels of air pollutants while berthed. Passenger and cruise ships, LNG carriers, tankers and container ships are the most common types of vessels which currently utilize onshore power supply. Cold Ironing significantly limits sulfur oxides (SO_X) and minimizes nitrogen oxides (NO_X) and carbon dioxides (CO_2) generated from berthed vessels within harbour ports and coastal areas which are harmful for the environment and human health. Additionally, noise pollution and vibrations produced by a ship's auxiliary engines are also substantially reduced.

This study mainly focused on providing a comprehensive solution that addresses the air pollution problem which is caused by passenger ships that berth at the port of Rafina, Attica in Greece. Greece is a country which is highly dependent on tourism and the port of Rafina is considered as the second busiest port of the country in terms of passenger traffic and number of berthing ferries. The port is situated within the city of Rafina which means that the produced ship emissions have a direct impact to the residents' health and to the deterioration of the area's air quality.

Therefore, considering the above, the implementation of a Cold Ironing facility that would provide shore power to the passenger ships was the main purpose of this thesis. In order to present a thorough and accurate proposal, an initial assessment of the daily and weekly power demands of each berthing passenger vessel was made. Moreover, a research into the main characteristics of the ships' auxiliary engines such as operating voltage and system frequency was also initiated. Power demand at the port of Rafina can range between approximately 500kVA and 3200kVA during summer months where passenger traffic is increased. It was also noticed that during peak season the number of simultaneously berthed vessels is six (6). Four (4) vessels have a system frequency of 60Hz while three (3) have a system frequency of 50Hz whereas their primary voltage varies between 380V to 450V.

The above mentioned power demand study was then followed by the technical design of the Onshore Power Supply facility for the port of Rafina. After a thorough evaluation of the different design configurations it was decided that the proposed topology would be based on a centrally placed frequency converter which is characterized by a higher system efficiency and a smaller overall footprint. The capacity of the frequency converter was selected at 4MVA which not only covers the port's current power needs but also is able to accommodate higher power demands in the future. In addition, five (5) berthing places that would provide power through their respective shore-side transformers were proposed. Furthermore, it was suggested that the landside transformers should be housed in two separate buildings in a group of three and two respectively for the purposes of preserving as much possible available space around the port's premises.

Quantification of the annual onboard emissions and comparison with those that are produced during shore electricity generation showed a substantial reduction in case OPS is implemented. More specifically, an annual decrease of 95% in NO_X and SO_X, 50% in CO_2 and 89% in PM emissions is achieved in case all berthing vessels are connected to shore power. It is safe to say that further reduction can be accomplished if electric power to the vessels is provided from renewable energy sources and not from thermal power plants.

Cold Ironing as a process does not provide direct economic benefits to the ship owners or the port authorities. For this reason, monetary values or shadow prices for all emissions produced though onboard and onshore electricity generation were calculated in order to highlight the indirect economic benefits that are gained through the use of shore power supply. The estimated health benefit which is calculated at 5,162,600.21€ and 3,644,889,22€ for two separate scenarios respectively is considered major even for the more realistic scenario when half of the berthing vessels connect to shore power.

A brief cost estimation for the OPS facility showed that the frequency converter covers almost one third of the overall installation costs which are calculated at 2.4 million euros whereas annual maintenance costs are much lower. Moreover, an analysis regarding the vessels' operating costs during berth times revealed that Cold Ironing can be beneficial for the ship operators since onshore electricity generation cost which is calculated at 0.0782€/kWh, excluding the power fee, is currently slightly lower than the costs of onboard electricity production. However, aforementioned costs are not fixed and highly depend on current MGO prices and electricity pricing in Greece. For this reason an effort of investigating several alternatives was made, which include different investment options as well as the possibility of electricity production within the port area through the use of renewable energy sources. Additionally, retrofitting costs for existing as well as newbuilding vessels should be absorbed by the ship operators and range between 280,000€ and 325,000€ while ships that utilize the same voltage with the one of the shore-side facility require a reduced retrofitting cost.

An investigation of the possible available spaces within the port's premises showed that a solar park of 1.57MWp capacity can be implemented providing in this way a significant amount of electricity required by the berthing vessels through the OPS facility. The 1.57MWp solar park was proposed to operate either under a feed-in-tariff scheme with a fixed price of 45€/MWh or alternatively under a net metering program. However the latter should be taken under consideration only in the case that an exception were to be provided since relevant legislation in Greece only allows systems with a maximum capacity of 500kWp to be included in the net metering program. For this reason, a third option was suggested of including a 500kWp solar park for self-consumption under the net metering policy.

As mentioned further above and for the purposes of making the Cold Ironing facility an even more competitive and profitable solution for the ship operators and the port authority, different investment options were examined. These investment options which also include the implementation of a solar park were analyzed by utilizing the Net Present Value method under three separate scenarios which differed on the usage of the Onshore Power Supply facility every year. In addition, different funding opportunities by the EU were also considered and applied for all three scenarios as well as two alternatives related with the onshore electricity price where tax exceptions have been proposed and incorporated within the study.

The economic analysis revealed that out of the three primary scenarios, independently of the EU's participation on the investment funding, only the second one, which considers an initial usage rate of 15%, provided negative outcomes for all cases where tax charges were included on the energy price. However, the environmental benefits were substantial across all three scenarios even for the ones that did not offer positive net present values and therefore the investment should still be considered.

All things considered it is safe to say that Cold Ironing offers significant health benefits and at the same time addresses the current environmental challenges in a direct way. Drastic reduction of the produced emissions and noise vibrations in coastal areas that result in significant environmental and health benefits are two of the main advantages that are achieved. Furthermore, depending on the MGO prices, ship operators might benefit from the occurring savings related to fuel costs and maintenance of the vessels' auxiliary engines. On the other hand, the implementation of a Cold Ironing facility requires high installation and vessel retrofitting costs which shall be covered by the port authorities and the ship owners. For this reason, countries shall introduce initiatives that will include specific exceptions such as a reduction on the electricity energy price or even a partial investment funding as proposed on this study. Direct dependence between the MGO prices and the profitability of the investment as well as the fact that Cold Ironing tackles the zero-emissions challenge only during berth are two additional drawbacks.

Future work could examine the possibility of implementing Onshore Power Supply facilities elsewhere in Greece and preferably in areas and ports that are characterized by a high number of vessel calls or possibly popular cruise destinations such as the port of Mykonos. In addition further research could focus on the feasibility of producing electricity from other renewable energy sources such as the development of wind farms providing in this way significant amount of energy to the Cold Ironing facilities.

References

[1] Olaf Merk, (2014). Shipping emissions in ports, International Transport Forum.

[2] D. Toscano, F. Murena, (2019). Atmospheric ship emissions in ports: A review. Correlation with data of ship traffic.

[3] Equasis, (2018). The world merchant fleet in 2018, statistics from equasis.

[4] United Nations Conference on Trade and Development, (2019). Review of maritime transport.

[5] International Chamber of Shipping, (2004). Shipping, world trade and the reduction of CO_2 emissions.

[6] Martin Otto Paul Ramacher, Matthias Karl, Johannes Bleser, Jukka-Pekka Jalkanen, Lasse Johansson, Chemistry Transport Modelling Department, Institute of Coastal Research, Finish Meteorological Institute, (2019). Urban population exposure to NO_X emissions from local shipping in three Baltic Sea harbour cities – a generic approach.

[7] Hans Otto Kristenen, Harilaos Psaraftis, The Technical University of Denmark, (2015). Energy demand and exhaust gas emissions of marine engines.

[8] International Maritime Organization, (2015). Third IMO GHG Study 2014 executive summary.

[9] Kampylis Panagiotis, (2016). An environmental, technical and economical approach for the use of shore-power in Piraeus port.

[10] International Maritime Organization, (2016). IMO Train the Trainer (TTT) course on energy efficient ship operation – Module 1 – Climate change and the shipping response.

[11] http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution

[12] Mar Viana, Pieter Hammingh, Augustin Colette, Xavier Querol, Bart Degraeuwe, Ina de Vlieger, John van Aardenne, (2014), Impact of maritime transport emissions on coastal air quality in Europe.

[13] Fenhann, J. Villy, The Technical University of Denmark, (2017). CO_2 emissions from international shipping.

[14] Kritikos Orfeas Markos, (2017). A Cold Ironing feasibility study and cost-benefit analysis.

[15] Tetra Tech Inc., American Association of Port Authorities, (2007). Use of shore-side power for ocean-going vessels.

[16] University of Strathclyde, National Technical University of Athens, Universidad Politecnica de Madrid, Oceanfinance, University of Genève, (2015). On shore power supply and LNG.

[17] Roberto Bernacchi, (2018). Shore-to-ship power and smart ports, paving the way to smarter, stronger, greener port electrical grids.

[18] J. Prousalidis, D.V. Lyridis, S. Dallas, C. Papaleonidas, P. Mitrou, E, Vergetis, E. Vaimaki, S. Aggelopoulos, T. Kourmpelis, V. Georgiou, P. Katsikas, T. Boutsika, D. Spathis, (2017). The ports as smart micro-grids: development perspectives.

[19] Patrik Ericsson, Ismir Fazlagic, Master of Science Thesis, Chalmers University of Technology, ABB, (2008). Shore-side power supply. A feasibility study and a technical solution for an on-shore electrical infrastructure to supply vessels with electric power while in port.

[20] Robert Louie, Westmar Consulting Engineers, (2007). TSI Terminal Systems Inc. – Final report for Deltaport third berth container terminal – Cold Ironing feasibility study.

[21] Pantazopoulos Dionysios, (2017). Investigation on the possibility of providing shore-power to vessels berthing at the ports of Piraeus and Killini.

[22] Tadeusz Borkowski, Dariusz Tarnapowicz, Maritime University of Szczecin (2015), Shore to ship system – an alternative electric power supply in port.

[23] IEC/ISO/IEEE 80005-3 Edition 1.0 2012-07, (2014). Utility connections in port – Part 3: Low voltage shore connection (LVSC) systems – general requirements.

[24] IEC/ISO/IEEE 60502-2 Edition 2.0 2005-03, (2005). Power cables with extruded insulation and their accessories for rated voltages from 1kV (U_m=1.2kV) up to 30kV (U_m=36kV) – Part 2: cables for rated voltages from 6kV (U_m=7.2kV) up to 30kV (U_m=36kV).

[25] Thalis Zis, Department of Management Engineering, Technical University of Denmark, (2018). Prospects of cold ironing as an emissions reduction option.

[26] Bakirtzoglou Christos, (2017). Techno-economical feasibility study on the retrofit of double-ended Ro/Pax ferries into battery-powered ones.

[27] 2006/339/EC, (2006). Commission recommendation of 8 May 2006 on the promotion of shore-side electricity for use by ships at berth in Community ports.

[28] Malta National Electromobility Platform, (2014). Feasibility study into the possibility of shore-side electrical supply for berthing vessels within Maltese harbours.

[29] A. Wilske, Port of Gothenburg, (2012). Preconditions for connecting ships to Onshore Power Supply in the Port of Gothenburg.

[30] Nurullah H. Peksen., World Maritime University, (2013). A new approach for Turkish ports to reduce ship emissions case study: application of cold ironing system for Marport container terminal.

[31] Entec UK Limited, European Commission, (2002). Quantification of emissions from ships associated with ship movements between ports in the European Community.

[32] Public Power Corporation S.A. Hellas, (2009). The role of coal in the production strategy of PPC.

[33] Alexandros Maronidis, International Hellenic University, School of Science & Technology (2018). Analysis of Greek electricity system and evaluation of the impact of the flexibility options for future energy scenarios.

[34] S. Bruyn, M. Bijleveld, L. de Graaff, E. Schep, A. Schroten, R. Vergeer, S. Ahdour, CE Delft, (2018). Environmental Prices Handbook EU28 version – Methods and numbers for valuation of environmental impacts.

[35] Entec UK Limited, European Commission, (2005). Service contract on ship emissions: Assignment, abatement and market-based instruments.

[36] Public Power Corporation S.A. Hellas, (2019). Monthly energy report, November 2019.

[37] ABB, (2011). Enabling the shore-to-ship power connection, static frequency converters.

[38] International Renewable Energy Agency, (2019). Future of solar photovoltaic – Deployment, investment, technology, grid integration and socio-economic aspects – A global energy transformation paper.

[39] Arno HM Smets, Klaus Jager, Olindo Isabella, Rene ACMM van Swaaij, Miro Zeman, (2015). Solar energy – the physics and engineering of photovoltaic conversion, technologies and systems.

[40] B. Parida, S. Iniyan, R. Goic, (2011). A review of solar photovoltaic technologies.

[41] ABB, (2013). Technical application papers no. 10 – Photovoltaic plants.

[42] International Renewable Energy Agency, (2012). Renewable energy technologies: Cost analysis series – Volume 1 – Solar photovoltaics.

[43] B. Mondoc, F. Pop, (2010). Factors influencing the performance of a photovoltaic power plant.

[44] K. V. Lagogiannis, G. A. Vokas, (2015). PV energy production over Greece: comparison between two simulation tools and real measurements.

[45] https://ec.europa.eu/jrc/en/pvgis

[46] A. S. Alghamdi, A. S. Bahaj, Y. Wu, (2017). Assessment of large scale photovoltaic power generation from carport canopies.

[47] C. Jackson. G. Hartnell, J. Williams, BRE National Solar Centre, (2016). Solar car parks – a guide for owners and developers.

[48] Andreas Poullikkas, (2013). A comparative assessment of net metering and feed in tariff schemes for residential PV systems.

[49] S. Tselepis, (2015). The PV market developments in Greece, net metering study cases.

[50] P. C. Godinho, A. R. Afonso, J. P. Costa, (2004). On the use of multiple financial methods in the evaluation and selection of investment projects.

[51] A. Nabradi, L. Szollosi, (2007). Key aspects of investment analysis.

[52] https://www.eia.gov/outlooks/aeo/

[53] https://www.scottmadden.com/insight

[54] www.jinkosolar.com

[55] IEC/ISO/IEEE 60364-5-52 Edition 3.0 2009-10. Low voltage electrical installations – Part 5-52: Selection and erection of electrical equipment – Wiring systems.

[56] https://new.abb.com/power-converters-inverters/solar-old/string/three-phase

Appendix

Table 42: Summer timetable and turnaround time at Rafina port

Vessel Name	Monday		Tuesday		Wednesday		Thursday		Friday		Saturday		Sunday		Weekly turnaround time (min)	Daily average turnaround time (min)
	D	A	D	A	D	A	D	A	D	A	D	A	D	A		
SUPERFERRY	07:50	-	-	22:00	07:50	-	-	22:00	07:50	-	-	22:00	07:50	-	1670	239
SUPERFERRY II	-	22:00	07:50	-	-	22:00	07:50	-	-	22:00	07:50	-	-	22:00	2210	316
SUPERUNNER	07:20	21:20	07:20	21:20	07:20	21:20	07:20	21:20	07:20	21:20	07:20	21:20	07:20	21:20	4200	600
FAST FERRIES ANDROS	07:30	18:00	07:30	18:00	07:30	18:00	07:30	18:00	07:30	18:00	07:30	18:30	07:30	18:30	4890	699
	18:45	23:00							19:30	23:00			19:30	00:00		
THEOLOGOS P	17:30	12:10	17:30	12:10	17:30	12:10	17:30	12:10	17:30	12:10	07:00	02:30	17:30	16:40	2010	287
											17:30	16:50	22:45	21:55		
EKATERINI P	08:05	20:50	08:05	20:50	08:05	20:50	08:05	20:50	08:05	20:50	08:05	21:20	08:05	21:20	4665	666
PAROS JET	07:00	00:10	15:10	14:20	15:10	14:20	15:10	14:20	14:50	14:00	15:10	14:20	14:50	14:00	775	111
	15:10	14:20							20:15	19:30			19:40	19:20		
TERA JET	07:40	17:20	07:40	17:20	07:40	17:20	07:40	17:20	07:40	17:20	07:40	17:40	07:40	17:40	5980	854
									19:00	22:00			19:00	22:00		

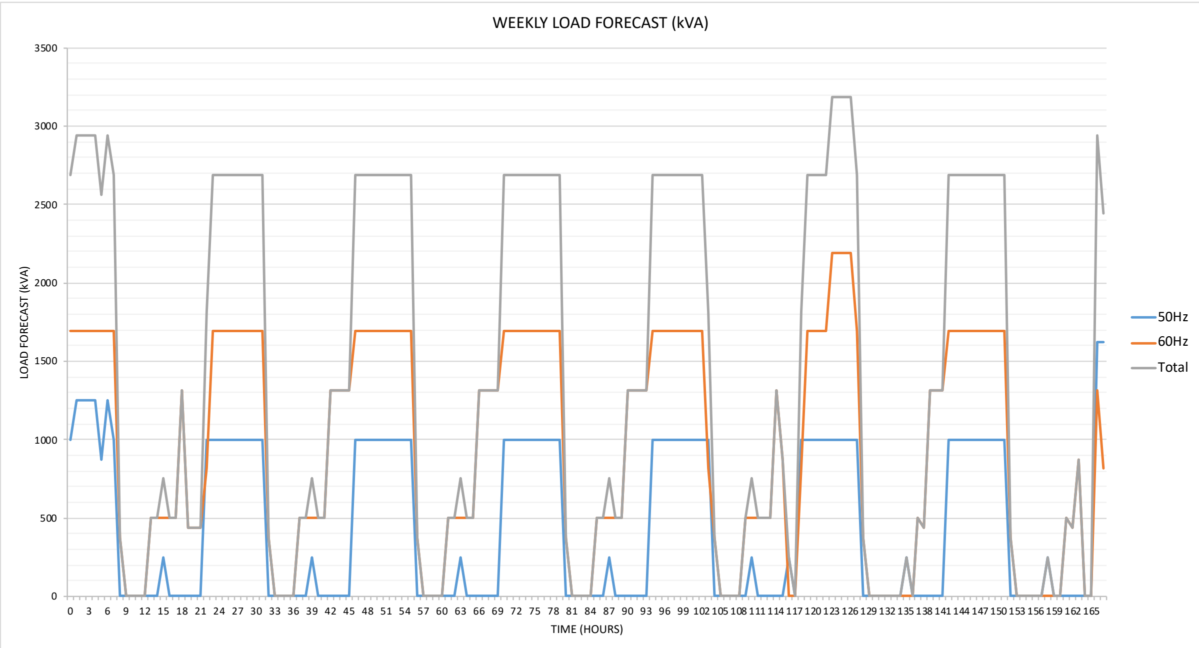

Figure 20: Weekly load forecast at Rafina port

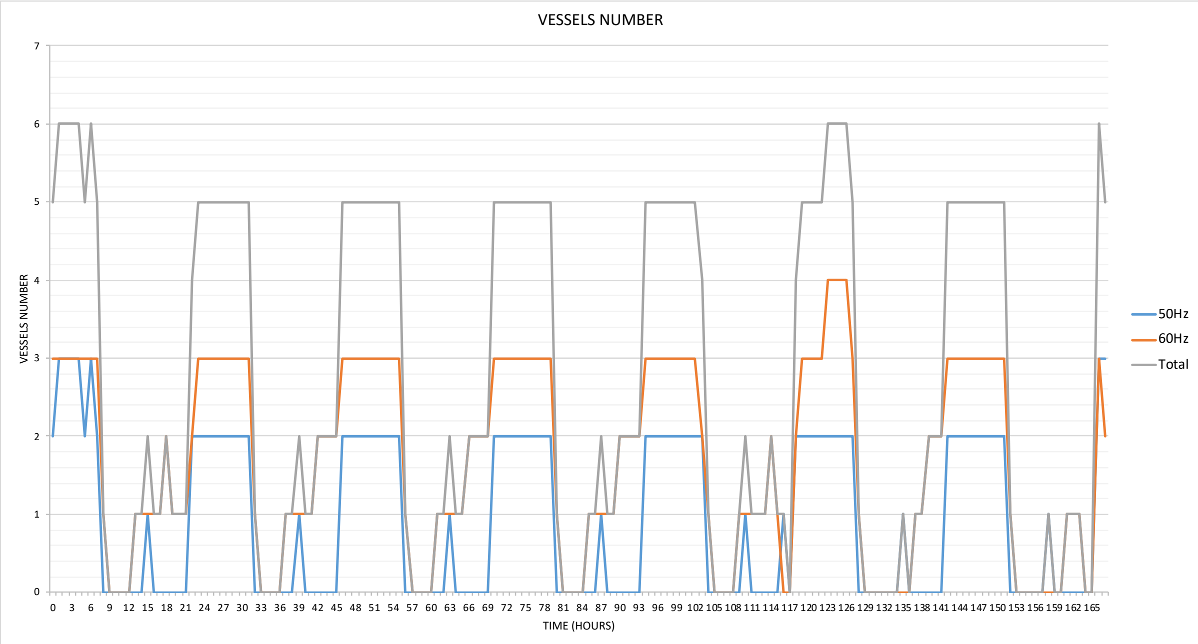

Figure 21: Number of berthed vessels at Rafina port

Table 43: NPV values for the solar car park scenarios

	NPV values		
Year	Scenario 1	Scenario 2	Scenario 3
1	75086.991	114490.686	36462.002
2	73613.159	112351.647	35780.779
3	72165.641	110250.153	35111.514
4	70743.983	108185.559	34454.000
5	69347.740	106157.234	33808.036
6	67976.471	104164.554	33173.425
7	66629.746	102206.908	32549.971
8	65307.141	100283.695	31937.482
9	64008.238	98394.324	31335.772
10	62732.629	96538.215	30744.654
11	61479.910	94714.795	30163.948
12	60249.685	92923.505	29593.473
13	59041.566	91163.792	29033.055
14	57855.170	89435.114	28482.520
15	56690.120	87736.937	27941.700
16	55546.048	86068.739	27410.426
17	54422.591	84430.002	26888.536
18	53319.390	82820.222	26375.867
19	52236.096	81238.899	25872.261
20	51172.363	79685.546	25377.562
21	50127.852	78159.680	24891.618
22	49102.230	76660.830	24414.277
23	48095.169	75188.529	23945.392
24	47106.347	73742.322	23484.816
25	46135.448	72321.760	23032.408
26	45182.161	70926.399	22588.025
27	44246.180	69555.808	22151.531
28	43327.203	68209.559	21722.790
29	42424.937	66887.233	21301.667
30	41539.090	65588.418	20888.031

Table 44: Values used for NPV method of Scenario 1

100% use of the facilities										
Year	kWh	On board cost	On shore cost	Difference 1	NPV values with annual costs	On shore with exception	Difference 2	NPV values with annual costs and tax exceptions	Environmental benefits	
1	9,492,429	1,324,147	1,110,601	213,547	47,385	875,568	448,579	280,784	5,162,600	5,126,713
2	9,492,429	1,365,196	1,127,260	237,936	71,107	888,702	476,494	306,360	5,198,738	5,126,713
3	9,492,429	1,407,517	1,144,169	263,348	95,499	902,032	505,485	332,621	5,235,130	5,126,713
4	9,492,429	1,451,150	1,161,331	289,819	120,577	915,563	535,587	359,583	5,271,775	5,126,713
5	9,492,429	1,496,136	1,178,751	317,384	146,360	929,296	566,839	387,264	5,308,678	5,126,713
6	9,492,429	1,542,516	1,196,433	346,083	172,865	943,236	599,280	415,683	5,345,839	5,126,713
7	9,492,429	1,590,334	1,214,379	375,955	200,111	957,384	632,950	444,858	5,383,260	5,126,713
8	9,492,429	1,639,634	1,232,595	407,040	228,118	971,745	667,889	474,809	5,420,942	5,126,713
9	9,492,429	1,690,463	1,251,084	439,379	256,904	986,321	704,142	505,555	5,458,889	5,126,713
10	9,492,429	1,742,867	1,269,850	473,017	286,489	1,001,116	741,751	537,116	5,497,101	5,126,713
11	9,492,429	1,796,896	1,288,898	507,999	316,895	1,016,133	780,763	569,513	5,535,581	5,126,713
12	9,492,429	1,852,600	1,308,231	544,369	348,142	1,031,375	821,225	602,767	5,574,330	5,126,713
13	9,492,429	1,910,031	1,327,855	582,176	380,252	1,046,846	863,185	636,899	5,613,350	5,126,713
14	9,492,429	1,969,242	1,347,773	621,469	413,246	1,062,548	906,693	671,932	5,652,644	5,126,713
15	9,492,429	2,030,288	1,367,989	662,299	447,147	1,078,486	951,802	707,888	5,692,212	5,126,713
16	9,492,429	2,093,227	1,388,509	704,718	481,978	1,094,664	998,563	744,791	5,732,058	5,126,713
17	9,492,429	2,158,117	1,409,337	748,781	517,763	1,111,084	1,047,033	782,664	5,772,182	5,126,713
18	9,492,429	2,225,019	1,430,477	794,542	554,525	1,127,750	1,097,269	821,531	5,812,587	5,126,713
19	9,492,429	2,293,994	1,451,934	842,061	592,291	1,144,666	1,149,328	861,417	5,853,275	5,126,713
20	9,492,429	2,365,108	1,473,713	891,395	631,084	1,161,836	1,203,272	902,349	5,894,248	5,126,713
21	9,492,429	2,438,426	1,495,818	942,608	670,931	1,179,264	1,259,163	944,351	5,935,508	5,126,713
22	9,492,429	2,514,018	1,518,256	995,762	711,859	1,196,953	1,317,065	987,451	5,977,057	5,126,713
23	9,492,429	2,591,952	1,541,030	1,050,923	753,895	1,214,907	1,377,045	1,031,676	6,018,896	5,126,713
24	9,492,429	2,672,303	1,564,145	1,108,158	797,067	1,233,131	1,439,172	1,077,055	6,061,028	5,126,713
25	9,492,429	2,755,144	1,587,607	1,167,537	841,403	1,251,628	1,503,517	1,123,615	6,103,456	5,126,713
26	9,492,429	2,840,554	1,611,421	1,229,132	886,932	1,270,402	1,570,152	1,171,387	6,146,180	5,126,713
27	9,492,429	2,928,611	1,635,593	1,293,018	933,686	1,289,458	1,639,153	1,220,400	6,189,203	5,126,713
28	9,492,429	3,019,398	1,660,127	1,359,271	981,693	1,308,800	1,710,598	1,270,685	6,232,527	5,126,713
29	9,492,429	3,112,999	1,685,028	1,427,971	1,030,987	1,328,432	1,784,567	1,322,275	6,276,155	5,126,713
30	9,492,429	3,209,502	1,710,304	1,499,198	1,081,598	1,348,358	1,861,144	1,375,200	6,320,088	5,126,713
Sums					**14,998,788**			**22,870,482**		**153,801,396**

Table 45: Values used for NPV method of Scenario 2

15 % the first year and 15% increase every year										
Year	kWh	On board cost	On shore cost	Difference 1	NPV values with annual costs	On shore with exception	Difference 2	NPV values with annual costs and tax exceptions	Environmental benefits	
1	1,423,864	198,622	202,472	-3,849	-168,500	167,217	31,405	-133,490	774,390	769,007
2	1,637,444	234,573	235,879	-1,307	-164,821	194,807	39,765	-124,318	895,969	883,556
3	1,883,061	269,950	271,307	-1,357	-163,725	224,066	45,883	-117,463	1,036,636	1,015,168
4	2,165,520	310,448	312,003	-1,556	-162,780	257,677	52,771	-109,948	1,199,388	1,166,385
5	2,490,348	357,015	358,804	-1,789	-161,873	296,328	60,687	-101,539	1,387,692	1,340,127
6	2,863,900	410,568	412,625	-2,057	-161,005	340,777	69,790	-92,103	1,605,560	1,539,748
7	3,293,485	472,153	474,518	-2,366	-160,180	391,894	80,259	-81,493	1,857,633	1,769,105
8	3,787,507	542,976	545,696	-2,721	-159,402	450,678	92,298	-69,541	2,149,281	2,032,626
9	4,355,633	624,422	627,550	-3,129	-158,677	518,280	106,142	-56,056	2,486,718	2,335,401
10	5,008,978	718,085	721,683	-3,598	-158,012	596,022	122,063	-40,818	2,877,133	2,683,276
11	5,760,325	825,798	829,935	-4,138	-157,413	685,425	140,373	-23,577	3,328,843	3,082,969
12	6,624,374	949,668	954,426	-4,758	-156,890	788,239	161,429	-4,048	3,851,472	3,542,200
13	7,618,030	1,092,118	1,097,590	-5,472	-156,451	906,474	185,643	18,096	4,456,153	4,069,836
14	8,760,735	1,255,935	1,262,228	-6,293	-156,108	1,042,446	213,490	43,225	5,155,769	4,676,068
15	9,492,429	1,363,081	1,368,744	-5,662	-154,455	1,130,414	232,667	60,197	5,965,224	5,372,603
16	9,492,429	1,405,337	1,389,275	16,062	-133,951	1,147,371	257,966	82,406	6,006,981	5,372,603
17	9,492,429	1,448,902	1,410,114	38,789	-112,835	1,164,581	284,321	105,241	6,049,030	5,372,603
18	9,492,429	1,493,818	1,431,266	62,553	-91,091	1,182,050	311,769	128,718	6,091,373	5,372,603
19	9,492,429	1,540,127	1,452,735	87,392	-68,701	1,199,781	340,346	152,854	6,134,013	5,372,603
20	9,492,429	1,587,871	1,474,526	113,345	-45,650	1,217,777	370,093	177,665	6,176,951	5,372,603
21	9,492,429	1,637,095	1,496,643	140,451	-21,921	1,236,044	401,051	203,169	6,220,189	5,372,603
22	9,492,429	1,687,845	1,519,093	168,752	2,506	1,254,585	433,260	229,383	6,263,731	5,372,603
23	9,492,429	1,740,168	1,541,879	198,288	27,647	1,273,403	466,764	256,327	6,307,577	5,372,603
24	9,492,429	1,794,113	1,565,008	229,105	53,521	1,292,504	501,609	284,018	6,351,730	5,372,603
25	9,492,429	1,849,731	1,588,483	261,248	80,148	1,311,892	537,839	312,476	6,396,192	5,372,603
26	9,492,429	1,907,072	1,612,310	294,762	107,546	1,331,570	575,502	341,720	6,440,965	5,372,603
27	9,492,429	1,966,191	1,636,495	329,697	135,736	1,351,544	614,648	371,770	6,486,052	5,372,603
28	9,492,429	2,027,143	1,661,042	366,101	164,738	1,371,817	655,326	402,647	6,531,454	5,372,603
29	9,492,429	2,089,985	1,685,958	404,027	194,573	1,392,394	697,590	434,372	6,577,175	5,372,603
30	9,492,429	2,154,774	1,711,247	443,527	225,262	1,413,280	741,494	466,966	6,623,215	5,372,603
Sums					**-1,882,767**			**3,116,855**		**116,867,114**

Table 46: Values used for NPV method of Scenario 3

25 % the first year and 20% increase every year										
Year	kWh	On board cost	On shore cost	Difference 1	NPV values with annual costs	On shore with exception	Difference 2	NPV values with annual costs and tax exceptions	Environmental benefits	
1	2,373,107	331,037	337,453	-6,416	-171,048	278,694	52,342	-112,699	1,290,650	1,281,678
2	2,847,729	407,506	410,005	-2,498	-165,996	338,614	68,893	-95,594	1,557,815	1,536,232
3	3,417,274	489,326	492,082	-2,756	-165,095	406,399	82,927	-81,186	1,880,282	1,841,343
4	4,100,729	587,201	590,499	-3,298	-164,475	487,680	99,521	-64,485	2,269,501	2,207,051
5	4,920,875	704,641	708,599	-3,958	-163,968	585,216	119,425	-44,814	2,739,287	2,645,393
6	5,905,050	845,570	850,319	-4,749	-163,587	702,259	143,310	-21,596	3,306,320	3,170,794
7	7,086,060	1,014,683	1,020,383	-5,699	-163,355	842,711	171,973	5,850	3,990,728	3,800,545
8	8,503,272	1,217,620	1,224,459	-6,839	-163,297	1,011,253	206,367	38,337	4,816,809	4,555,370
9	9,492,429	1,361,894	1,368,177	-6,283	-161,640	1,129,946	231,947	62,094	5,813,888	5,460,110
10	9,492,429	1,404,112	1,388,700	15,413	-140,282	1,146,896	257,217	85,229	5,854,585	5,460,110
11	9,492,429	1,447,640	1,409,530	38,110	-118,287	1,164,099	283,541	109,017	5,895,567	5,460,110
12	9,492,429	1,492,517	1,430,673	61,844	-95,636	1,181,561	310,956	133,473	5,936,836	5,460,110
13	9,492,429	1,538,785	1,452,133	86,651	-72,314	1,199,284	339,501	158,615	5,978,394	5,460,110
14	9,492,429	1,586,487	1,473,915	112,572	-48,303	1,217,273	369,214	184,461	6,020,243	5,460,110
15	9,492,429	1,635,668	1,496,024	139,644	-23,584	1,235,532	400,136	211,028	6,062,385	5,460,110
16	9,492,429	1,686,374	1,518,464	167,910	1,860	1,254,065	432,309	238,337	6,104,821	5,460,110
17	9,492,429	1,738,651	1,541,241	197,410	28,049	1,272,876	465,775	266,404	6,147,555	5,460,110
18	9,492,429	1,792,550	1,564,360	228,190	55,001	1,291,969	500,580	295,250	6,190,588	5,460,110
19	9,492,429	1,848,119	1,587,825	260,293	82,738	1,311,349	536,770	324,895	6,233,922	5,460,110
20	9,492,429	1,905,410	1,611,643	293,768	111,278	1,331,019	574,391	355,359	6,277,560	5,460,110
21	9,492,429	1,964,478	1,635,817	328,661	140,643	1,350,984	613,494	386,663	6,321,502	5,460,110
22	9,492,429	2,025,377	1,660,355	365,022	170,854	1,371,249	654,128	418,829	6,365,753	5,460,110
23	9,492,429	2,088,164	1,685,260	402,904	201,932	1,391,818	696,346	451,877	6,410,313	5,460,110
24	9,492,429	2,152,897	1,710,539	442,358	233,901	1,412,695	740,201	485,831	6,455,185	5,460,110
25	9,492,429	2,219,636	1,736,197	483,440	266,782	1,433,886	785,751	520,714	6,500,372	5,460,110
26	9,492,429	2,288,445	1,762,240	526,205	300,600	1,455,394	833,051	556,549	6,545,874	5,460,110
27	9,492,429	2,359,387	1,788,673	570,714	335,378	1,477,225	882,162	593,361	6,591,695	5,460,110
28	9,492,429	2,432,528	1,815,504	617,024	371,141	1,499,383	933,145	631,173	6,637,837	5,460,110
29	9,492,429	2,507,936	1,842,736	665,200	407,913	1,521,874	986,062	670,012	6,684,302	5,460,110
30	9,492,429	2,585,682	1,870,377	715,305	445,722	1,544,702	1,040,980	709,902	6,731,092	5,460,110
Sums					**1,172,923**			**7,472,885**		**141,160,836**