National Technical University of Athens

School of Naval Architecture and Marine Engineering

Thesis

An Environmental, Technical and Economical Approach for the Use of Shore-Power in Piraeus Port

Kampylis Panagiotis

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Acknowledgements

For his help, advices and encouragement during my thesis, I would like to thank my supervisor, Professor J.M. Prousalidis.

I would also like to thank Eirini Arvanitaki, Christina Christopoulou and Fragkiskos Perris for their help and the valuable information that they kindly offered.

Last but not least, I would like to thank my family for their patience and full support during my studies.

Abstract

Air pollution is a significant problem for all busy ports around the world and Piraeus port is no exception. Strict regulations about marine fuel's quality and ship's emissions have been introduced in several areas of the world obliging ship-owners to take measures in order to make ships more ecological and human friendly. This particular study will focus on the implementation of Cold-Ironing in Piraeus port, as a method for the control and reduction of air pollution caused by ferries, cruise ships and container carriers.

Chapter one and two of this study will attempt to present the actual situation in maritime industry, the environmental damage which results from ship's activity, the negative impact of marine engine's emissions to human health as well as the basic principals of Cold-Ironing with examples of implementation in other countries.

For each type of vessel, it is necessary to create a "Berthing Power Demand Profile" which includes berthing time, average and peak hoteling load and electrical system details such as frequency and primary voltage. Dimensioning of the Cold-Ironing equipment and preliminary design of the shore-side installations, are based on these power demand profiles.

The last chapter of this study will focus on the economic aspect of Cold-Ironing both from the perspective of ship-owners and the perspective of port operators.

Περίληψη

Η μόλυνση της ατμόσφαιρας είναι ένα σημαντικό πρόβλημα για όλα τα πολυσύχναστα λιμάνια του κόσμου με το λιμάνι του Πειραιά να μην αποτελεί εξαίρεση. Οι αυστηροί κανονισμοί που επιβλήθηκαν σε αρκετές περιοχές του κόσμου και αφορούν την ποιότητα των ναυτιλιακών καυσίμων και τις εκπομπές ρύπων των πλοίων έχουν αναγκάσει τους πλοιοκτήτες να λάβουν μέτρα ώστε να καταστήσουν τα πλοία περισσότερο οικολογικά και φιλικότερα προς τον άνθρωπο. Η εργασία αυτή θα επικεντρωθεί στην εφαρμογή του Cold-Ironing στο λιμάνι του Πειραιά, ως μέτρο ελέγχου και μείωσης της ατμοσφαιρικής ρύπανσης η οποία προκαλείται από τα Ε/Γ-Ο/Γ, τα κρουαζιερόπλοια και τα πλοία μεταφοράς εμπορευματοκιβωτίων.

Στα πρώτα κεφάλαια αυτής της εργασίας θα παρουσιαστεί η σημερινή κατάσταση που επικρατεί στην παγκόσμια ναυτιλία, η περιβαλλοντική καταστροφή που οφείλεται στην δραστηριότητα των πλοίων, η αρνητική επίδραση των ρύπων των ναυτικών μηχανών στην ανθρώπινη υγεία καθώς και οι βασικές αρχές εφαρμογής του Cold-Ironing με παραδείγματα από άλλες χώρες.

Για κάθε τύπο πλοίου, είναι απαραίτητο να δημιουργηθεί ένα «προφίλ ενεργειακών αναγκών στο λιμάνι» το οποίο περιέχει τον χρόνο παραμονής στο λιμάνι, τη μέση και μέγιστη ανάγκη ισχύος καθώς και λεπτομέρειες του ηλεκτρικού συστήματος όπως συχνότητα και τάση λειτουργίας. Η διαστασιολόγηση του εξοπλισμού διασύνδεσης με την ξηρά και ο προκαταρκτικός σχεδιασμός των εγκαταστάσεων ηλεκτροδότησης βασίζονται σε αυτά τα προφίλ ενεργειακών αναγκών.

Το τελευταίο κεφάλαιο αυτής της εργασίας θα επικεντρωθεί στην οικονομική σκοπιά του Cold-Ironing τόσο από τη μεριά των πλοιοκτητών όσο και από τη μεριά των διαχειριστών του λιμένα.

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1. Shipping industry, emissions, impact on environment and public health

1.1 World fleet

According to Equasis[18], an information system collating existing safety-related information on ships from both public and private sources founded by the European Commission and the French Maritime Administration, the world fleet in 2014 consisted of 85,094 vessels with 53,854 of them having a Gross Tonnage of more than 500GT. In the following tables one can see the total number and Gross Tonnage of the world fleet. The vessels are separated in small, medium, large and very large, depending on their Gross Tonnage.

Table 1 – Number of vessels in 2014

NUMBER OF VESSELS IN 2014								
Ship Type	GT<500		500<GT<25000		25000<GT<60000		GT>60000	
General Cargo Ships	4,356	13.94%	11,650	30.89%	212	1.94%		
Specialized Cargo Ships	8	0.03%	201	0.53%	56	0.51%	2	0.04%
Container Ships	17	0.05%	2,255	5.98%	1,619	14.82%	1,193	22.89%
Ro-Ro Cargo Ships	30	0.10%	653	1.73%	619	5.67%	180	3.45%
Bulk Carriers	320	1.02%	3,700	9.81%	5,374	49.19%	1,602	30.74%
Oil and Chemical Tankers	1,815	5.81%	6,597	17.49%	2,414	22.10%	1,537	29.50%
Gas Tankers	39	0.12%	1,070	2.84%	216	1.98%	378	7.25%
Other Tankers	315	1.01%	531	1.41%	5	0.05%		
Passenger Ships	3,657	11.71%	2,528	6.70%	271	2.48%	156	2.99%
Offshore vessels	2,531	8.10%	5,227	13.86%	115	1.05%	157	3.01%
Service Ships	2,405	7.70%	2,361	6.26%	23	0.21%	6	0.12%
Tugs	15,747	50.41%	946	2.51%				
Total Number of Vessels	**31,240**	**100%**	**37,719**	**100%**	**10,924**	**100%**	**5,211**	**100%**

Table 2 – Gross Tonnage of World Fleet in 2014

GROSS TONNAGE IN 2014 (in 1000GT)								
Ship Type	GT<500		500<GT<25000		25000<GT<60000		GT>60000	
General Cargo Ships	1,455	17.57%	49,815	22.82%	6,942	1.68%		
Specialized Cargo Ships	2	0.02%	1,596	0.73%	2,107	0.51%	153	0.03%
Container Ships	7	0.08%	26,425	12.10%	62,925	15.22%	116,771	22.18%
Ro-Ro Cargo Ships	11	0.13%	6,306	2.89%	29,320	7.09%	11,696	2.22%
Bulk Carriers	125	1.51%	54,518	24.97%	198,021	47.90%	157,251	29.87%
Oil and Chemical Tankers	586	7.08%	39,595	18.14%	88,677	21.45%	168,038	31.92%
Gas Tankers	15	0.18%	6,349	2.91%	9,477	2.29%	40,813	7.75%
Other Tankers	94	1.14%	1,350	0.62%	162	0.04%		
Passenger Ships	922	11.13%	10,579	4.85%	9,649	2.33%	15,397	2.92%
Offshore vessels	719	8.68%	13,334	6.11%	5,258	1.27%	15,374	2.92%
Service Ships	595	7.19%	7,510	3.44%	850	0.21%	992	0.19%
Tugs	3,750	45.28%	931	0.43%				
Total 1000GT	**8,281**	**100%**	**218,308**	**100%**	**413,388**	**100%**	**526,485**	**100%**

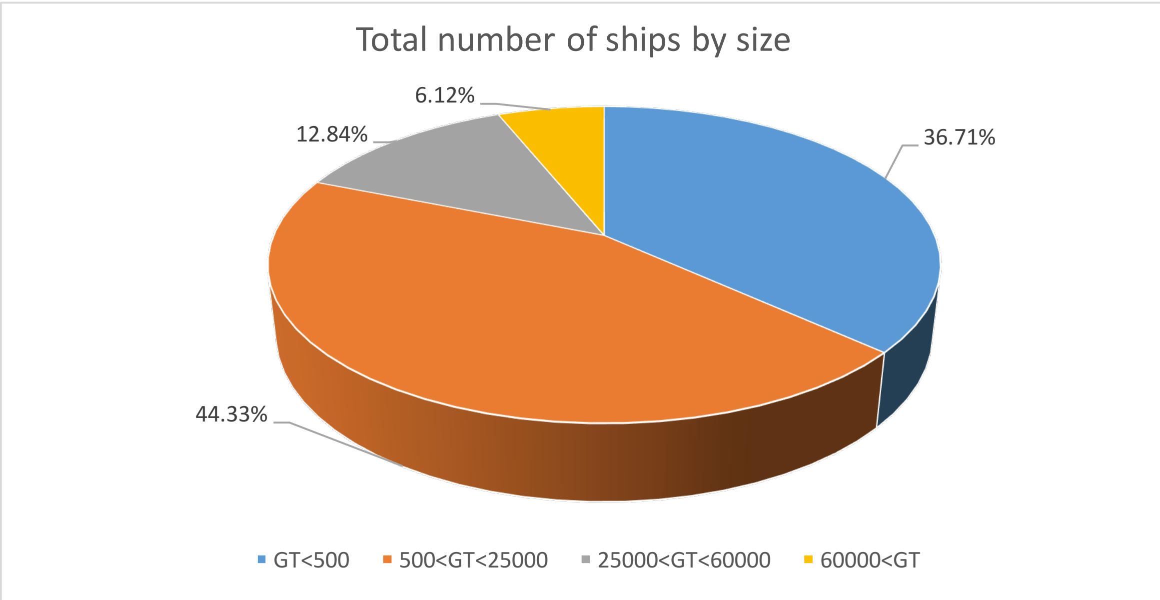


Figure 1 – Number of Vessels in 2014 by size

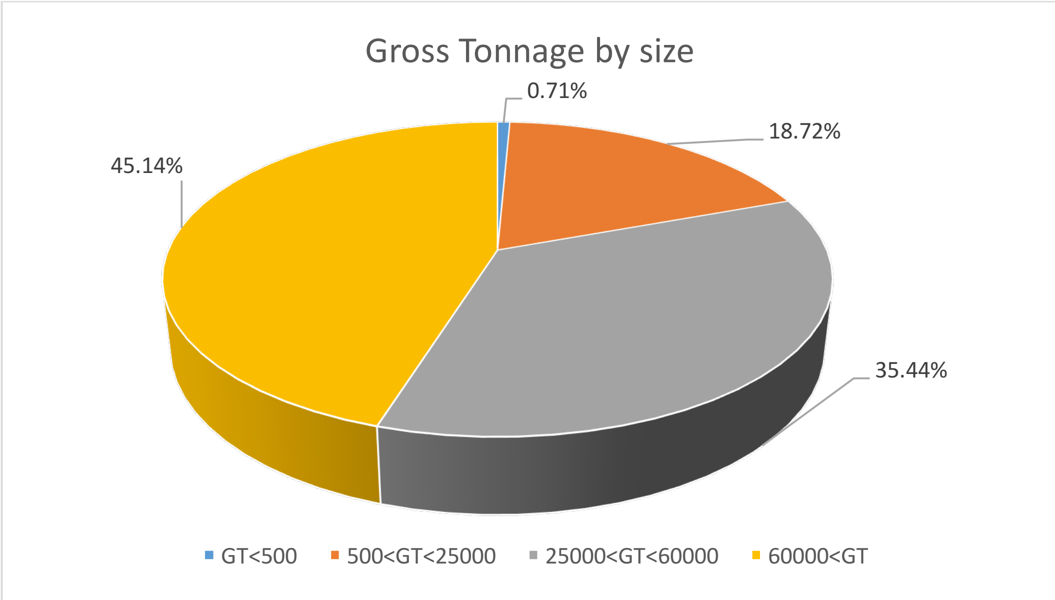


Figure 2 – Gross Tonnage in 2014 by size

When at berth, ships require electric power for accommodation needs, such as air conditioning, cooking, lighting and crew activities but also require electricity for cargo management (cranes or pumps). The amount of energy required is in most cases produced by diesel generators or shaft generators at sea and by diesel generators at port. The electrical power needed while at berth, varies from a few kilowatts for smaller ships to several megawatts for big cruise ships. If we consider that ships spend almost 100 days a year at berth and that the world fleet numbers more than 50000 vessels, it is clear that the amount of energy needed for hoteling is rather significant. Almost 190 grams of fuel are consumed for each produced kWh of electricity and 594 grams of carbon dioxide are produced. In a global scale, one ship only can pollute as much as 50 million average cars do, in one year.

1.2 Ship emissions and their impact in public health

Emission from marine diesel engines can be categorized as following:

- Nitrogen Oxides (**NO_X**)
- Sulphur Oxides (**SO_X**)
- Carbon Dioxide (**CO_2**)
- Carbon Monoxide (**CO**)
- Particulate Matter (**PM**)
- Volatile Organic Compounds (**VOC**)

According to IMO[19] (International Maritime Organization), before the global economic crisis in 2007 the contribution of international shipping activities to the global **CO_2** emissions was of about 2.8%, that is, 885 million tons of CO_2 while in 2012 international shipping emitted about 2.2% of the global CO_2 emissions which accounts for 796 million tons of CO_2. Before judging international shipping and accusing it of excessive pollution, one must consider that almost 90% of global trade is carried by sea (Lloyds). According to UNCTAD[20] (United Nations Conference on Trade and Development) the total amount of goods transported through sea has raised from 8034 million in 2007 to 9197 millions in 2012. It is clear that despite the augmentation of the international seaborne trade even during the 2010 economic crisis, technological development and environmental legislation have led to a decreasing contribution of international shipping in air pollution. However, we must not forget that during the economic crisis and because of the high oil prices, the majority of shipping companies adopted slow-steaming techniques in order to reduce fuel consumption and therefore save money. This fact led to reduced fuel consumption and therefore to reduced CO_2 emissions.

Ship emissions in major ports have a significant influence in human health. Despite the fact that ship emissions in port are only a small part of the total shipping contribution in environmental pollution, these emissions directly affect human population and atmospheric ecosystem in urbanized ports such as Piraeus in Greece. Combustion of fuels which contain sulphur produce **SO_X** which are harmful to the flora, corrode metal structures and affect the respiratory system of people leaving near ports. SO_X cause irritant effects by stimulating nerves in the respiratory system. This leads to cough, irritation and a feeling of chest tightness. In addition to that, **NO_X** are produced from ship engines because of the combustion in conditions of high temperature and pressure inside the engine's cylinders. These emissions are said to cause cancer, respiratory problems such as asthma and emphysema, aggravation of existing heart disease and contribution in extended damage to lung tissues. NO_X include various nitrogen compounds like nitrogen dioxide (NO_2) and nitric oxide (NO) that play an important role in the atmospheric reactions that create harmful particulate matter, ground level ozone (smog) and acid rain. Moreover, NO_X is a major cause of photochemical pollution and acid rain. Particulate Matters (**PM**) are also a dangerous kind of pollutant. PM's are usually consisted of soot, metal oxides and sulfates, all of them produced during the incomplete combustion of fuel or the dirt inside the fuels and lubricating oil being used in ships. PM's are of great range in terms of size, shape and chemical composition. Based on their diameter, PM's are separated in PM_{10} (inhalable PM's with less than 20 μm diameter) and in $PM_{2.5}$. In October 2013, the specialized cancer agency of the World Health Organization (WHO), International Agency for Research on Cancer (IARC)[15] announced that it has classified outdoor air pollution as carcinogenic to humans. IARC concluded that there is sufficient evidence that exposure to outdoor air pollution causes lung cancer and that there is a positive association with an increased risk of bladder cancer. **PM**, a major component of outdoor air pollution was evaluated separately and was also classified as carcinogenic to humans. Volatile Organic Compounds, known as **VOC** are organic chemicals that have a high vapor pressure at ordinary room temperature. Their high vapor pressure results from a low boiling point, which causes large numbers of molecules to evaporate or sublimate from the liquid or solid form of the compound and enter the surrounding air, a trait known as volatility. The most important VOC linked with ship activity is benzene which is a natural constituent of crude oil and one of the most elementary petrochemicals. Benzene is known as a human carcinogen and it is found in car's exhaust fumes and in stored fuel. All Crude oil carriers are obliged to maintain and apply a VOC management plan for compliance with MARPOL Annex VI, Resolution MEPC.185 (59).

CO_2 is the most important emission in every internal combustion engine, therefore ships do produce large amounts of it. For example, during a 10-hour stay at berth, the diesel generators of a medium sized cruise ship consume 20 metric tons of fuel and produce almost 60 metric tons of CO_2. The same amount of CO_2 is produced by 25 average European cars annually. In 2012, international shipping was estimated to have contributed about 2.2% to the global emissions of carbon dioxide (CO_2). Although international shipping is the most energy efficient mode of mass transport and only a modest contributor to overall CO_2 emissions, a global approach to further improve its energy efficiency and effective emission control is needed as sea transport will continue growing apace with world trade. As already acknowledged by the Kyoto Protocol, CO_2 emissions from international shipping cannot be attributed to any particular national economy due to its global nature and complex operation. Therefore, IMO (International Maritime Organization) has been energetically pursuing the limitation and reduction of greenhouse gas (GHG) emissions from international shipping, in recognition of the magnitude of the climate change challenge and the intense focus on this topic.

Table 3 - Piraeus port emissions from cruise ships in 2013 - NTUA report

Piraeus Port Emissions 2013 in tons						
Cruise Ship Maneuvering and Hoteling Emissions		Summer	Autumn	Winter	Spring	Total
	NO_X	218.588	116.532	9.523	79.232	423.875
	SO_2	70.493	38.958	3.188	26.034	138.673
	$PM_{2.5}$	6.695	4.517	0.372	2.759	14.343
	Total	295.776	160.007	13.083	108.025	576.891

Based on the NTUA report about cruise ship emissions in major Greek ports we can observe that in 2013, the total NO_X emissions from cruise ships calling in the port of Piraeus were almost 424 tons. A comparison figure can be found in ordinary cars. It is said that 1 ton of NO_X is produced by 1 million cars per day. But the Port of Piraeus is a rather weak example of the international shipping contribution in NO_X emissions. Back in 2002-2003, a study was made by Port of Los Angeles and Port of Long Beach in order to determine the NO_X emissions from ships at the port during a period from June 1st 2002 to May 31st 2003. In the study, the data came from 1148 vessels making 2913 calls in both ports and the ship types were mostly container vessels, tankers and dry bulk cargo vessels. The results showed that the total amount of NO_X produced per day in the Port of Los Angeles and Port of Long Beach combined, taking into account ship emissions during cruise, maneuvering and hoteling was 33 tons. 13 tons of NO_X per day (39% of the total NO_X emissions) were produced during hoteling. This fact demonstrates that hoteling power demands are a major contributing factor in air pollution caused by ships. While docked at berth, ships could benefit from the shore power grid instead of using their auxiliary diesel engines in order to produce the required electricity. Having in mind that in most cases shore power is produced with less emissions and a more environmentally friendly way, switching from diesel generators to shore power would be a great benefit for the environment. Even with MGO fuels, emissions of onboard power generation are higher than the average emission factors for onshore electricity production in Greece as it is shown in 3.4.

1.3 Legislation and measures to reduce air pollution caused by ships

Air quality is a matter of great importance for all living creatures on earth, including of course humans, as it has a strong impact in health, life quality and environmental equilibrium. Human activities, both land-based and offshore, such as transport of goods and people or industrial production are important contributing factors in air pollution. Even household activities such as heating and lighting play a major role in air pollution.

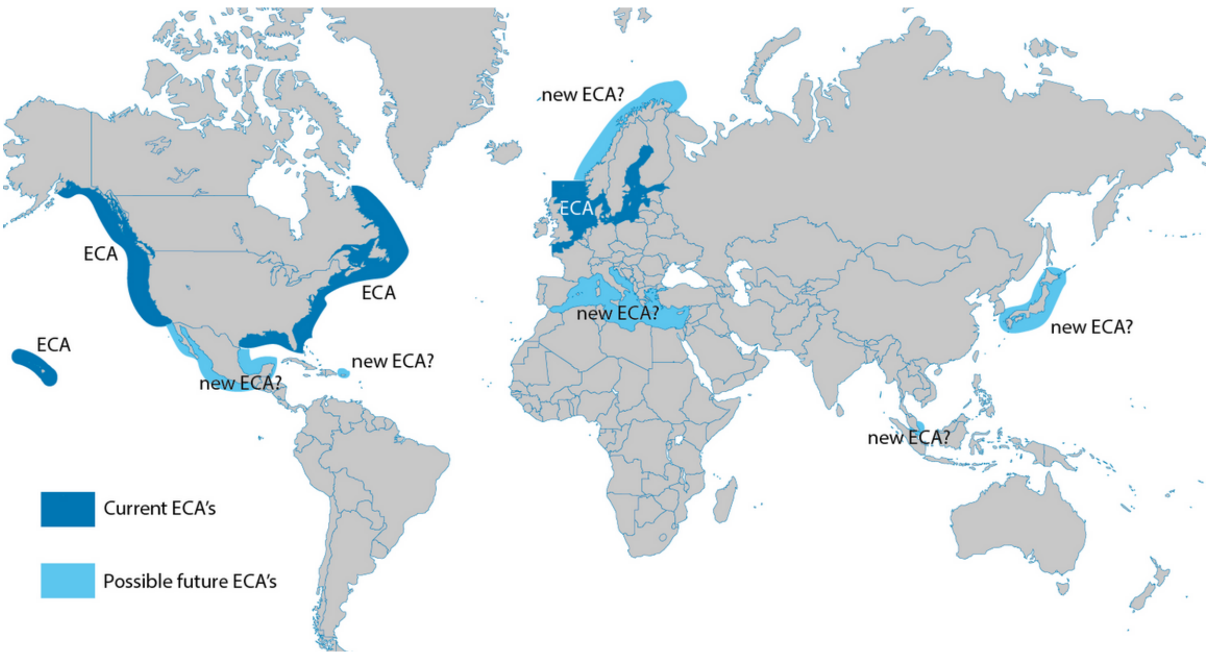
It is true that over the past decades many efforts have been made in order to cut down polluting emissions from land-based human activities. European and worldwide legislation have imported stricter rules concerning exhaust gas fumes from industrial sites, automobiles and public transportation, especially in terms of reducing the emission of CO_2 NO_X, SO_X and Particulate Matters (PM) into the atmosphere. On the other hand, establishing of environmental standards in international shipping has so far been inferior to those of land-based activities. This can be explained due to the closer proximity of land-based resources to populated human areas in opposition to international shipping "imperceptible" contribution to air pollution. It is a fact that the vast majority of citizens observes ship's emissions only during a visit in a busy port and neglects the emissions which are produced when the ship is sailing in open seas.

Nevertheless, during the past decades, major steps have been made to the direction of reducing air pollution caused by shipping activity. MARPOL Annex VI, first adopted in 1997, has limited the main air pollutants contained in ships exhaust gas, including sulphur oxides (SO_x) and nitrous oxides (NO_x), and has prohibited deliberate emissions of ozone depleting substances (ODS). MARPOL Annex VI also regulated shipboard incineration, and the emissions of volatile organic compounds (VOC) from tankers. IMO's Marine Environment Protection Committee (MEPC) revised the MARPOL Annex VI by reducing the global sulphur limits of marine fuels from 4.5% to 3.5% in 2012 and stepwise to 0.5% by 2020 depending on the outcome of a feasibility study due to be completed in 2018. In certain areas of the world which are particularly affected by acidification, special legislation is adopted. In these areas known as ECA's (Emission Control Areas) the limits applicable for SO_X and PM were reduced to 0.1% as of January 1st 2015. Progressive reductions in NOx 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 1 January 2011, and a more stringent "Tier III" emission limit for engines installed on a ship constructed on or after 1 January 2016 operating in ECA's.

All these rules, legislations and revised measures are expected to have a beneficial impact on the atmospheric environment and human health, especially in residential areas near major ports where atmospheric pollution is significant. It is important to mention that new regulations require the shipping industry to invest in environmental technologies not only in order to reduce exhaust gas emissions but also in terms of waste management and disposal and ballast water treatment.

Table 4 - IMO regulations in Sulphur percentage of marine fuels

Maximum sulphur content in marine fuels	
IMO	
SECA's	1.0% as of 2010
	0.1% as of 2015
outside of SECA's	from 4.5% to 3.5% as of 2012
	0.5% as of 2020*



Picture 1 – Current and possible future ECA's

NO_x emission limits are set for diesel engines depending on the engine maximum operating speed n(rpm).

Table 5 - MARPOL Annex VI NO_X Emission Limits

Marpol Annex VI NOx Emission Limits				
Tier	**Date**	**NOx Limit, g/kWh**		
		n<130	**130≤n<2000**	**n≥2000**
Tier I	2000	17	$45 \cdot n^{-0.2}$	9.8
Tier II	2011	14.4	$44 \cdot n^{-0.23}$	7.7
Tier III*	2016	3.4	$9 \cdot n^{-0.2}$	1.96
*In NOx Emission Control Areas (NECA's)				

New legislation marks new standards in ship emissions. A number of solutions will enable ship owners to comply with the more stringent regulations. New, more fuel efficient engines and propelling systems are among the most promising ones. The use of low sulphur fuel and natural gas also leads to a reduction in SO_X and NO_X and together with scrubbers, these are the three options for compliance with the regulations governing sulphur oxide and nitrogen oxide emissions. However, when at berth, ship-owners can profit of a fourth option which does not only reduce ship emissions but also can be potentially profitable. Connecting and providing a ship with shore power, drastically cuts down all direct ship emissions and under circumstances it can lead to significant savings for the ship-owners. This procedure is also known as *Cold-Ironing.*

2. Cold Ironing

2.1 Cold Ironing Concept

The term “Cold Ironing” is dated way back in time, in the steam ships era. Back then, the amount of steam needed in a steam engine or a steam turbine for the propulsion was produced in large iron boilers. During the voyage, stokers fed the iron boilers with coal in order to produce steam but while in port when there was no need for steam, the boilers were shut down therefore the iron was cooling down.

Nowadays the term has a slightly different meaning. In most cases, while in port ships use their auxiliary engines in order to produce electrical power required for hoteling, loading or unloading activities. As a result, ships at berth consume a significant amount of fuel and produce an even more significant amount of exhaust fumes. These emissions consist a major issue and a direct threat to human health in ports near cities and living areas. A solution to that issue can be found in Cold Ironing.

Shore-power or “Cold Ironing” enables ships at berth to use shore-side electricity from the local power grid through a substation at the port and to shut down their diesel power generators. This switchover from onboard power to side-shore power eliminates ship emissions associated with power generation and shifts these emissions to a power plant onshore. This leads to a significant reduction of air pollution in ports. One can think that this just passes the emissions problem from the port areas to the power generation areas onshore. Considering that in many countries, including Greece, a significant amount of electricity is produced by renewable energy sources (15.8 % of total electricity produced in 2013 according to E.E.A.)[22] and having in mind that the efficiency of a shore power plant is significantly higher that this of an onboard diesel generator that previous thought is not exactly true.

Moreover, cold ironing could be beneficial for ship-owners not only because of the fuel savings but also because of the reduced running time of diesel generators. Passenger ships, Ro/Ro or Cruise ships, spend a significant amount of their time at berth so in that case, switching of the diesel generators would save in spare parts, servicing and maintenance. Another advantage of shore-side power is the reduction of noise levels near ports. This is extremely important for residential areas nearby large port such as Piraeus in Greece as people suffer from high noise levels.

Cold Ironing does eliminate ship emissions related to electricity production but does not eliminate ships emissions related to steam production. Steam is used for various reasons on a ship such as heating, providing of hot water, cooking, driving cargo pumps in oil and products carriers, cargo heating, engine warm up, fuel heating and many others. The required amount of steam when the ship is sailing is usually provided by exhaust gas boilers but when the ship is at berth the amount of steam needed is provided by oil-fired boilers. Unfortunately, these emissions cannot be reduced with cold-ironing.

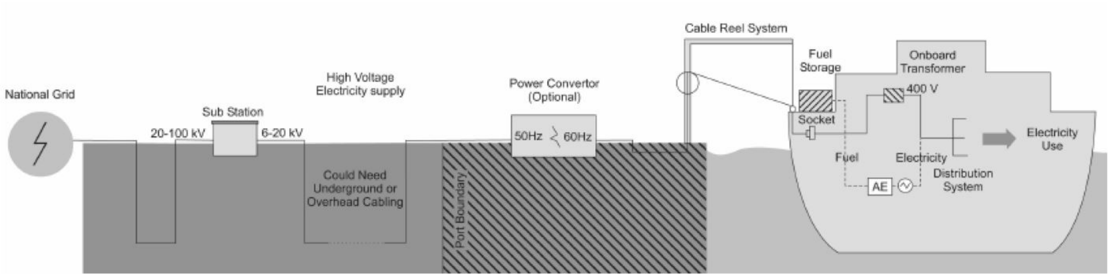
2.2 Implementation Issues

As we know, international commercial fleet consists of many types of ships with varying age and country of construction. Due to the absence of a universal method and standardization in the design and construction of ship's electrical installations, voltage and frequency of electrical current may vary from ship to ship. For example, the diesel generators of a bulk carrier made in Japan in 1990 produce electrical current of 450 Volt and 60Hz. A containership built in Korea in 2008 uses 6600 Volts at a frequency of 60 Hz while a cruiseferry built in Finland in 1985 uses 380 Volts at 50 Hz. On the other hand, shore power frequency is 50Hz in Europe, Asia and Africa but 60 Hz in USA. Because of that variety in terms of voltage and frequency, expensive voltage and frequency converters are needed in order to accommodate every ship. Of course, not every ship is fitted with the equipment needed in order to receive shore power and there is a great chance that most of the ship-owners will not be willing to absorb the financial burden of this investment unless there is solid proof that this investment will be profitable.

A second implementation problem is that of power needs. It is probable that the shore power grid of the port may not be able to handle the power needs of the ships at berth. Four cruise ships at berth may require up to 25MW of electrical power. As a result, the local power grid may require major upgrades and expansion.

2.3 Equipment and Connection

A typical shore-side power supply configuration, presented by the European Union in the recommendation 2006/339/EC[6] is consisted of the following equipment for supply, handling and distribution of electrical power.



Picture 2 – Typical shore side power supply configuration

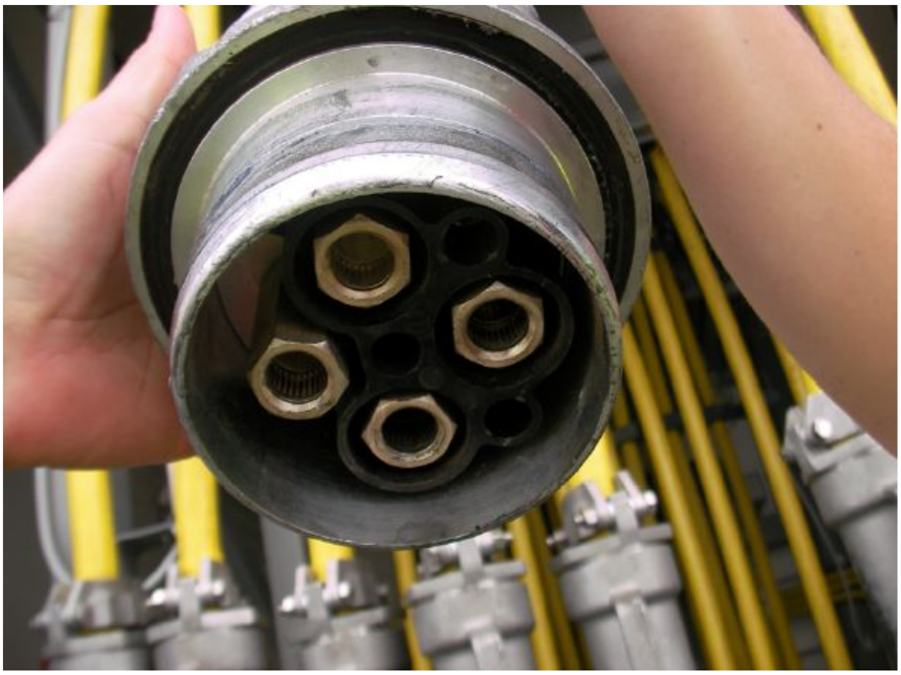
1. A connection to the national grid to a local substation where electricity will be transformed to 6-20 kV.
2. Cables to deliver the 6-20kV power from the substation to the port terminal.
3. Power conversion in the port terminal where necessary. Power conversion includes frequency conversion when frequency on board is different than local grid frequency.
4. Underground installed cables within existing or new conduits for the distribution of electricity to the terminal.
5. A cable reel system for the handling of the high voltage cables.
6. A socket onboard the vessel for the connecting cable.
7. A transformer onboard the vessel to transform the high voltage current to the voltage of the ship systems.

Port of Stockholm

A typical installation of shore-side power supply is that of Port of Stockholm[11] which exists since 1985 and provides shore-side power to local big ferries which operate from Stockholm to Aland Island. These ships are connected with a low voltage connection at 400V/50Hz. The connection process takes approximately 5 minutes and the power is delivered through 9 cables which are attached to the ship via a cable arrangement mechanism as shown in picture 3.

Picture 3 – Cable arrangement mechanism at Port of Stockholm

In 2006, another shore-side low voltage connection at 690V/50Hz was installed in Port of Stockholm in order to serve ferries at Freeport terminal. Power distribution is achieved through 12 cables which are connected to the ferry prior to the auxiliary engines shutdown. A connection plug of this type is shown in picture 4.



Picture 4 – A 690V connection plug at Port of Stockholm

The substation at the port terminal is powered directly from the port grid and with the use of transformers, provides electricity at 400V/690V which is compatible with the ferries electrical systems.

Port of Los Angeles

Apart from providing electricity to passenger ships in northern Europe, major steps have also been made in order to provide shore-side power to cargo ships. In June 2004, the Port of Los Angeles[16] in cooperation with China Shipping Container Line (CSCL) announced the opening of the container terminal at berth 100 of Los Angeles Port. This terminal is supplied with a high-voltage current of 6.6kV at 60 Hz and a transformer reduces this voltage at 440V/60Hz when necessary. The major difference between the equipment in Port of Stockholm and in Port of Los Angeles is that in Port of Los Angeles the transformer is placed on a barge. When a container vessel is cold-ironed the barge is moored at the stern of the ship and then the cable is attached to the ship, at a special socket as can be seen in picture 5. Because of this barge, connection time is significantly higher than the time needed in Port of Stockholm. The connection procedure takes approximately 1 hour.

Picture 5 – The barge carrying the voltage transformer and the cable reel in Port of Los Angeles

2.4 Summary of Existing Installations

Table 6 – Technical Characteristics of Existing cold-ironing installations

Port	Country	Voltage	Frequency
Port of Goteborg	Sweden	400V/6.6kV/10kV	50 Hz
Port of Stockholm	Sweden	400V/690V	50 Hz
Port of Helsingborg	Sweden	400V/440V	50 Hz
Port of Pitea	Sweden	6kV	50 Hz
Port of Antwerp	Belgium	6.6kV	50/60 Hz
Port of Zeebrugge	Belgium	6.6kV	50 Hz
Port of Lubeck	Germany	6kV	50 Hz
Port of Kotka	Finland	6.6kV	50 Hz
Port of Oulu	Finland	6.6kV	50 Hz
Port of Kemi	Finland	6.6kV	50 Hz
Port of Los Angeles	USA	440V/6.6kV	60 Hz
Port of Long Beach	USA	6.6kV	60 Hz
Port of Seattle	USA	6.6kV/11kV	60 Hz
Port of Pittsburg	USA	440V	60 Hz
Port of Juneau	USA	6.6kV/11kV	60 Hz

As demonstrated in the above table 6, in most cases except for Port of Antwerp, the available power frequency matches the local grid frequency (60 Hz for USA, 50 Hz for Europe). Only in Port of Antwerp both frequencies are available thanks to the frequency converter. In most commercial ports, the 6.6kV current is offered as large modern cargo and cruise ships tend to use higher voltage for various reasons. In passenger ports such as Port of Goteborg or Port of Stockholm, 400V are offered because that is the voltage for Ro-Ro and Passenger ships which berth there.

2.5 Preliminary cost prediction of Cold-Ironing for ports and ships.

In the cold-ironing cost effectiveness study[1] realized by ENVIRON for the Port of Long Beach in 2004, it was calculated that for high voltage applications (6.6kV), the ship retrofit costs ranged between 200,000$ and 574,000$ with an average cost of 400,000$. For low voltage applications, because of the need for a transformer, the ship retrofit cost was calculated between 240,000$ - 1,100,000$ with an average cost of 588,000$. In the same cost effectiveness study, it was calculated that the total power infrastructure costs in order to accommodate 12 vessels where 22,263,000$ so almost 1,855,000 $ per vessel.

Apart from modification and installation costs for ships and ports, running costs of cold ironing must be taken into account as well. Using data available from Eurostat, EIA (Energy Information Administration), Wikipedia and bunker fuel prices monitoring site www.bunkerworld.com it is easy to create the above tables 7 and 8 regarding bunker prices of MGO all around the world as well as shore electricity prices in different countries of Europe and America. It is to be mentioned that bunker prices change with time, supply and demand circumstances, market sentiment or geopolitical situations so values of the above table only represent oil prices in March 2016.

Table 7 – MGO Prices in major ports of Europe and America (March 2016)

Fuel Prices	$/mt	€/mt
	MGO	
Piraeus	352.50	321.37
Antwerp	313.00	285.36
Hamburg	328.50	299.49
Rotterdam	320.00	291.74
Genoa	371.00	338.24
Algeciras	350.50	319.55
Halifax	522.50	476.36
Quebec	572.00	521.49
Philadelphia	358.50	326.84
L.A - Long Beach	400.00	364.68
Vancouver	450.50	410.72
Houston	352.00	320.92
Rio De Janeiro	585.50	533.80
Buenos Aires	814.00	742.12
AVERAGE	435.04	396.62

Table 8 – Shore electricity industrial prices (2014)

Shore Electricity Prices € / kWh (2014)	
Country	**€ / kWh**
Belgium	0.109
Sweden	0.067
Finland	0.072
Netherlands	0.089
Denmark	0.088
France	0.091
Greece	0.130
Italy	0.174
Spain	0.117
Turkey	0.081
Portugal	0.119
USA	0.067
Canada	0.068
Brazil	0.103
Argentina	0.035
LAC	0.107
Average	**0.095**

Electricity prices are less volatile than oil prices. Table 8 shows indicative values of electricity prices in countries of Europe and North and South America. Therefore, an average price for shore side electricity is to be considered 0.095 €/kWh. The big question is if onboard generated electricity is produced at a higher or a lower cost. To find out, project guides of a well-known marine engines manufacturer are used, in order to determine specific fuel consumption of marine generating sets. These specific fuel consumption values can be found in table 9 (Appendix I). The average price from table 7 is used as price for MGO fuel in order to determine the €/kWh cost of onboard electricity generation. This can be shown in table 11 below

Table 10 – Price comparison between onboard produced electricity and shore power

Onboard electricity generation cost	
$ / kWh	**€ / kWh**
0.0815	0.0743
Average electricity price in America	**Average electricity price in Europe**
€ / kWh	
0.0760	0.1034

It is clear that with the current low oil prices it is cheaper to generate the necessary electricity onboard using the ship's auxiliary engines rather than using shore power. Although, because this is a preliminary cost prediction, engine's maintenance, spare parts and consumption of lubricating oil are not taken into account. A more detailed economic analysis can be found on chapter 5.2. Moreover, before rejecting cold ironing as a non-profitable alternative of electricity supply, one must consider economical and health impacts from exhaust fumes at berth. It is well known that ship emissions lead to a deterioration of human health and the ecosystem, which is why the valuated cost of emissions must be taken into account as well. Cost of installing and maintaining an exhaust after treatment system such as scrubber must be also calculated. These systems will probably be necessary in order to meet strict port emission laws in the future, if of course the ship cannot be connected to shore power.

It is more than clear that one cannot easily reach a conclusion on whether cold-ironing is economically beneficial or not for ship-owners. More than one parameters such as power demand, time at berth, area and prices of bunkering as well as electricity prices determine whether there is a potential profit or not. Especially for the example of an average ferry in Piraeus port, this is to be determined through a cost analysis in 5.3.1.

3. Shore power for Piraeus port

3.1 Shore power for Ro-Ro passenger ferries at Piraeus Port

3.1.1 Summary of Piraeus port coastal shipping activities

Piraeus is the largest port of Europe and one of the largest ports in the world in terms of passenger traffic. It has a throughput volume of about 20 million passengers per year and it is the main link between the mainland, the Aegean islands and Crete. As a result, more than 20 ferries use Piraeus port as their main hub for service between mainland and Cyclades, Crete, Dodecanese, Saronic Gulf.

Picture 6 – Piraeus passenger port

Because of the port's proximity τo highly dense urban areas, ship emissions are a major issue for air quality, environment and public health. Latest measurements[21] that were carried out by NABU (Nature And Biodiversity Conservation Union) in 2015, showed that PM concentration near passenger terminal in Piraeus port was more than 100.000 particles per cubic centimeter of air when normal concentrations in urban areas vary from 3000 to 5000 PM/cm^3. This air pollution problem mainly occurs due to marine engine activity while the ships are at berth. A solution to this issue would be to shut down auxiliary engines while at port and use shore power instead.

3.1.2 Power demand analysis

The first step in order to determine whether shore side electricity would be beneficial for the port of Piraeus is to gather and process information about the number, type, capacity, installed auxiliary engines horsepower and electrical power needs of ferry vessels which use port of Piraeus as their primary hub. Moreover, the turnaround time of each vessel at Piraeus port is required in order to calculate the total amount of electricity needed at berth. Most of the ships using Piraeus as their main port can be found in the following table 12.

Table 11 – Passenger ships using Piraeus Port as their main hub

	MAIN DIMENSIONS					GENERATORS	
	L (m)	B(m)	Passengers	Cars	G.R.T.	Number	Output (kW/gen)
FESTOS PALACE	214	26.4	2200	600	24352	3	2300
KNOSSOS PALACE	214	26.4	2200	600	24352	3	2300
BLUE STAR DELOS	145.9	23.2	2400	430	18498	3	1320
BLUE STAR PATMOS	145.9	23.2	2400	430	18498	3	1320
BLUE STAR PAROS	124.2	18.9	1474	230	10438	3	990
BLUE STAR NAXOS	124.2	18.9	1474	230	10438	3	990
BLUE GALAXY	192	27	1740	780	29992	3	1000
BLUE HORIZON	187.1	27	1497	780	27230	4	1325
BLUE STAR 1	176.1	25.7	1890	641	29858	3	1260
BLUE STAR 2	176.1	25.7	1890	641	29560	3	1260
NISSOS MYKONOS	141	21	1915	418	8129	3	1080
ARIADNE	196	27	1845	650	30882	3	1100
						1	1100
NISSOS RODOS	192.5	27.3	850	748	29733	3	1000
SPEEDRUNNER III	100.3	17.1	688	120	4697	3	455
PHIVOS	99.5	17	1200	125	3437	3	500
HELLENIC SPIRIT	204	25.8	1850	1100	32694	3	1485
OLYMPIC CHAMPION	204	25.8	1850	1100	32694	3	1485
KYDON	192	27	1750	703	29991	3	1000
SUPERFAST XII	199.9	25	1637	649	30902	3	2000
DIAGORAS	141.5	23	1462	274	12499	1	1180
						2	1220
HIGHSPEED IV	92.04	24	1045	188	6274	4	350
FLYING DOLPHIN	32.24	5.8	155	0	161	2	28

Ships berthing at Piraeus can be categorized in 2 types. Smaller ferries with a capacity of almost 1000 passengers and small hydrofoils are used for short trips to islands of Poros, Hydra, Aigina and Spetses inside Saronic Gulf. Bigger ferries which have a capacity of 1500-2200 passengers and large catamarans are used for longer trips to Cyclades, Dodecanese, North Aegean Islands and Crete. Timetables can be found on Piraeus Port Authority website as well as through www.marinetraffic.com. Piraeus port winter timetable can be found on table 13.

Table 12 – Winter timetable and turnaround time at Piraeus Port

WINTER TIMETABLE				
	ARRIVAL AT PIRAEUS	DEPARTURE FROM PIRAEUS	TURNAROUND TIME (min)	WEEKLY TURNAROUND TIME (min)
BLUE HORIZON/KYDON	6:00	21:00	900	2250
KNOSSOS PALACE/FESTOS PALACE	6:00	21:00	900	2250
ELYROS/BLUE GALAXY	6:00	21:00	900	2250
BLUE STAR PAROS	20:00	7:30	690	4830
BLUE STAR NAXOS	15:00	17:30	150	1050
DIAGORAS	9:40	15:00	320	960
BLUE STAR PATMOS/BLUE STAR DELOS	23:25	7:25	480	3360
BLUE STAR 2	7:45	18:00	615	1845
SUPERFAST XII	6:10	19:00	770	2310
BLUE STAR 1	7:55	20:00	725	2175
ARIADNE	7:25	21:00	815	2445
NISSOS MYKONOS	0:00	16:00	960	2880
NISSOS RODOS	7:25	21:00	815	2445
VINTSENTZOS KORNAROS	6:30	17:00	630	1260
ADAMANTIOS KORAIS	20:30	14:30	1050	2625
POSEIDON HELLAS	9:30	10:00	30	6405
	12:45	13:15	30	
	13:00	13:30	30	
	17:30	7:15	825	
PHIVOS/APOLLON HELLAS	19:35	10:00	865	7280
	13:05	16:00	175	

Because many trips require more than a day to be completed it is more convenient to measure berthing time in a weekly rather than in a daily basis.

Small vessels which operate between Piraeus port and islands of the Saronic Gulf have in general limited power demand and spend little time at berth due to dense schedule. These vessels are basically hydrofoils and catamarans which carry 150-250 passengers and also small ferries with a capacity of around 1000 passengers. Considering that, these vessels should not be part of this cold ironing study. Also, aging ships should be excluded from this study because cold ironing retrofitting would be far too expensive to pay off in their remaining operational life. Therefore, this analysis should be focused on newer, bigger ships with a significant hoteling load and berth time.

Determining power demand of ferries at berth will be based on actual data of four large ferries which use Piraeus as their main port. Dividing the hoteling load with the total power output of the diesel generators provides us with the load factor which is a useful tool in order to predict the hoteling load for other ferries as well. Load factor varies from 0.34 to 0.41 meaning that when in port ferries use 34-41% of their total diesel generators available power. An average value of 0.37 will be used to predict power demand at port for other ferries as well.

Table 13 – Hoteling Load and Load factors for 4 large ferries berthing at Piraeus port

Ship	Hotelling Load (kW)	Load Factor
Ferry 1	2800	0.406
Ferry 2	1362	0.344
Ferry 3	1280	0.395
Ferry 4	1220	0.337
Average		0.370

Table 14 –Prediction of Hoteling load using the average load factor value 0.37

<table>
<tr><th>Vessel Name</th><th>Number of D/G</th><th>D/G Output (kW)</th><th>Hoteling Load (kW)</th></tr>
<tr><td>FESTOS PALACE</td><td>3</td><td>2300</td><td>2553</td></tr>
<tr><td>KNOSSOS PALACE</td><td>3</td><td>2300</td><td>2553</td></tr>
<tr><td>BLUE STAR DELOS</td><td>3</td><td>1320</td><td>1465</td></tr>
<tr><td>BLUE STAR PATMOS</td><td>3</td><td>1320</td><td>1465</td></tr>
<tr><td>BLUE STAR PAROS</td><td>3</td><td>990</td><td>1099</td></tr>
<tr><td>BLUE STAR NAXOS</td><td>3</td><td>990</td><td>1099</td></tr>
<tr><td>BLUE GALAXY</td><td>3</td><td>1000</td><td>1110</td></tr>
<tr><td>BLUE HORIZON</td><td>4</td><td>1325</td><td>1961</td></tr>
<tr><td>BLUE STAR 1</td><td>3</td><td>1260</td><td>1399</td></tr>
<tr><td>BLUE STAR 2</td><td>3</td><td>1260</td><td>1399</td></tr>
<tr><td>NISSOS MYKONOS</td><td>3</td><td>1080</td><td>1199</td></tr>
<tr><td rowspan="2">ARIADNE</td><td>3</td><td>1100</td><td rowspan="2">1628</td></tr>
<tr><td>1</td><td>1100</td></tr>
<tr><td>NISSOS RODOS</td><td>3</td><td>1000</td><td>1110</td></tr>
<tr><td>KYDON</td><td>3</td><td>1000</td><td>1110</td></tr>
<tr><td>SUPERFAST XII</td><td>3</td><td>2000</td><td>2220</td></tr>
<tr><td rowspan="2">DIAGORAS</td><td>1</td><td>1180</td><td rowspan="2">1339</td></tr>
<tr><td>2</td><td>1220</td></tr>
</table>

Results of this study:

- Power demand for large ferries berthing at Piraeus port varies from 1100 to 2600 kW.
- Berthing time also varies from 950 to 4500 minutes per week depending on schedule and voyage.
- Unfortunately, no information is available regarding main voltage and frequency. Usually these vessels have a main voltage of 380-450V but frequency may be 50 or 60 Hz because some vessels are made in Japan (60 Hz) and others in Europe (50 Hz).
- None of the above vessel is ready to connect with shore power. All vessels have a connection point for shore power when on dry-dock but it is not clear whether this equipment is capable of handling the hoteling load.

3.1.3 Fuel Consumption and Emissions

Fuel consumption and emissions will be calculated for ships that are eligible to undergo modifications and be ready to receive shore power in the near future, as stated in table 15. This calculation of fuel consumption and CO_2, SO_X, NO_x and PM emissions will be done, assuming that the diesel generators are operated at 75% and based on data which are available from two major marine engines manufacturers[23.24] and can be found in Appendix I. Using the monthly berth time for each vessel, it is easy to predict fuel consumption and emissions in a monthly basis.

$$Fuel\ cons.\left(\frac{t}{month}\right) = \frac{SFOC\left(\frac{g}{kWh}\right) \cdot Hotelling\ Load\ (kW) \cdot Berth\ time(h)}{1000^2} \quad (1)$$

Table 15 – Prediction of Fuel consumption at berth in a monthly basis

Vessel Name	Hotelling Load (kW)	Weekly Berth Time (min)	Monthly Berth Time (h)	Fuel Consumption (kg/h)	Fuel Consumption (t/month)
FESTOS PALACE	2553	1125	75	467.29	35.05
KNOSSOS PALACE	2553	1125	75	467.29	35.05
BLUE STAR DELOS	1465.2	1680	112	268.19	30.04
BLUE STAR PATMOS	1465.2	1680	112	268.19	30.04
BLUE STAR PAROS	1098.9	4830	322	201.14	64.77
BLUE STAR NAXOS	1098.9	1050	70	201.14	14.08
BLUE GALAXY	1110	1125	75	203.17	15.24
BLUE HORIZON	1961	1125	75	358.94	26.92
BLUE STAR 1	1398.6	2175	145	256.00	37.12
BLUE STAR 2	1398.6	1845	123	256.00	31.49
NISSOS MYKONOS	1198.8	2880	192	219.42	42.13
ARIADNE	1628	2445	163	297.98	48.57
NISSOS RODOS	1110	2445	163	203.17	33.12
KYDON	1110	1125	75	203.17	15.24
SUPERFAST XII	2220	2310	154	406.34	62.58
DIAGORAS	1339.4	960	64	245.16	15.69

As evident, monthly fuel consumption varies from 30 to 65 tons depending on berthing time and power demand at berth. Having in mind that bunkering price for MGO in Piraeus is 420$/t (May 2016), actual fuel cost for hoteling may reach up to $27000 per month.

Table 16 – Prediction of emissions in a monthly basis

Vessel Name	Hotelling Load (kW)	Monthly Berth Time (h)	CO_2 emissions (t/month)	SO_X emissions (t/month)	NO_X emissions (t/month)	PM emissions (t/month)
FESTOS PALACE	2553	75	112.97	1.91	1.85	0.11
KNOSSOS PALACE	2553	75	112.97	1.91	1.85	0.11
BLUE STAR DELOS	1465.2	112	96.82	1.64	1.59	0.10
BLUE STAR PATMOS	1465.2	112	96.82	1.64	1.59	0.10
BLUE STAR PAROS	1098.9	322	208.77	3.54	3.43	0.21
BLUE STAR NAXOS	1098.9	70	45.38	0.77	0.74	0.05
BLUE GALAXY	1110	75	49.12	0.83	0.81	0.05
BLUE HORIZON	1961	75	86.77	1.47	1.42	0.09
BLUE STAR 1	1398.6	145	119.65	2.03	1.96	0.12
BLUE STAR 2	1398.6	123	101.50	1.72	1.67	0.10
NISSOS MYKONOS	1198.8	192	135.80	2.30	2.23	0.14
ARIADNE	1628	163	156.56	2.65	2.57	0.16
NISSOS RODOS	1110	163	106.75	1.81	1.75	0.11
KYDON	1110	75	49.12	0.83	0.81	0.05
SUPERFAST XII	2220	154	201.71	3.42	3.31	0.20
DIAGORAS	1339.4	64	50.58	0.86	0.83	0.05

Table 17 – Prediction of fuel consumption and emissions of coastal shipping in Piraeus port for one year

Fuel (t/year)	CO_2 (t/year)	SO_X (t/year)	NO_X (t/year)	PM (t/year)
6445.22	20775.47	352.13	340.86	20.78

Air pollution caused by ferries at berth is severe. If we sum up the monthly emissions of CO_2 per vessel, we end up with 1730 tons of CO_2. Almost 29 and 28 tons of SO_X and NO_X respectively are produced and almost 2 tons of PM are released into the air. Considering that these results are derived only from the above 16 vessels and smaller or older vessels (with older and less efficient engines) are excluded from the study, it is obvious that the pollution problem due to coastal shipping activities is bigger than the numbers indicate.

In order to make a comparison between the cost of Shore-side power and onboard electricity generation in Chapter 5, three ferries are selected.

3.2 Shore power for cruise ships at Piraeus Port

3.2.1 Summary of Piraeus port cruise activities

The Port of Piraeus is an important destination for cruise ships in the Mediterranean Sea. Because of Athens being a popular holiday destination for many people around the globe, Piraeus cruise terminal is busy especially during summer and autumn. Piraeus cruise terminal has 11 berthing places for the simultaneous berthing of vessels and can accommodate even the largest cruise ships. The maximum ship dimensions that can be accommodated are 394 meters in length, 45 meters in width and 11 meters in draught with no restriction in ship's air draught.

During their stay at Piraeus port, cruise ships have a high demand of electrical power compared to other vessel types. The voyage itself, the time at port and the ship amenities are part of the cruise experience so cruise companies do their best in order to satisfy the customer needs. Because of their high passenger capacity, which may vary from 500 to 4000 passengers, electrical power demands for refrigeration, cooking, heating, cooling, water and sewage processing and lighting is particularly high. That ofcourse depends on the level of equipment and amenities available to the travellers.

Picture 7 – The cruise terminal in Piraeus port

3.2.2 Port traffic

The scope of this chapter is to determine whether shore-side electricity at Piraeus cruise ship terminal would be beneficial for ship-owners, local residents and environmental protection. For ship-owners, beneficial stands for reduced fuel expenses and less maintenance costs. For the environment and the local residents, beneficial means less exhaust gas emissions and therefore less air pollution. In order to come to a conclusion, the following data is required: The first thing needed is the number of cruise ship arrivals and the number of cruise passengers at Piraeus port in a yearly basis. This information can be found in Piraeus Port Authority annual reports which are available on the port's website.

Table 18 - Cruise ship statistics at Piraeus Cruise Terminal

	2010	2011	2012	2013	2014	2015
Cruise Passengers	1,864,657	2,517,371	2,066,925	2,296,457	1,854,916	1,678,490
Cruise Ships Arrivals	805	921	763	710	683	622

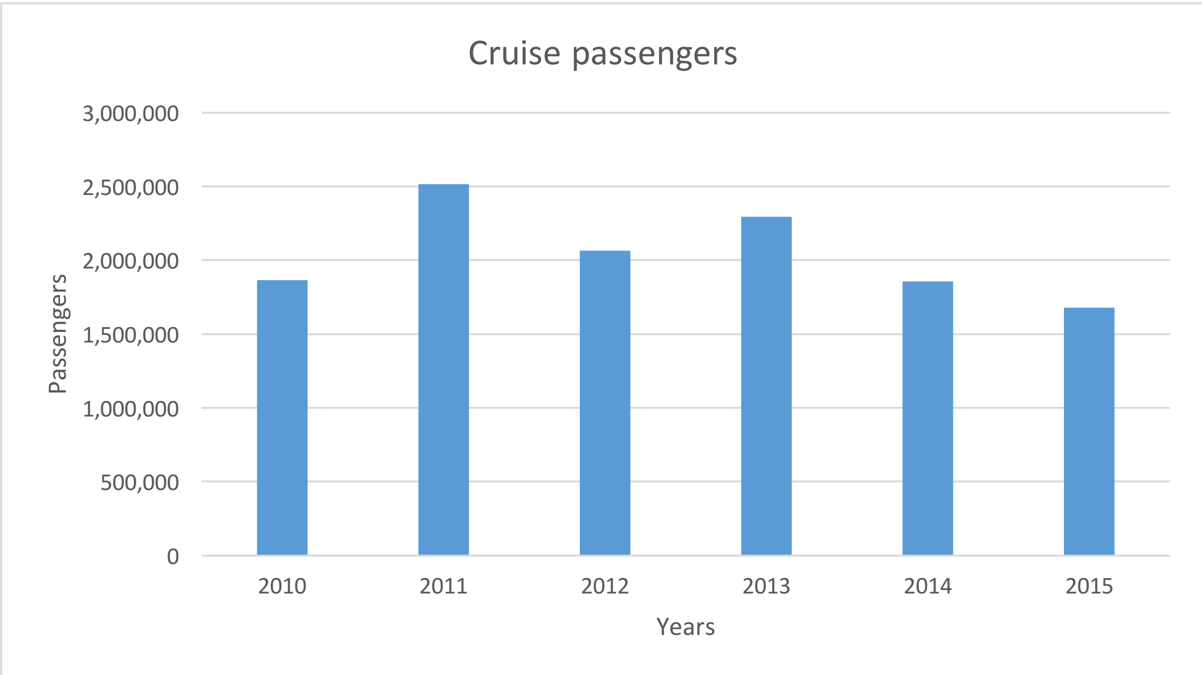


Figure 3 – Cruise passengers 2010-2015

Despite the fact that the purpose of this thesis is not to comment the prosperity or development of the Piraeus cruise terminal it cannot go unnoticed that there has been a significant decrease in passenger traffic after 2011. According to 2014 annual report, this decrease is mainly due to war events in the Middle East (Syria, Israel, Iraq). It is also important to mention that decrease in cruise passengers' traffic is smaller than the decrease in cruise ship arrivals, therefore bigger cruise ships of higher capacity are sailing to Piraeus.

The average time at berth and also the monthly port calls can be determined from the cruises timetable for 2016 which is available on Piraeus port website.

Figure 4 – Cruise ships arrivals in Piraeus port 2012-2015

Figure 5 – Monthly cruise ships arrivals in 2016

Table 191 – Monthly cruise ship arrivals in 2016

Month	Arrivals
January	6
February	5
March	23
April	49
May	76
June	72
July	79
August	84
September	86
October	86
November	38
December	10
Total	**614**

As expected, cruise traffic is significantly high in spring and autumn with the majority of cruise ship arrivals occurring between August and September. Practically the cruise season begins in March and finishes in November as cruise traffic is particularly low from December to February. For at least six months per year, Piraeus cruise terminal is really busy.

The majority of cruise ships visiting Piraeus port, arrive early in the morning between 5:00 and 9:00 AM so that passengers can spend the day sightseeing in Athens. The average berthing time is almost 15 hours as many of these vessels depart between 19:00 and 23:00 PM. The maximum berth time shown at the table above is of 108 hours for 2016 and it concerns one particular vessel which is scheduled to remain at berth for 4 days, although this is an exception.

Table 20 – Cruise ships berth time in Piraeus port

Piraeus Cruise Terminal			
2016 Berths	Average Berth Time (h)	Max Berth Time (h)	Min Berth Time (h)
614	14:52	108	5

3.2.3 Power demand analysis

The data which will be used can be found in "Air pollution emission inventory", a report prepared by US Forest service and Alaska department of environmental conservation for Skagway, Alaska in 2008[9]. In this report, data concerning hotel load, fuel consumption, emissions and engine type are gathered from 24 different cruise vessels berthing at Skagway. Many of these ships also visit Piraeus port. This particular dataset is of great value because cruise ships under consideration use different engine types and configurations. Two of the above ships use gas turbine for propulsion and sometimes for electricity production. Other use mechanical propulsion and diesel generators for electricity while some of them use electrical propulsion, therefore diesel engines or a combination of diesel engines and gas turbines produce the electrical power required.

Knowing the average birth time in Piraeus cruise terminal as well as the number of berths per year, the only information needed in order to calculate the total amount of energy for hoteling of cruise ships is the hotel load (kW) for cruise ships berthing at Piraeus. Having access to that information is highly unlucky because every year different cruise ships visit Piraeus port. Because hotel load varies, depending on actual number of passengers onboard, outside temperature, time of the day etc., average values from a range of cruise ships will be used.

A good practice, in order to be able to predict hotel load for other cruise ships except those of the dataset, would be to calculate the hotel load factor by dividing the actual hotel load demand with the total capacity of the auxiliary diesel generators. However, this is complicate enough as many cruise ships use electric propulsion. That means that engines onboard produce electricity which is then distributed for propulsion, accommodation and all other needs of the vessel. One engine may produce electricity for propulsion and hoteling at the same time, therefore it is difficult to separate the amount of power dedicated to propulsion from the amount of power dedicated to electricity generation for hoteling. It is preferable to use a power per passenger ratio (PL). A power per passenger average can be calculated from the below dataset and can be used to predict the total power demand in Piraeus cruise terminal.

Table 21 – Skagway 2008 Cruise ships data[9]

Name	L	B	Passengers	Crew	Hotel Load (kW)	kW/passenger
Mein Schiff 2	264	32	2130	850	4100	1.925
Norwegian Sun	260	32	2002	968	5600	2.797
Norwegian Pearl	294	32.3	2399	1100	7200	3.001
Norwegian Star	294	32.3	2240	1100	9000	4.018
Star Princess	290	32.6	2600	1200	10500	4.038
Diamond Princess	288.33	37.5	3078	1060	11500	3.736
Golden Princess	252	32.6	2598	1060	10500	4.042
Island	293	32.2	1970	905	7200	3.655
Saphire Princess	288.3	37.5	3078	1060	9600	3.119
Rhapsody of the Seas	278	32	2435	765	5300	2.177
Serenade of the Seas	285	32	2400	900	5500	2.292
Radiance of the Seas	293.2	32.2	2501	859	5300	2.119
Dawn Princess	261	56	1998	924	6800	3.403
Pacific Dawn	245	56	2020	660	6700	3.317

Using the power per passenger ratio, the energy consumption for one cruise ship can be found as:

$$Energy\ (kWh) = PL\left(\frac{kW}{passenger}\right) \cdot Passengers \cdot berth\ time(h) \quad (2)$$

Therefore, if we accept that the average power per passenger ratio of 3.117 kW/passenger can be considered as an acceptable universal value for all cruise ships berthing at Piraeus, the electricity needs of the past 6 years can be calculated as following:

$$year\ Energy\ (GWh) = PL\left(\frac{kW}{passenger}\right) \cdot year\ pax \cdot abt(h) \cdot \frac{1}{10^6} \quad (3)$$

Table 22 – GWh of electricity consumed by cruise ships 2010-2015 in Piraeus port

Cruise ships energy consumption at Piraeus Port (GWh)					
2010	2011	2012	2013	2014	2015
82.85	111.84	91.83	102.03	82.41	74.57

3.2.4 Cruise ships electrical system

Voltage and frequency of the electrical system onboard cruise vessels are an important parameter in cold ironing. As mentioned in 2.1.2 one big issue in cold ironing is matching port's local grid voltage and frequency with that onboard the vessel. This is achieved using voltage and frequency converters. Because this equipment can be really expensive, ports usually only provide electricity of a specific voltage and frequency. With the exception of Port of Antwerp, all other ports which provide shore-side electricity only offer electrical power of a specific frequency (usually 50 Hz in Europe and 60 Hz in USA) and of one or two voltages e.g. 440/6600V. Cruise vessels visiting Piraeus port are different every year with a few exceptions which come mainly from Greek cruise companies. Therefore, in order to decide which kind of equipment should be used it is preferable to lean on general statistics regarding voltage and frequency onboard cruise ships. Having a sample of 30 cruise vessels with a capacity from 2000 to 3500 passengers, the following conclusions are extracted, regarding voltage and frequency.

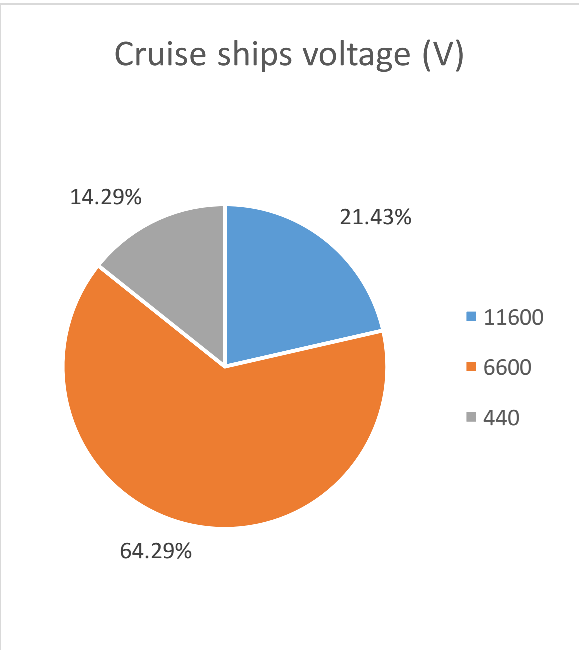


Figure 6 – Primary electrical system voltage distribution

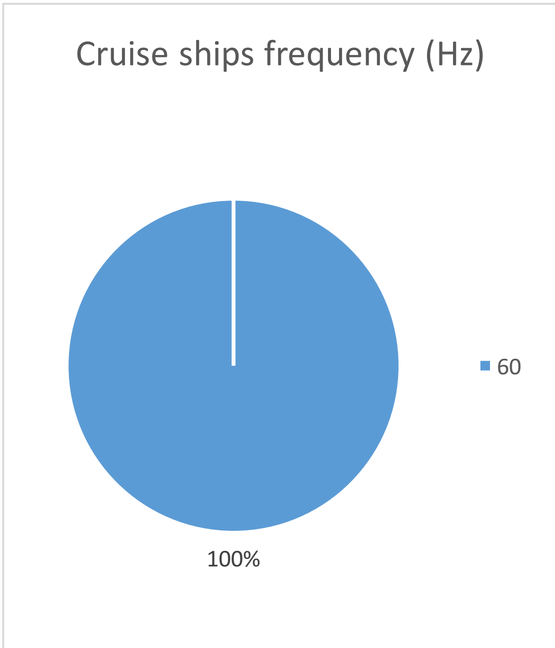


Figure 7 – Electrical system frequency distribution

All of the 30 ships used to extract the figures above use 60 Hz electrical current. 50 Hz electrical current can be found only in small (<180m) and older cruise vessels. Given that the average cruise vessel capacity visiting the Port of Piraeus is of about 2700 passengers, these smaller vessels can be excluded from this analysis. Most modern cruise ships use 60 Hz and 6600 or 11000 Volts current to their primary electric system. That is because high voltage current allows for smaller cables to be used for power transmission. Also, a high voltage of 6600 or 11000 Volts allows for smaller size motors (e.g. bow thruster) when compared to motors of the same power at 440 Volts. Moreover, high voltage leads to small electric current so protection devices like circuit breakers can be rated at lower amperes.

3.2.5 Fuel consumption and Emissions

In order to calculate fuel consumption and emissions from hoteling activities, data from engine manufacturers are required. Most of the cruise ships in Skagway 2008 dataset are equipped with MAN and Wärtsilä engines and generating sets, therefore fuel consumption and emissions calculations will be based on manufacturer's values which are available in the engine's project guides[23,24]. Because ships use different engines, average values will be used to predict fuel oil consumption and engine's emissions at berth. The corresponding tables can be found in Appendix I.

As it is not possible to examine every single ship visiting Piraeus as an individual case, fuel consumption and emissions will be calculated for 3 typical cruise ships with a capacity of 2000, 2500 and 3000 passengers respectively. In these cases, the average berth time is considered to be 14:52 hours, consumption and emissions will be calculated considering with auxiliary engines operating at 75% and 50% respectively and power per passenger ratio is taken as 3.117 kW/passenger. The generator efficiency η is considered to be n=0.95.

Table 23 – Prediction of Cruise ship fuel consumption at berth

Vessel	Capacity (Pass)	Hotel Load (kW)	Fuel Consumption at 75% Load (mt/h)	Fuel Consumption at 50% Load (mt/h)
Ship 1	2000	6234.1	1.22	1.27
Ship 2	2500	7792.6	1.53	1.58
Ship 3	3000	9351.2	1.83	1.90

Table 24 – Prediction of hourly Cruise ship emissions at berth

Vessel	Capacity (Pass)	Hotel Load (kW)	CO_2 (kg/h)	SOx (kg/h)	NOx (kg/h)
Ship 1	2000	6234.1	3678.13	62.34	60.35
Ship 2	2500	7792.6	4597.66	77.93	75.43
Ship 3	3000	9351.2	5517.19	93.51	90.52

Table 25 – Predication of Cruise ship emissions per berth

Vessel	Capacity (Pass)	Hotel Load (kW)	CO_2 (t/berth)	SOx (t/berth)	NOx (t/berth)
Ship 1	2000	6234.1	54.694	0.927	0.897
Ship 2	2500	7792.6	68.367	1.159	1.122
Ship 3	3000	9351.2	82.041	1.391	1.346

The above emissions calculations are based on manufacturer's values for engines running on fuel with 2.5% sulphur content. Because Piraeus in not yet a SECA zone, there are no specific requirements in fuel oil quality used at berth. Moreover, these emissions represent the total emissions of a cruise ship during its berth. Berth time should be adjusted so that connection time for cold ironing is taken into account before a comparison is made between emissions for onboard power generation and shore side power. Usually, connection procedure requires about 1 hour and disconnection about 30 minutes.

Table 26 – Fuel consumption and emissions of cruise ships in Piraeus port for the past 6 years

	2010	**2011**	**2012**	**2013**	**2014**	**2015**
Fuel (t)	15164	20472	16809	18675	15085	13650
CO_2 (t)	48879	65988	54181	60198	48623	43999
SO_X (t)	828	1118	918	1020	824	746
NO_X (t)	802	1083	889	988	798	722
PM (t)	49	66	54	60	49	44

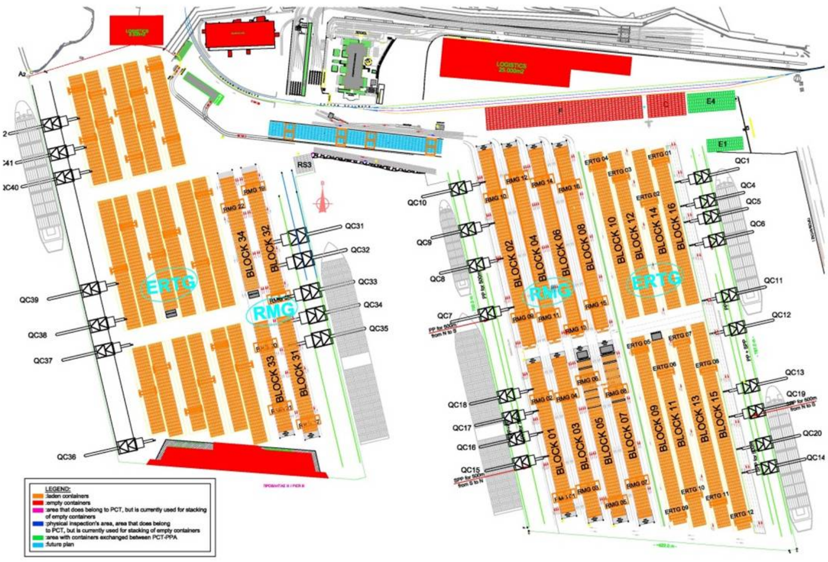
3.3 Shore power for container vessels at Piraeus port

3.3.1 Summary of Piraeus container terminal activities

Piraeus port container terminal consists of 3 piers. Until today, Pier I is under the management of Piraeus Port Authority (ΟΛΠ) but it is scheduled to get under Chinese control (PCT. S.A.) which is owned by Cosco once the process of transfer of a majority stake is completed. Pier II and Pier III are operated by PCT. S.A. since 2009 and in that period of 6 years, container traffic has significantly raised. The agreement between the Greek government and Cosco Pacific has propelled Piraeus port into Europe’s top 10 container terminals and Piraeus is the fastest growing of the 22 container terminals that Cosco Pacific operates around the globe.

Numbers always tell the truth and Piraeus terminal container traffic is no exception. In 2009, only 665,000 twenty-feet containers (TEU) were handled by Piraeus container terminal while in 2013 this number was rocketed to 3,160,000 TEU’s, an increase of 476%. In 2014 the total number of containers that were handled by Piraeus container terminal reached 3.7 million TEU’s. This rapid growth rate is believed to decrease in 2015 and 2016 as container traffic is limited by the port’s TEU capacity. Pier I has a capacity of 1 million TEU’s and the combined capacity of East and West Pier II is of 3.2 million TEU’s. East side of Pier III can handle up to 1.6 million TEU’s. When construction of West side Pier III is completed, the combined capacity of Pier II and III is to raise up to 6.2 million TEU’s per year. According to company officials, 2015 and 2016 rise in container traffic is also due to the significant increase in container intended for transport by rail in Central and Eastern Europe.

Calculations based on the schedule of PCT show that the average amount of vessels berthing at the container terminal is around 190 per month. This number only represents vessels berthing at Pier II and III as no data was available for Pier I. Ship sizes vary from small feeders of around 500 to 2000 TEU’s, medium capacity containerships of 4000-5000 TEU’s and large containerships of 10000-14000 TEU’s. Transshipment business represent an important share of the port’s activities so Piraeus container terminal is a hub for both large containerships and feeders.



Picture 8 – Future layout of Piers II and III

Increased ship traffic and equipment used in the terminal have considerable negative environmental impacts. The rapid growth of Piraeus container terminal has led to a significant air quality deterioration of the surrounding municipalities and the highly dense urban areas nearby. Moreover, seawater and marine environment have suffered from severe degradation due to increased vessel activity and also noise levels in the area have raised significantly. Piraeus container terminal, in its current state is a rather energy consuming facility.

In order to confine this environmental problem and limit the exposure of the nearby residents to the adversities of the ship exhaust emissions generated within the terminal, it necessary to examine the possibility of a cold ironing installation as a feasible solution. The implementation of such an installation would efficiently cut down an important portion of the ship emissions and would be beneficial for the air quality of surrounding urban areas. Container vessels power demands, emissions, and berthing time will be calculated using a dataset with the latest port calls of 12 container vessels, provided by a major shipping company in the container sector. This dataset includes vessels of various sizes, from small feeders of around 1500 TEU to large containerships of 10000 TEU, therefore it is a representative sample of the types of vessels visiting Piraeus container terminal. Moreover, actual berthing times and ship's traffic in Piraeus port can be directly found via the company's website where all schedules are available.

3.3.2 Port traffic

Since 2009, container ships traffic at Piraeus port has increased of about 400%. Detailed information about ship arrivals in the past 4 years was not available so ship traffic was predicted using the arrivals schedule of the past 3 months which was available in PCT website. The same procedure was followed for the prediction of the average berth time at the port. At this point, it is useful to remark that berth time basically depends on the amount of necessary container moves that have to be made and on the port's facilities and equipment. Of course parameters such as refueling time, ship size and number of refrigerated TEU's are also important contributing factors to an increased berthing time. As calculated, the average berth time for Piraeus port is almost 19 hours. There are cases that require up to 42 hours while other need only 5 hours.

Table 27 – Piraeus container terminal traffic data

Piraeus Port Container Terminal			
Port calls per month	Average time at berth (h)	Max time at berth (h)	Min time at berth (h)
190	19	42	5

Assuming that the average number of port calls per month that was predicted applies to all twelve months of the year, the total number of container vessels berthing at Piraeus terminal should be around 2300 vessels per year. This is a prediction based on the actual container traffic, therefore this number shall increase if the growth rate of Piraeus container terminal remains that high.

3.3.3 Power demand analysis

In general, specific information on the power supply requirements by vessels at berth is not readily available, therefore the way to gather this kind of information is through other studies that are available or through contact with shipping lines. In this report, a combination of the two sources of information will be used so that optimal and reliable results can be achieved. Power demands while at berth will be calculated using a 2006 report conducted by Port of Rotterdam authority and also a dataset of 12 container vessels latest port calls which was obtained after a contact made with a major shipping company.

The Port of Rotterdam research[4]

The Port of Rotterdam report was based on a voluntary electrical system questionnaire which was distributed to various container vessels berthing at the container terminal of Rotterdam. A total of 19 feeder and 34 deep sea container vessels participated in the research. In this research, vessels with a length of less than 140 m are categorized as feeders and vessels that exceed 140 m in length are categorized as deep sea container vessels. Vessel particulars (length, TEU capacity Reefer capacity), electrical system particulars (main voltage, frequency) and also power demands at berth (average hoteling load, maximum hoteling load) are available in this research.

All ships which participated in the research were able to receive shore power for maintenance purposes, for example during drydocking, but only one vessel was equipped with a connector capable of handling the full power load under normal operating conditions. In general, the absence of a specific plan and standardization of equipment and specifications about shore power has held off many ship-owners from installing such equipment onboard their vessels. Cold Ironing installations that exist around the world serve mostly vessels that frequently berth at the same port such as ferries and cruise ferries.

In the following figures, one can find the results of this research in terms of power consumption at port and electric system characteristics such as voltage and frequency for both feeder and deep sea container vessels.

Power consumption

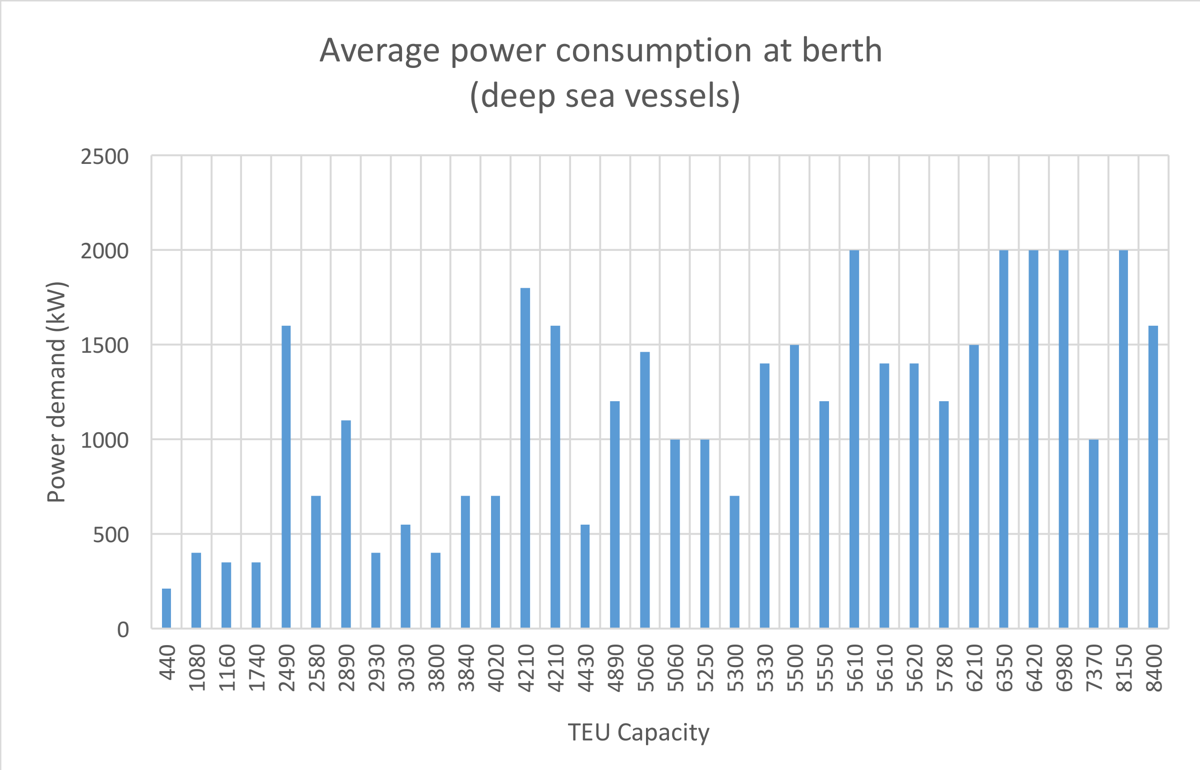


Figure 8 – Deep sea container vessels power consumption at Rotterdam port

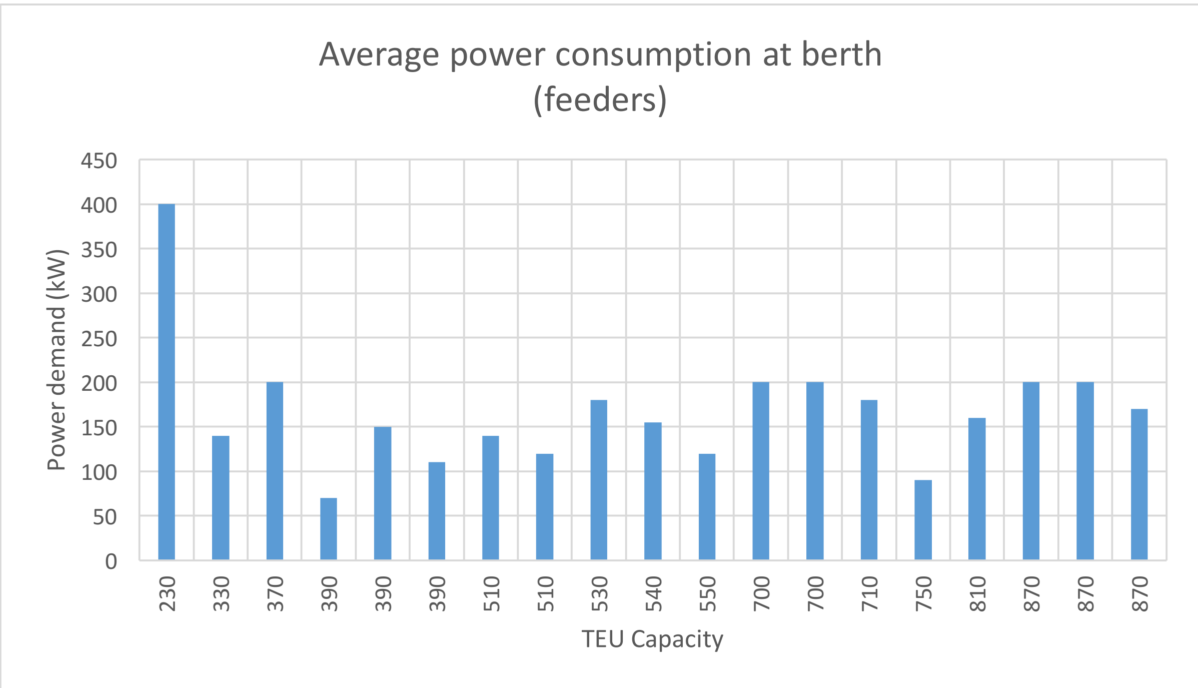


Figure 9 – Feeder container vessels power consumption at Rotterdam port

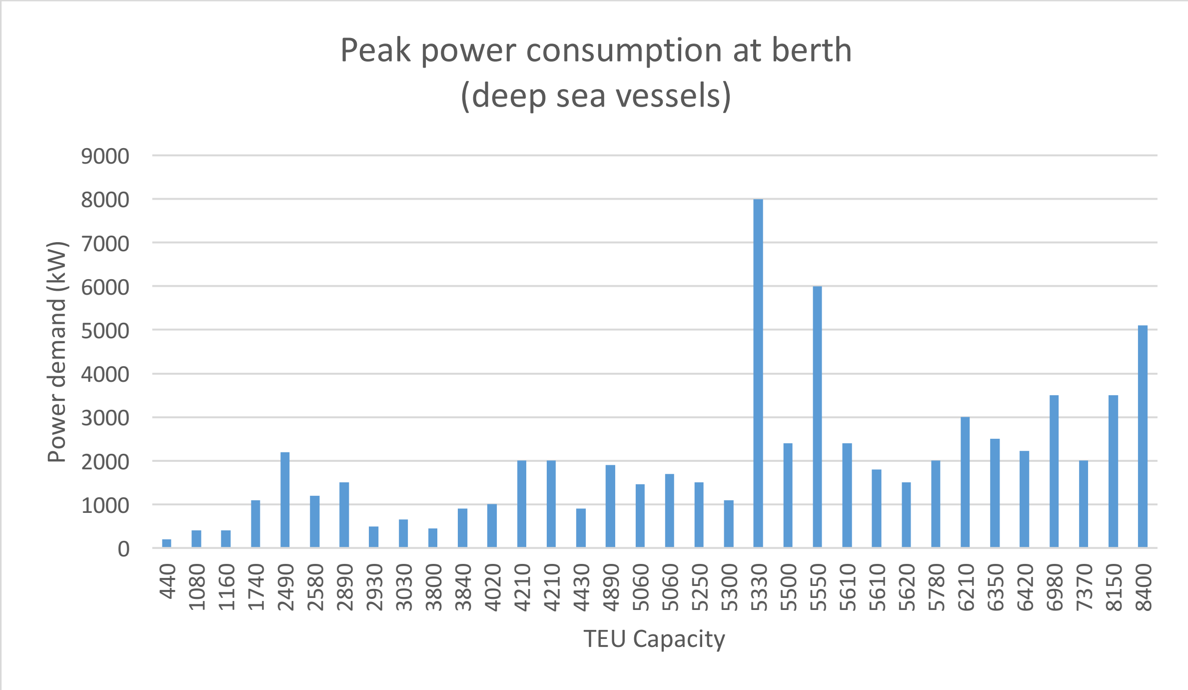


Figure 10 – Deep sea container vessels peak power consumption at Rotterdam port

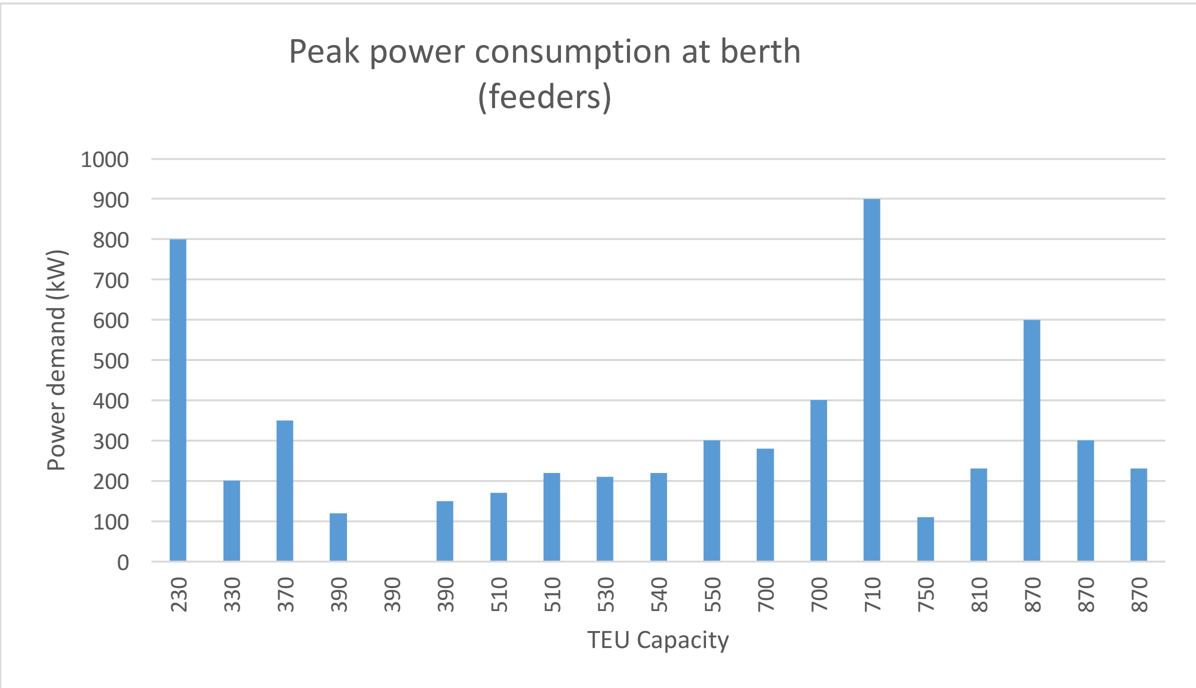


Figure 11 – Feeder container vessels peak power consumption at Rotterdam port

Voltage and Frequency

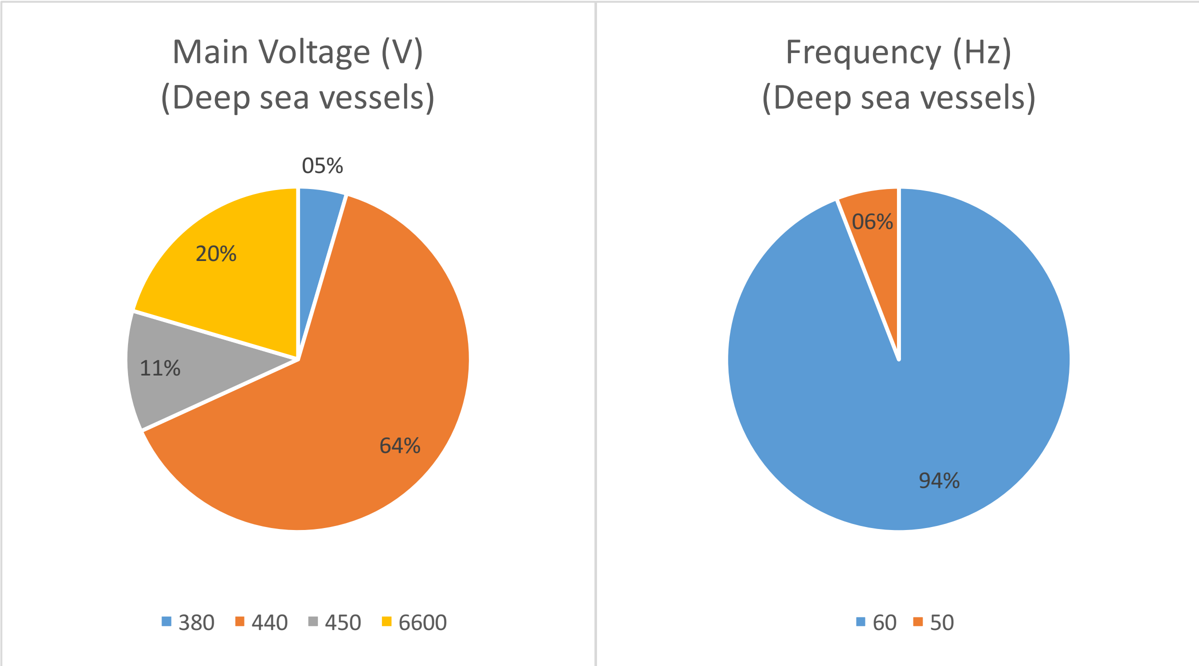


Figure 12 – Deep sea container vessels voltage and frequency

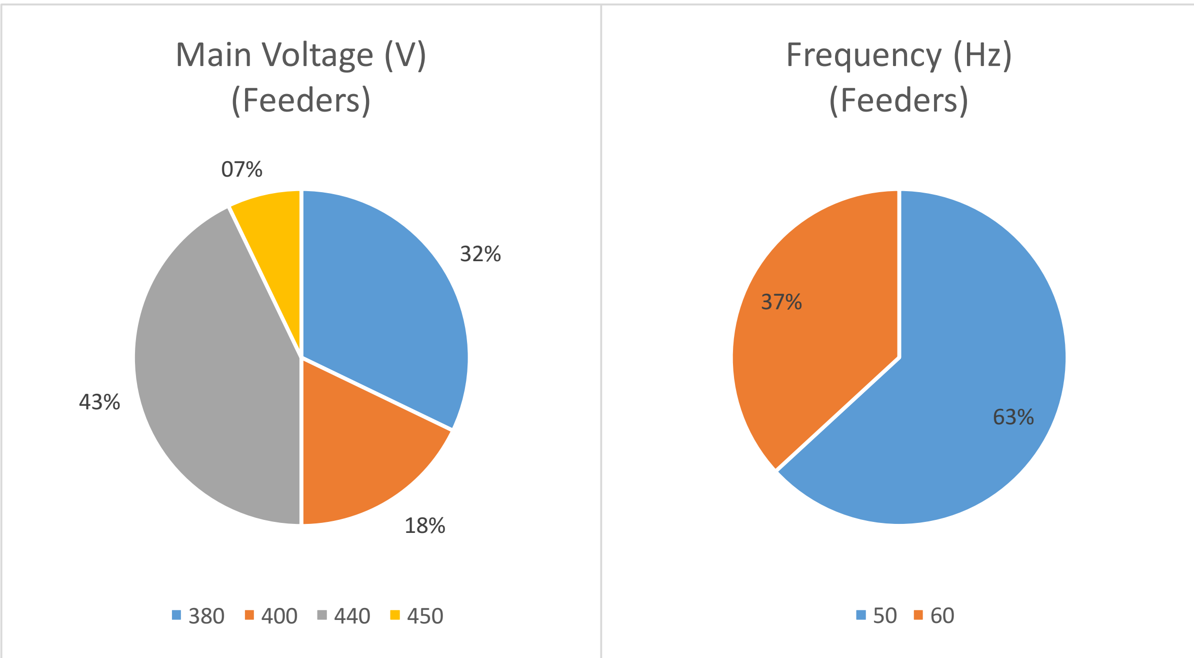


Figure 13 – Feeder container vessels voltage and frequency

The most significant conclusions from this power demand study are:

-The reported power demand at berth varied significantly even between vessels of the same size and it seems that power demand is only partially related to the vessel characteristics such as Length, TEU Capacity or Tonnage. Number of reefer containers onboard, outside temperature or even the use of ship's cranes significantly affect power demand at berth.

-According to this research, the hoteling load varies from 100 kW to 2000kW, depending on ship size.

-Peak power consumption can reach 8000 kW under certain circumstances.

-The majority of feeder container vessels uses 50 Hz power frequency while almost all of the deep sea vessels uses 60 Hz electrical power. This indicates that 60 Hz is now the standard for large containerships while 50 Hz is still common aboard feeders.

-In general, 440V is the most common voltage onboard but newer designs of large container vessels tend to use 6600V. High voltage systems are becoming a popular choice onboard containerships for various reasons. For deep sea container vessels, a system of 6.6 kV/60Hz and 440V/60Hz should be used while for feeders a 440V/50-60Hz would be preferable.

-The vast majority of the container vessels cannot use shore side power in operational conditions and only 1 vessel out of 53 in this research could benefit from cold ironing facilities at ports.

Power demand at berth for container vessels:

- The average power consumption for deep sea container vessels is of 2 MW.
- The peak power consumption for deep sea container vessels is of 7 MW.
- The average power consumption for a feeder is of 200 kW.
- The peak power consumption for a feeder is of 1000 kW.

The 12 container vessels dataset

In the 12 container vessels dataset, information concerning more than 100 port calls of each vessel can be found. Among these, the most important are: TEU capacity, berthing time, energy consumption at each port (kWh), fuel consumption at each port, diesel generator's output, number of reefers onboard and also reefer's energy consumption. In order to calculate power demand at berth for each one of the vessels, the energy consumption at each port is divided by the corresponding berthing time. In each port, power demand varies. Power demand at each port highly depends on the amount of reefers onboard, therefore in ports that handle large amounts of reefer cargo, energy consumption is significantly higher. Let's examine the case of an 8850 TEU vessel found in that dataset. The hoteling power demand of this vessel and the amount of reefers onboard for 185 port calls can be found in the following figures.

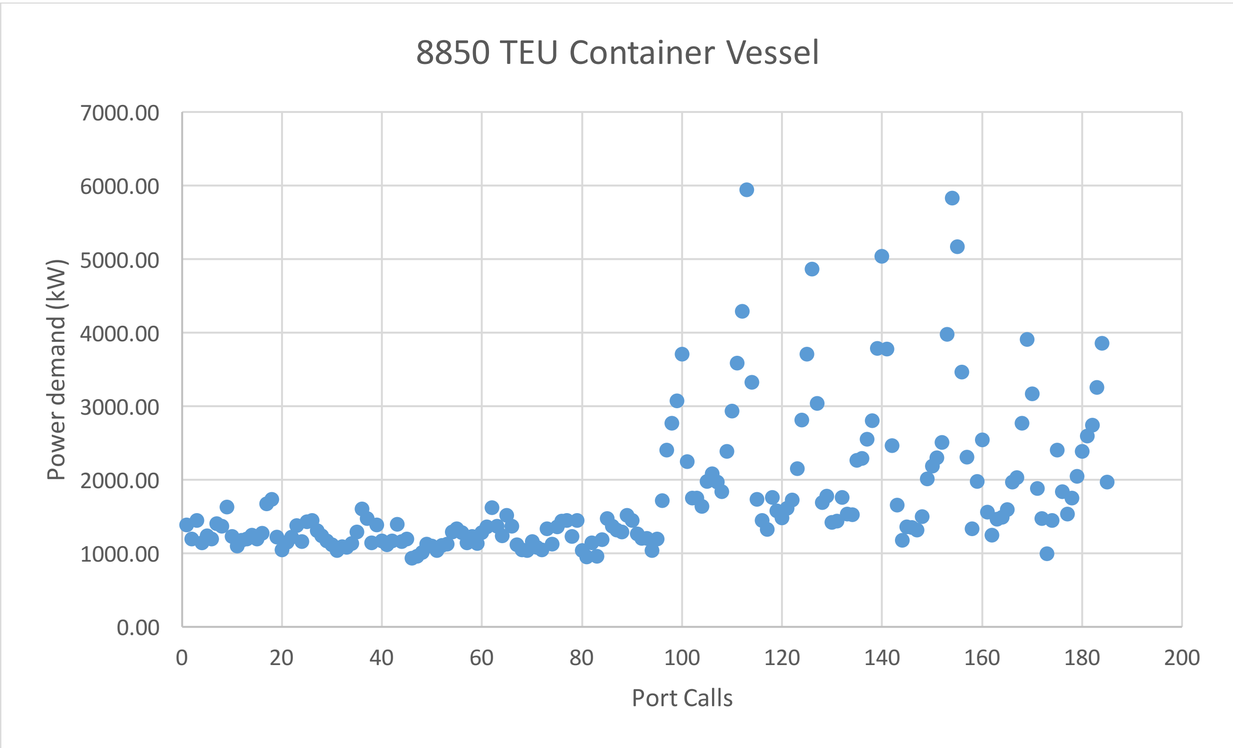


Figure 14 – 8850 TEU container vessels power demand at different ports

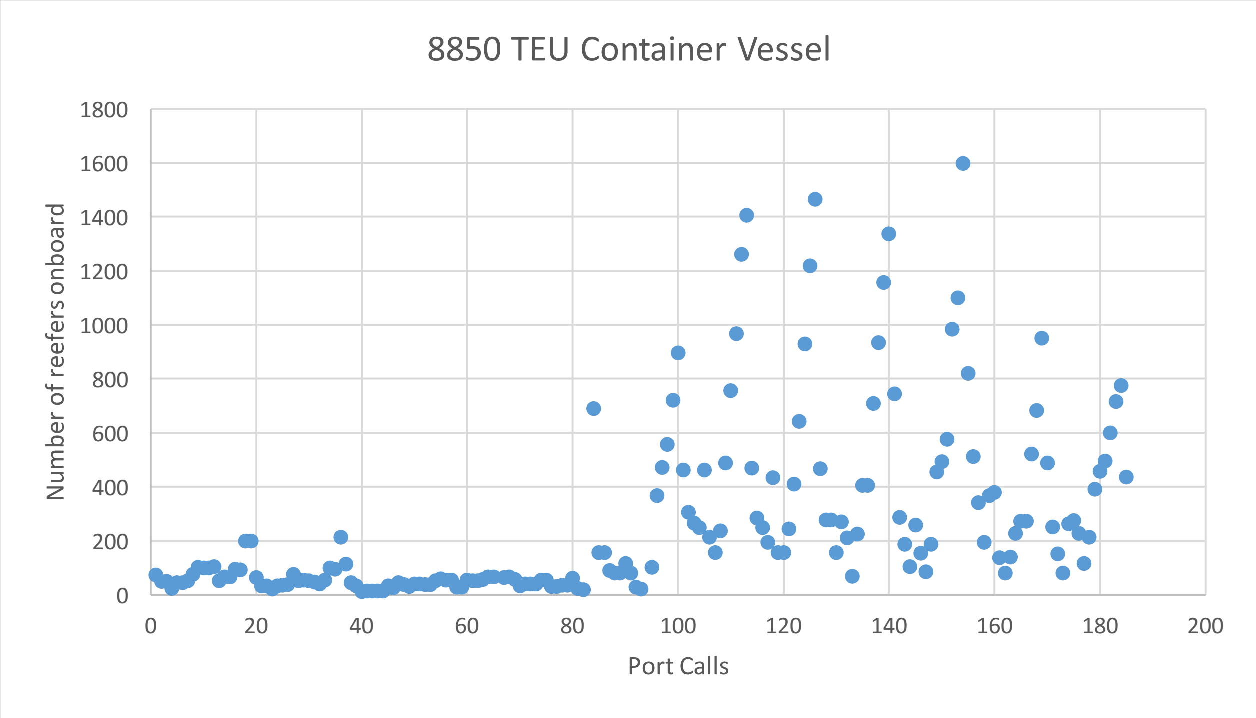


Figure 15 – Reefer containers onboard 8850 TEU vessel at different ports

The first 91 port calls were made when the vessel was operated on routes between Asia and Europe via the Suez channel while the remaining port calls were made when the company operated the ship between South America and Europe were the transportation needs of refrigerated cargo are higher. The refrigerated cargo is loaded from ports in South America and unloaded in ports of Europe, which is why power demand increases and decreases periodically. It is obvious that the significant increase in hoteling power is due to the increased amount of reefers handled. Another representative example of this remark can be found in a 3075 TEU container vessel with 830 reefer connection points which is operated in round trips between Ecuador, Panama and Europe. Reefer cargo is loaded in Ecuador and Panama (mostly bananas) and unloaded in several ports in Europe. The Power demand/Port call and Reefer onboard/Port call figures are of high importance.

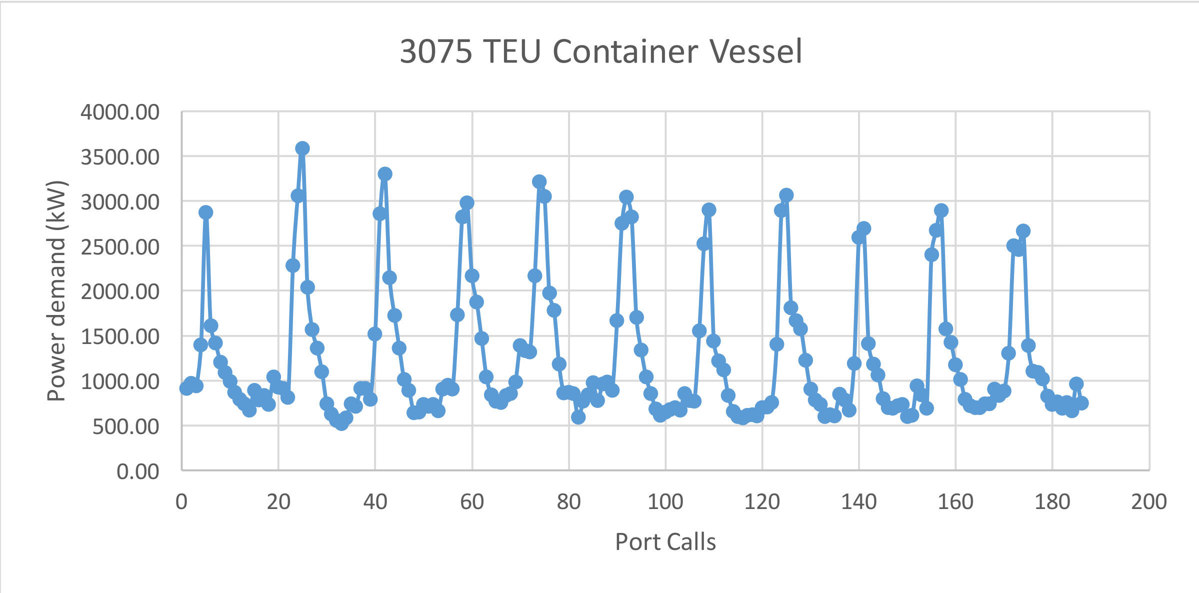


Figure 16 – Power demand while at berth in different ports

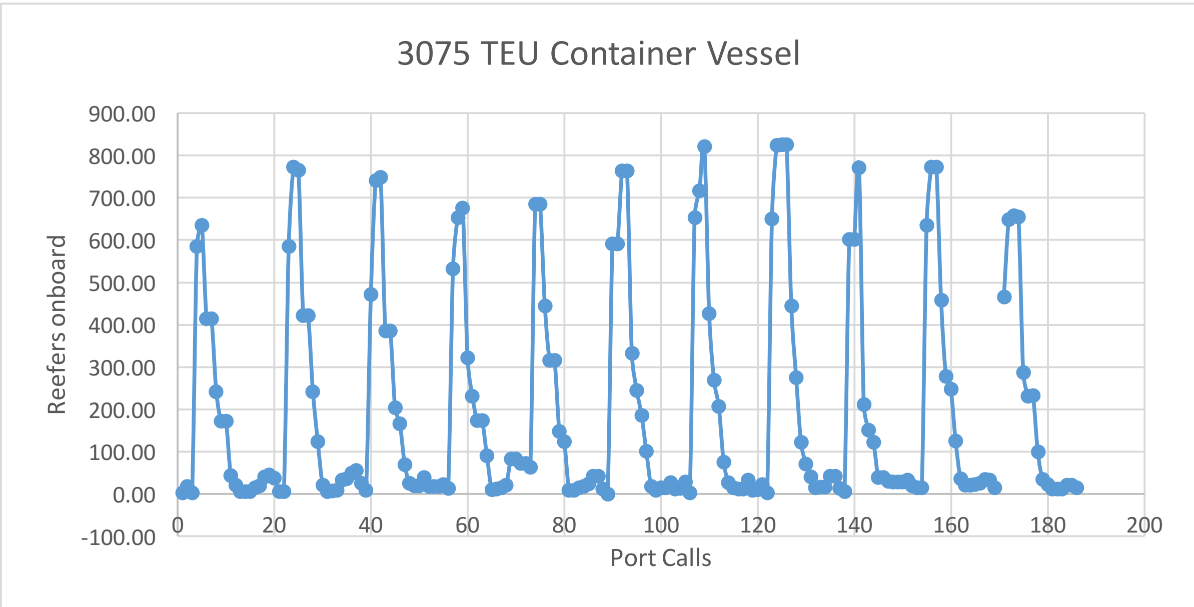


Figure 17 – Number of reefer containers onboard the vessel while at berth in different ports

For Piraeus port, unfortunately no information is available about reefer container handling and therefore an average value of the power demands in total will be considered as representative. The following figures will present the power consumption of the 12 vessels while at berth at various ports around the globe.

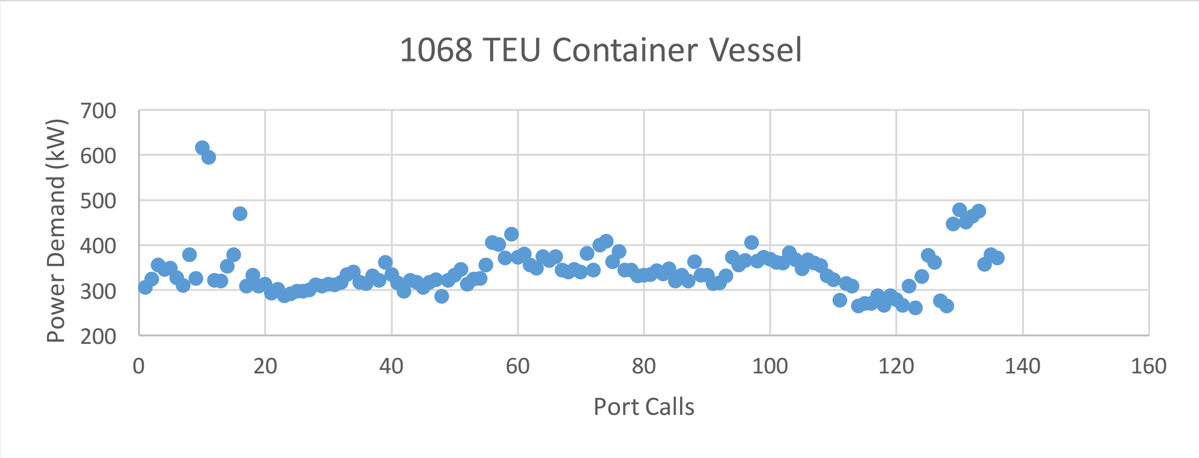


Figure 18 – Hoteling load of a 1068 TEU Container vessel in various ports

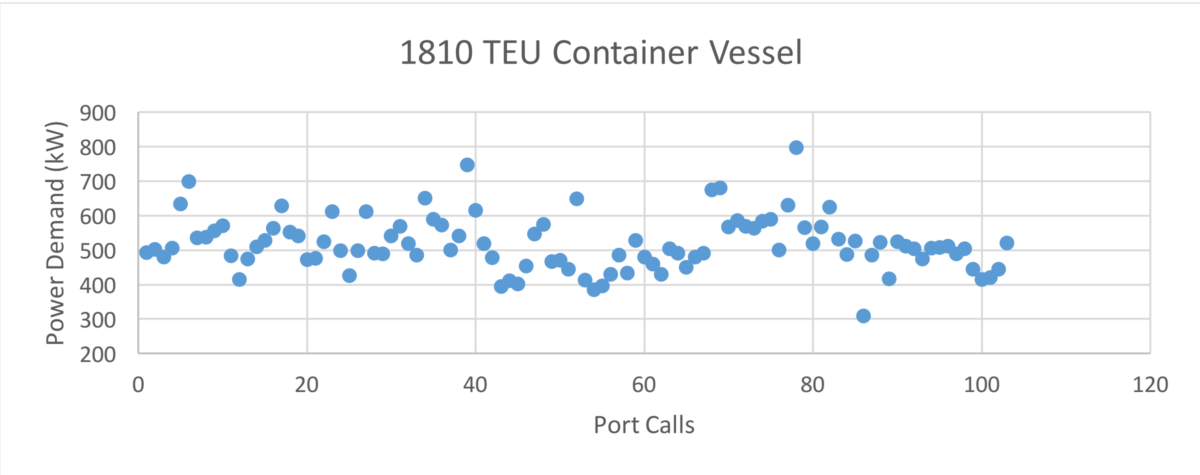


Figure 19 – Hoteling load of a 1810 TEU Container vessel in various ports

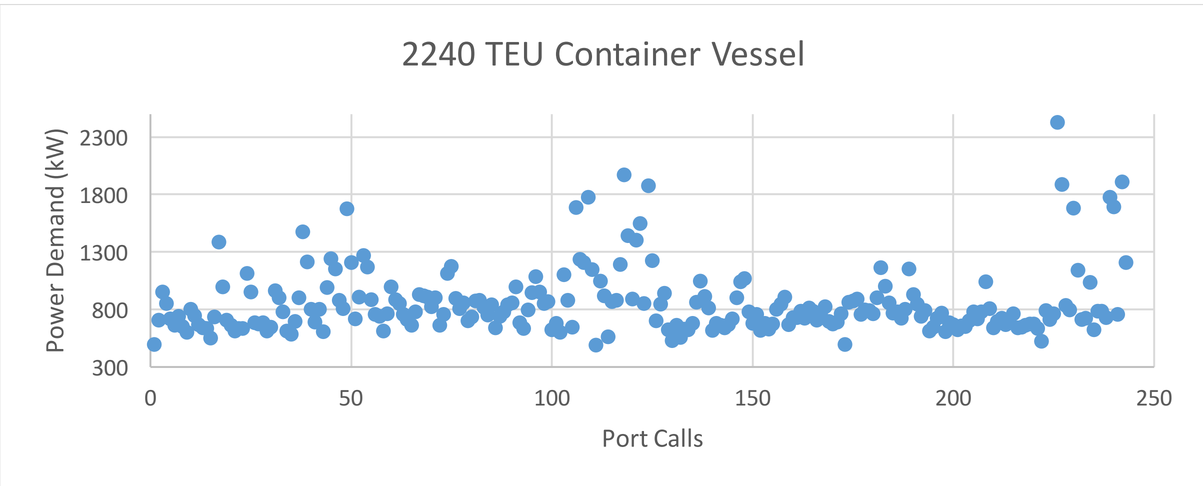


Figure 20 – Hoteling load of a 2240 TEU Container vessel in various ports

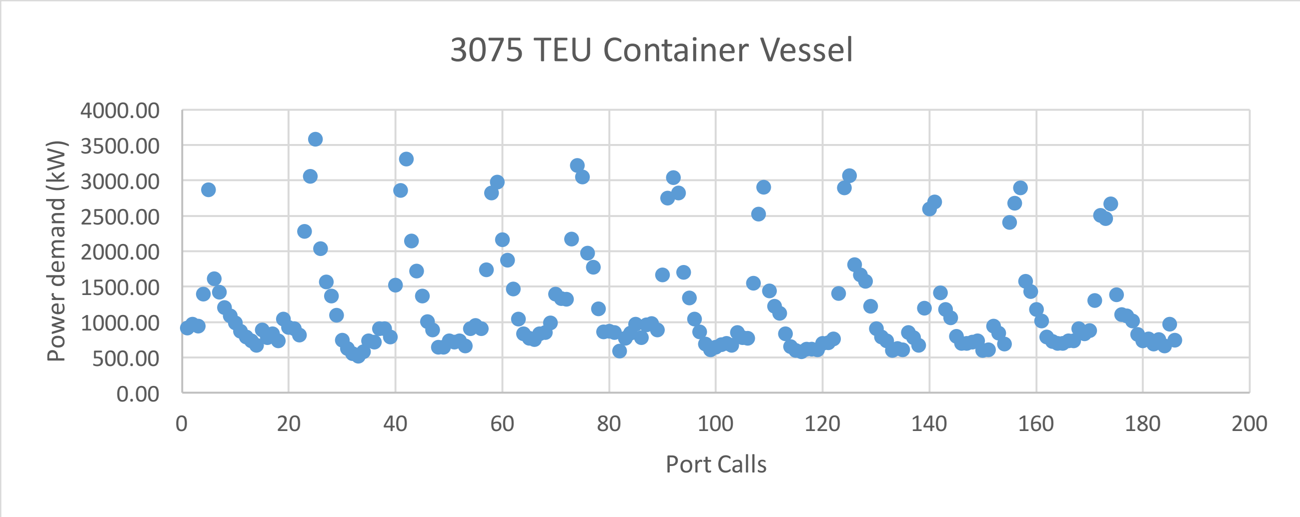


Figure 21 – Hoteling load of a 3075 TEU Container vessel in various ports

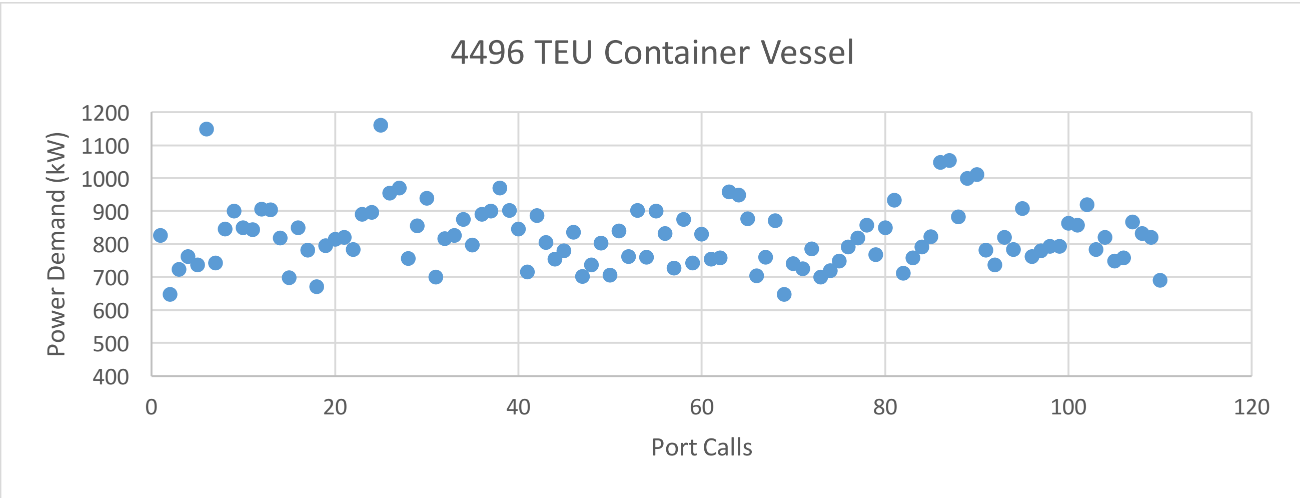


Figure 22 – Hoteling load of a 4496 TEU Container vessel in various ports

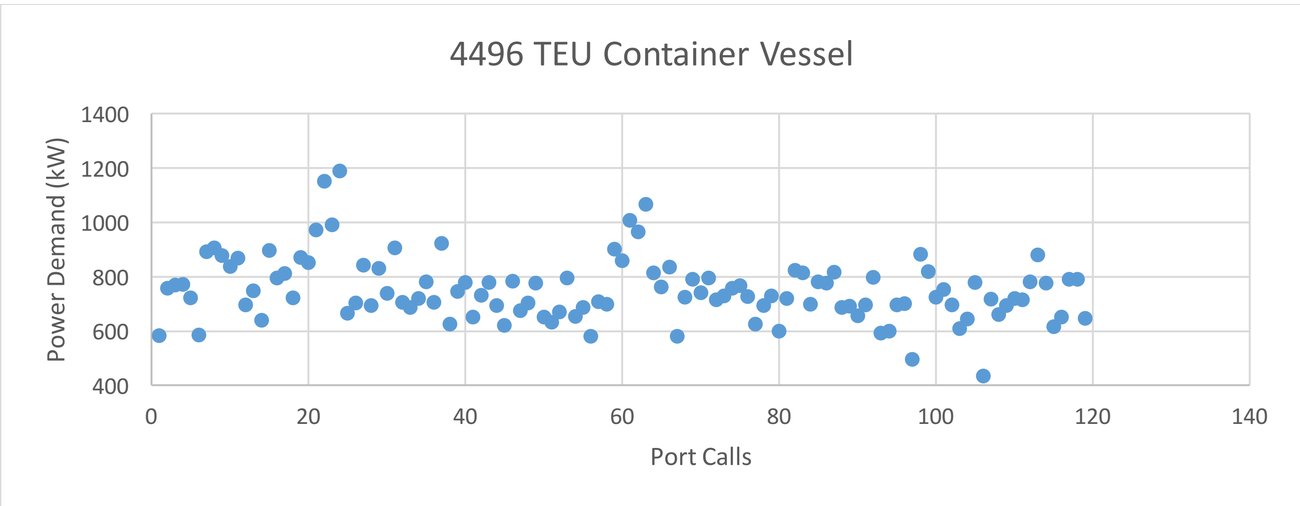


Figure 23 – Hoteling load of a 4496 TEU Container vessel in various ports

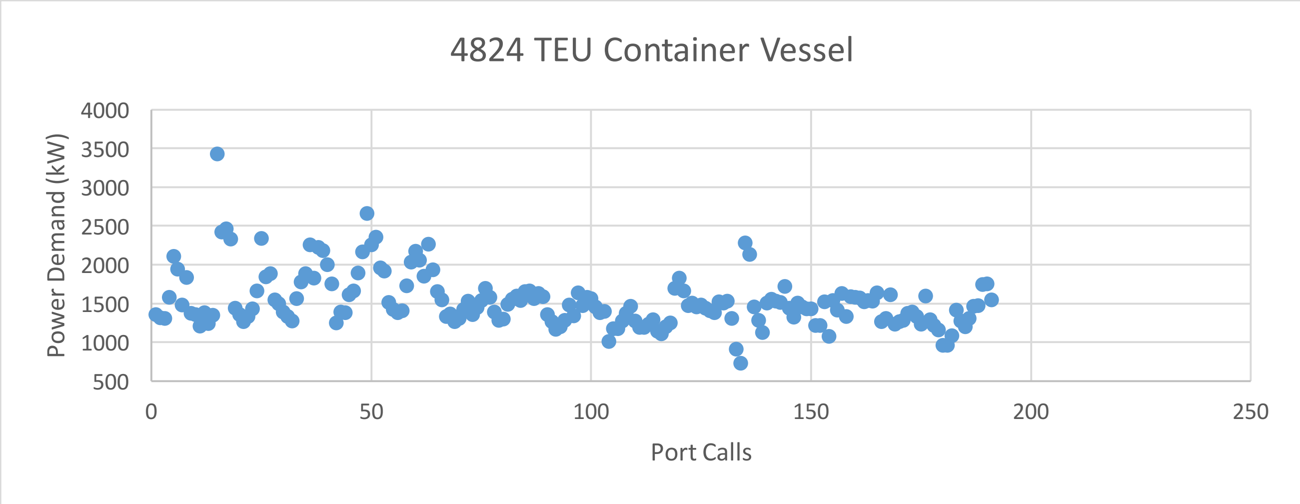


Figure 24 – Hoteling load of a 4824 TEU Container vessel in various ports

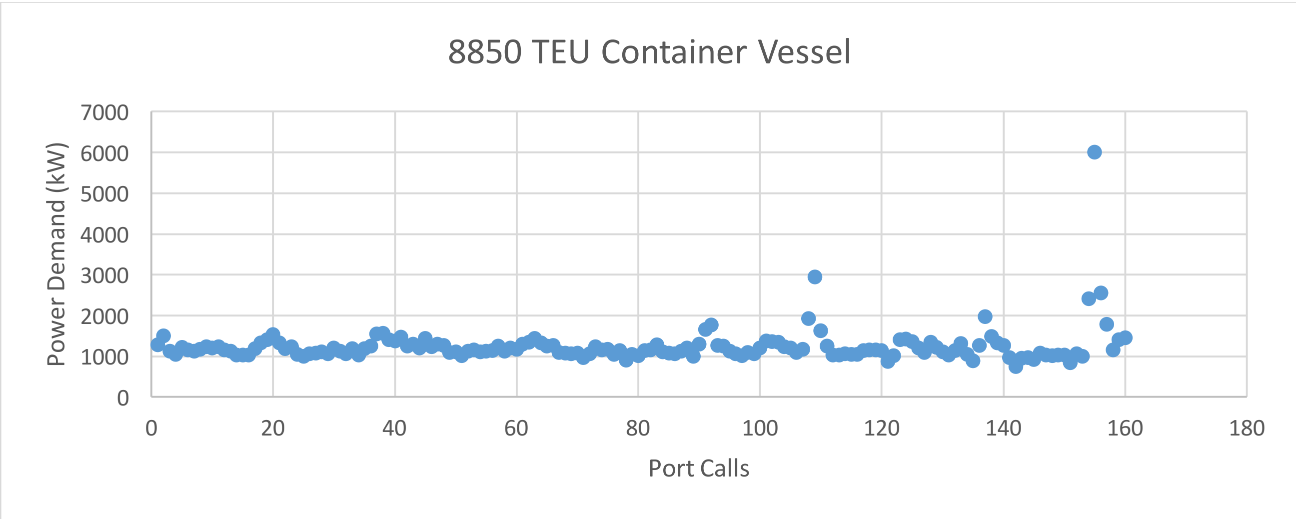


Figure 25 – Hoteling load of a 8850 TEU Container vessel in various ports

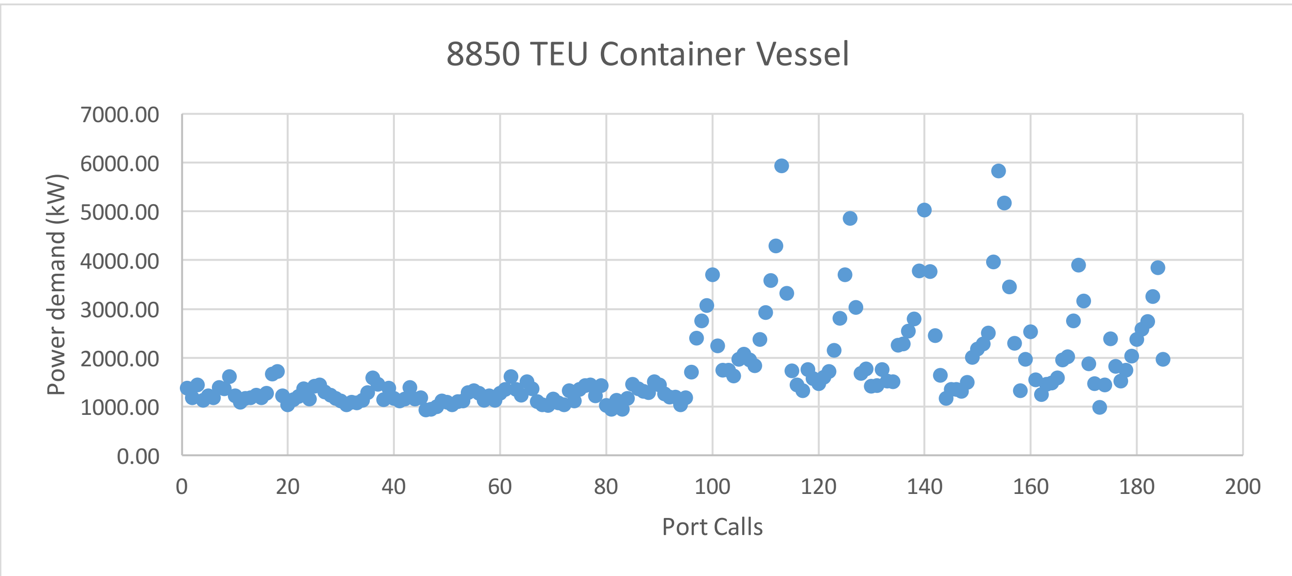


Figure 26 – Hoteling load of a 8850 TEU Container vessel in various ports

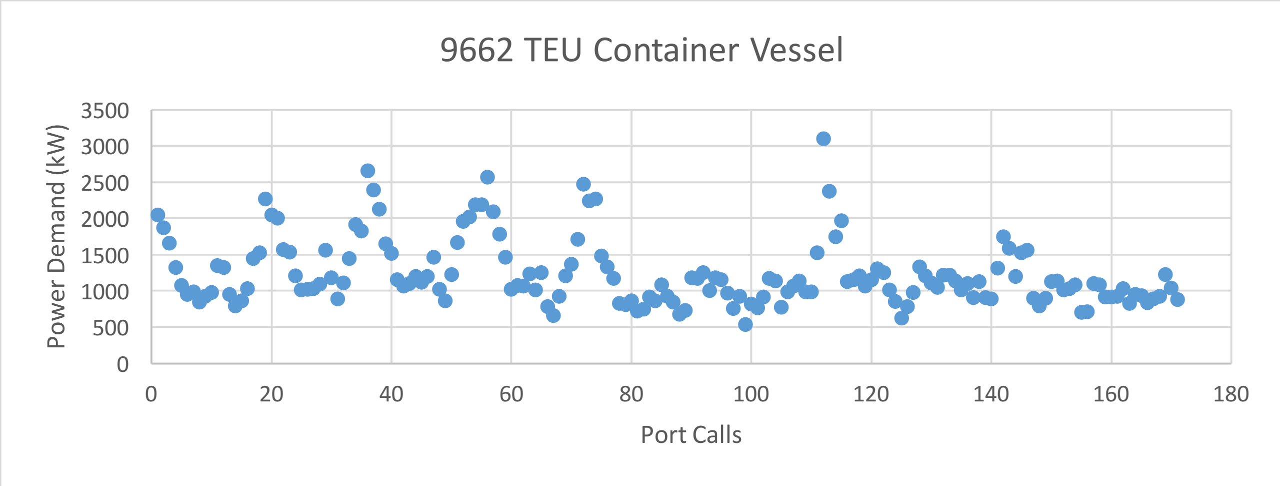


Figure 27 – Hoteling load of a 9662 TEU Container vessel in various ports

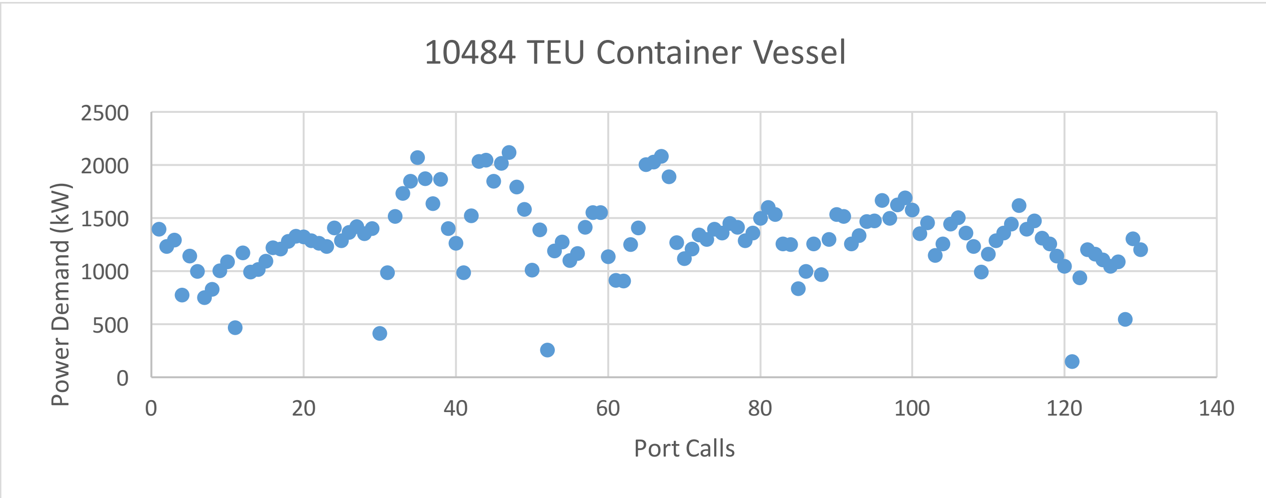


Figure 28 – Hoteling load of a 10484 TEU Container vessel in various ports

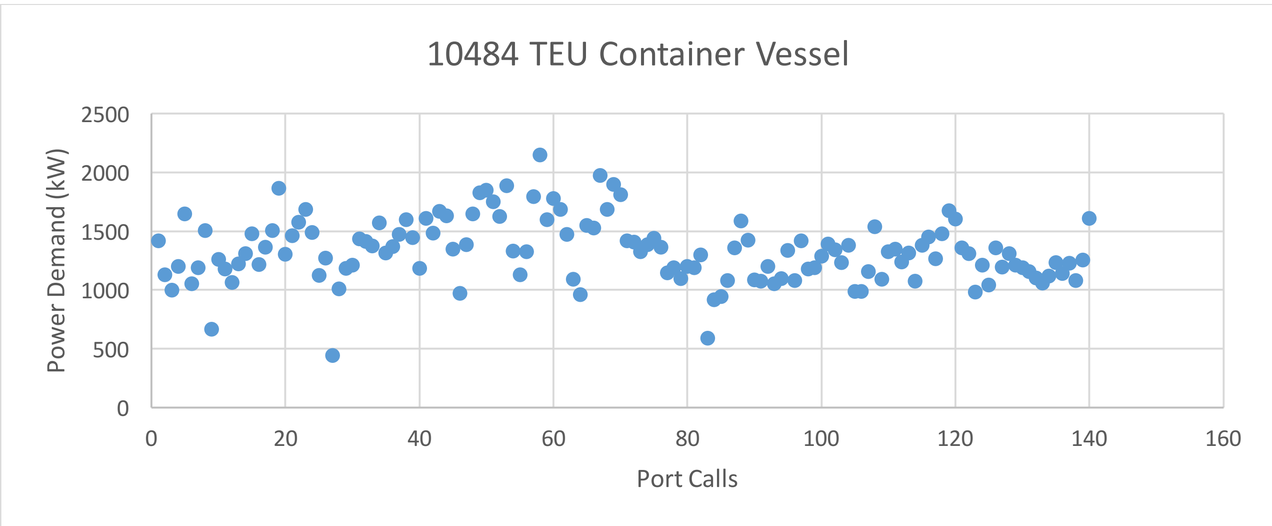


Figure 29 – Hoteling load of a 10484 TEU Container vessel in various ports

Results of the study:

- The number of the reefer containers aboard the vessel leads to a significant increase in power demand at berth. This is why power consumption of the vessels in figures 19,20,21,26,27,28 has great fluctuation while power consumption of vessels in figures 18 and 25 is almost stable. Demands of the market and the operational area of the vessel determine the amount of transferred reefers and that is why in some cases power demand varies highly between ports while in other cases power demand remains almost stable.
- Onboard lifting appliances (cranes, winches) require a noticeable amount of electrical power. For example, the 4496 TEU (figures 22,23) vessel which participated in the research shows a significant fluctuation of the power demand at berth even if the amount of reefer containers aboard is low (around 50). This increased power demand can be explained due to the use of the ship's cranes for loading and unloading of the cargo at ports without the adequate facilities.
- Even sister ships can have a different power consumption profile when operated in different areas/markets (figures 22,23).
- The average hoteling load is of 1500 kW while the peak power load can reach up to 6000 kW. In hoteling, the average load factor is 13% (8%-18%) and the peak load factor is 27% (15%-48%).

Table 28 – Average and Peak power consumption at port, D/G Load factors

TEU	Hoteling Load		Total D/G Output	Load Factor	Peak Load Factor
	Average	Max			
1068	344	616	3645	0.09	0.17
1810	518	796	5160	0.10	0.15
2240	857	2426	7832	0.11	0.31
3075	1236	3586	7760	0.16	0.46
4496	910	1262	6150	0.15	0.21
4496	751	1188	6150	0.12	0.19
4496	825	1161	6150	0.13	0.19
4824	1529	3431	8640	0.18	0.40
8850	1243	5938	12500	0.10	0.48
9662	1238	3099	14936	0.08	0.21
10484	1331	2146	9600	0.14	0.22
10484	1320	2122	9600	0.14	0.22
Average				0.13	0.27

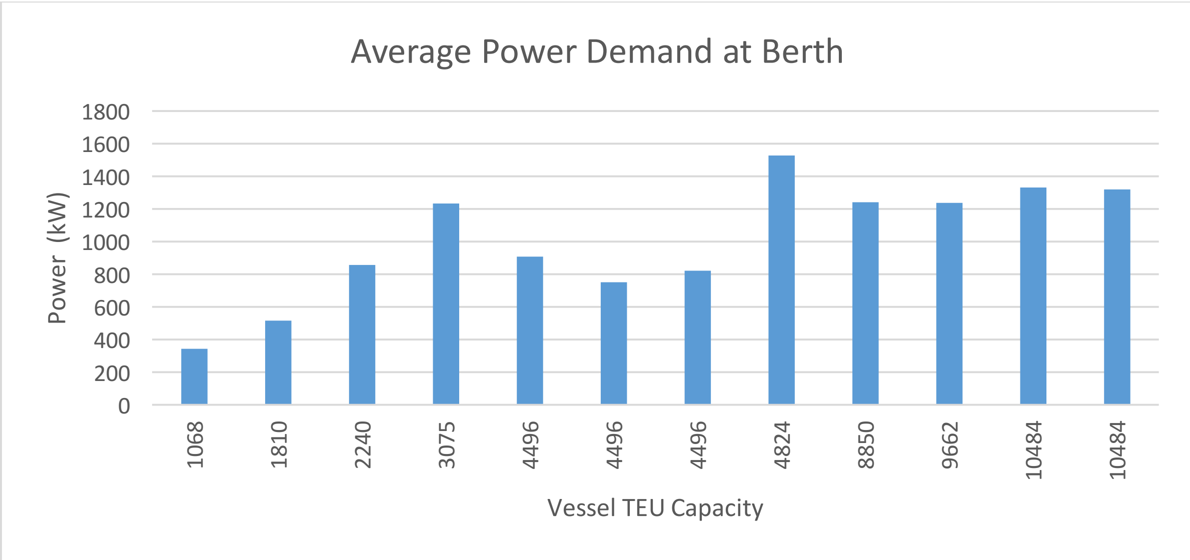


Figure 30 – Average power demand at berth

3.3.4 Fuel Consumption and Emissions

Four exemplary vessels of 2240, 4496, 9660 and 10484 TEU will be examined in order to calculate fuel consumption and exhaust gas emissions during docking at Piraeus Container terminal. The method that will be used is the same that was used in order to calculate fuel consumption and emissions for cruise ships in 3.2.5. Fuel consumption and emissions are calculated using available data from 2 major marine engine manufacturers. All calculations are done with the acceptance that auxiliary engines are running on Marine Gas Oil (MGO) and at a 75% and 50% Load respectively and also assuming a generator efficiency of 95%.

Table 29 – Fuel consumption of 4 exemplary container vessels

Vessel	TEU Capacity	Hotelling Load (kW)	Fuel Consumption at 75% (mt/h)	Fuel Consumption at 50% (mt/h)
Ship 1	2240	857	0.168	0.174
Ship 2	4496	910	0.178	0.185
Ship 3	9660	1238	0.243	0.252
Ship 4	10484	1330.73	0.261	0.270

Berth time is needed so the actual fuel consumption and emissions during the ship's stay at port can be calculated. Based on Piraeus Container Terminal (PCT) schedule which is available online, the average berth time is 19 hours. Using the information available from the 12 container ships sample, shown in table 58 (Appendix I) the average berth time can be calculated at 29 hours. To compensate for this 10-hour difference, an average berth time of 24 hours is used in the calculations.

Table 30 – Fuel consumption during a 24 h berth

Vessel	TEU Capacity	Hotelling Load (kW)	Berth Time (h)	Fuel Consumption at 75% (mt/berth)	Fuel Consumption at 50% (mt/berth)
Ship 1	2240	857	24	4.032	4.180
Ship 2	4496	910		4.281	4.438
Ship 3	9660	1238		5.828	6.042
Ship 4	10484	1331		6.263	6.492

Table 31 – Auxiliary engine emissions during a 24 h berth

Vessel	TEU Capacity	Hotelling Load (kW)	Berth Time (h)	CO_2 (t/berth)	SO_X (t/berth)	NO_X(t/berth)
Ship 1	2240	857	24	12.132	0.206	0.199
Ship 2	4496	910		12.881	0.218	0.211
Ship 3	9660	1238		17.536	0.297	0.288
Ship 4	10484	1331		18.843	0.319	0.309

Almost 190 container vessels visit Piraeus Container Terminal in a monthly basis for loading and unloading of cargo. Using average values for hoteling power, fuel consumption and exhaust gas emissions, it can be shown that 990 tons of fuel are used every month for the power needs of the container vessels berthed at Piraeus terminal. Almost 3000 tons of CO_2, 50 tons of SO_X and 48 tons of NO_X are produced, harming the environment and leading to a significant air quality deterioration of the highly dense urban areas nearby.

Table 32 – Prediction of yearly emissions in Piraeus Container Terminal

	Energy (GWh)	Fuel (t)	CO_2	SO_X	NO_X	PM
(/year)	59.32	11843.04	34993.37	593.11	574.13	34.99

3.4 Comparison of emissions between onboard and shore electricity generation

Electricity in Greece is produced with various methods. An important fraction of the total production (30%) comes from the lignite power plants which are rather pollutant but are still in use because of the great lignite availability in Greek soil. Almost 20% of the electricity is produced in natural gas power plants and another 20% comes from power exchange from Italy, Bulgaria, FYROM and Albania. Renewable energy from solar power, wind power and hydroelectric power accounts for 20% of the total electricity generation.

Table 33 – Electricity generation in Greece by type (January-March 2016)

January - March 2016		
Type	GWh	%
Natural Gas	2458	19.22%
Lignite	3862	30.20%
Hydroelectric	1224	9.57%
Renewable Sources	1460	11.42%
Exchange	2722	21.29%
Other	1061	8.30%
Total	12787	

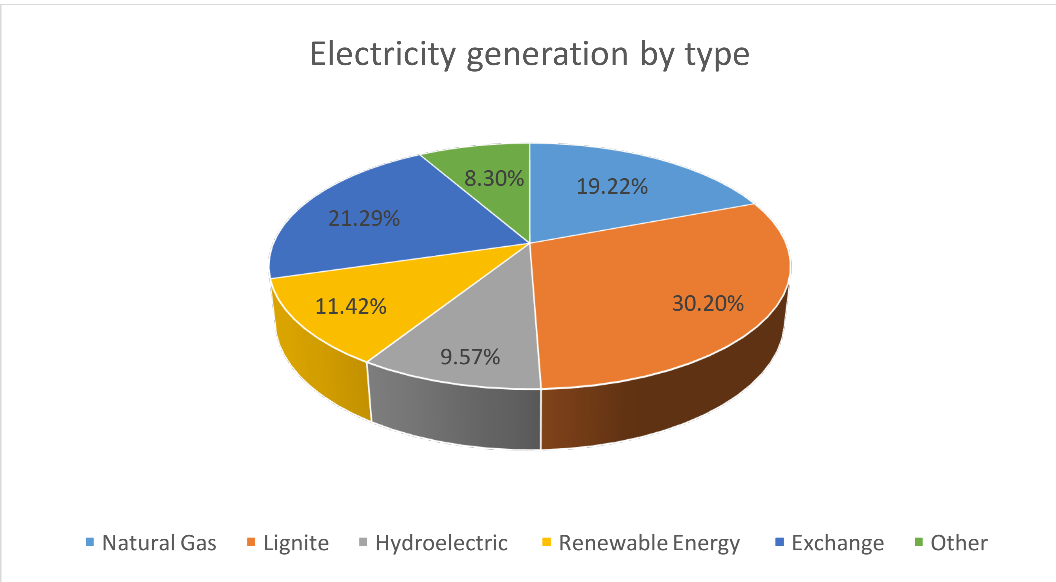


Figure 31 – Electricity generation in Greece by type (January-March 2016)

Based on information which is available in the annual reports of the Public Power Corporation[10,25], the methods of electricity generation can be categorized based on their emissions of CO_2, SO_X, NO_X and PM in g/kWh. Lignite power plants are the most polluting with almost 1000grams of CO_2 and 2.8 grams of SO_X per generated kWh of electricity. In general, lignite and natural gas power plants in Greece are located far from populated cities and therefore there is a small percentage of the population that is directly affected by their emissions. Macroscopically, electricity generation in Greece contributes to air pollution with 403 g of CO_2, 0.85 g of SO_X, 0.75 g of NO_X and 0.31 g of PM per generated kWh.

Table 34 – Emissions from energy generation in Greece

Type	Usage	CO_2	SO_X	NO_X	PM
	%	g/kWh			
Natural Gas	19.223%	548.844	0.020	0.300	0.030
Lignite	30.203%	984.290	2.800	2.300	1.020
Hydroelectric	9.572%	0.000	0.000	0.000	0.000
Renewable Energy	11.418%	0.000	0.000	0.000	0.000
Exchange	21.287%	0.000	0.000	0.000	0.000
Other	8.297%	0.000	0.000	0.000	0.000
Total		**402.783**	**0.850**	**0.752**	**0.314**

Table 35 – Emissions of diesel generators based on manufacturer's project guide

Emissions			
Fuel: 2.5% w/w sulphur			
CO_2		590	g/kWh
SO_X		10	
NO_X		9.68	
PM	Soot	0.3	
	Fuel Ash	0.25	
	Lub. Oil Ash	0.04	

Comparing shore power emissions with those of onboard electricity generation, provided by the engine manufacturers, the obvious conclusion is that shore power is a far greener option. With the use of shore-side power ship owners can achieve a reduction of 32% in CO_2 emissions, 92% in SO_X and NO_X emissions and 47% in PM emissions. The use of shore power would positively affect air quality in the urban areas nearby Piraeus port and significantly ameliorate

Piraeus city quality of life. Even in Greece, where renewable sources like solar or wind power act as supplement in power generation and combustion of lignite is still the main source of power, it is eventually proven that using shore power is greener than generating electricity onboard. Because of Greece's climate, sunshine and winds, it is logical to assume that renewable sources will gain ground in the future, allowing for a further decrease in emissions and air pollution. In order to quantify the potential reduction of ship's emissions during their stay at berth, it is useful to examine and compare the yearly emissions of each vessel type (ferries, cruise vessels, container vessels) when electricity is generated onboard and when electricity is provided by shore-side facilities. The following figures show the decrease in emissions when all vessels at berth use shore power.

Table 36 – Annual emissions using diesel generators or shore-side power

Using Diesel Generators					
	Fuel (t/year)	CO_2 (t/year)	SO_X (t/year)	NO_X (t/year)	PM (t/year)
Ferries	6445	20775	352	341	21
Cruise	16642	53645	909	880	54
Containers	11843	35000	593	574	35
Using Shore-side electricity					
Ferries	0	14127	28.16	27	11
Cruise	0	36478	73	70	28
Containers	0	23800	48	46	19
Reduction	**-34930**	**-35015**	**-1705**	**-1652**	**-52**
Reduction %	**100%**	**32.0%**	**92.0%**	**92.0%**	**47.1%**

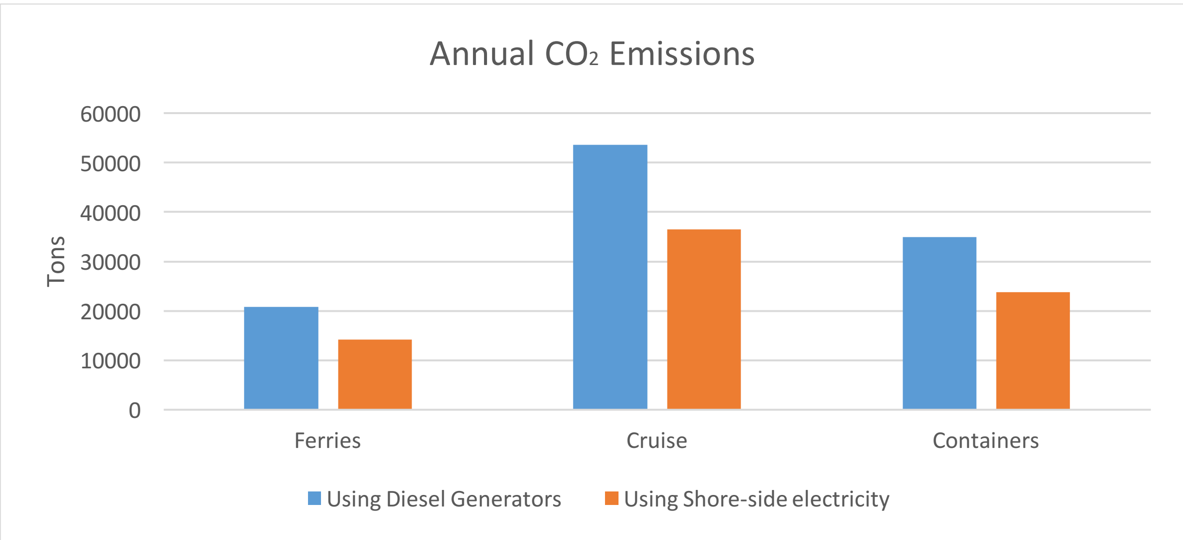


Figure 32 – Annual CO_2 emissions

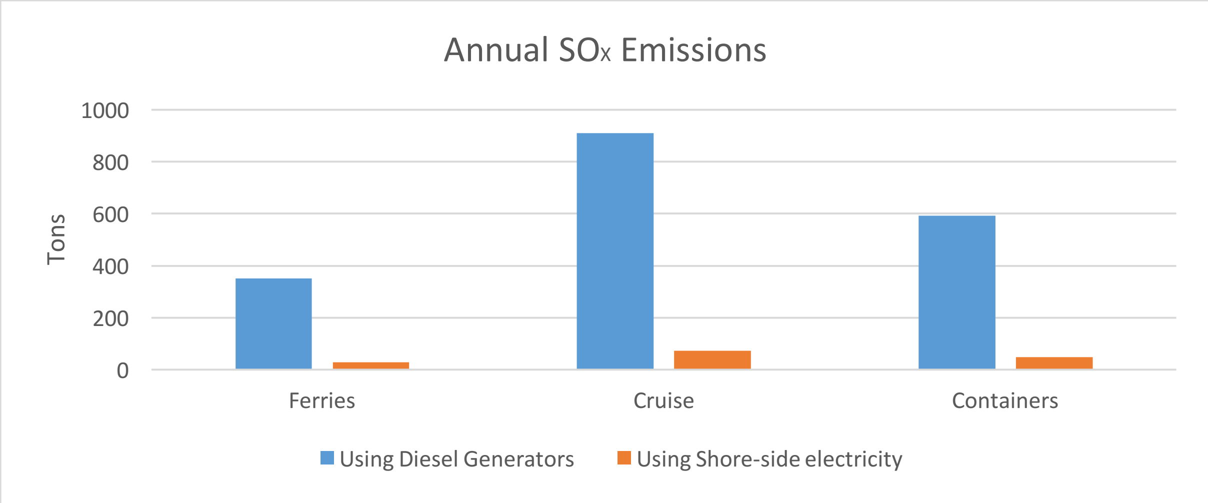


Figure 33 – Annual SO_X emissions

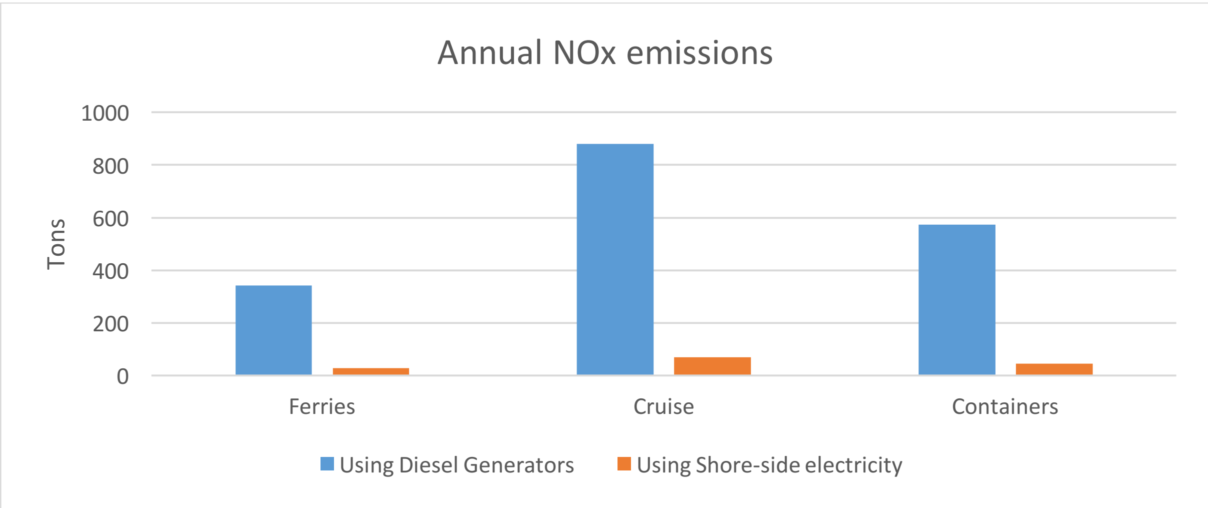


Figure 34 – Annual NO_X emissions

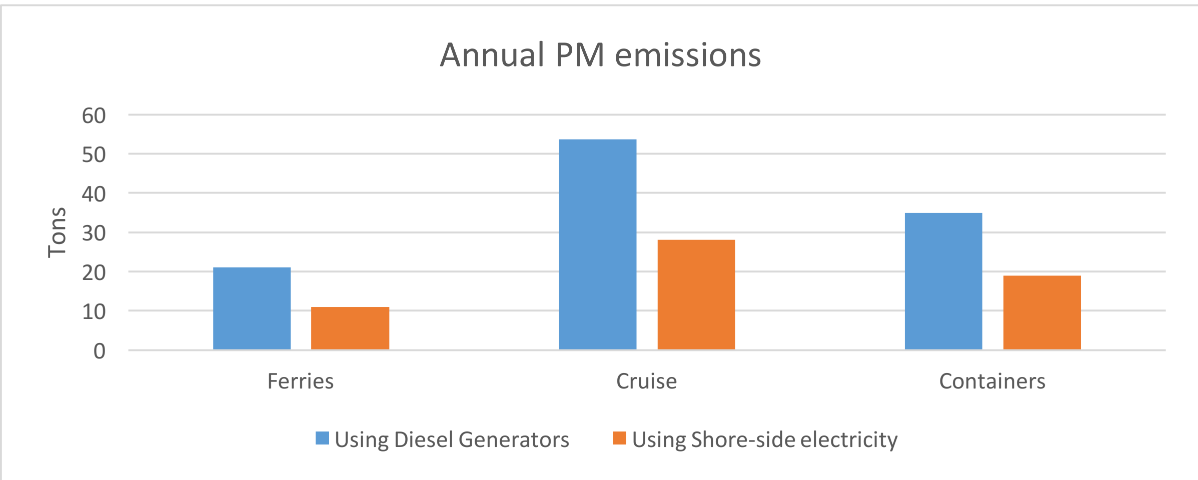


Figure 35 – Annual PM emissions

4. Port infrastructure

4.1 Shore-side Installations

4.1.1 Typical configuration according to the European Union

In November 2002, in order to reduce atmospheric emissions from seagoing ships, the European Commission adopted a strategy which urged port authorities to require, incentivize or facilitate ship's use of land-based electricity while they stay at berth (Recommendation 2006/339/EC)[6]. To this direction, the European Commission has proposed a typical configuration and requirements for a shore-side electricity connection system between the national grid and berthing vessels. According to this configuration, the process of Cold Ironing is divided into 8 steps. A graphic overview of this shore-side configuration can be found in Picture 2, 2.1.3

1. A connection to the national grid carrying 20-100 kV electricity from a local substation, where it is transformed to 6-20 kV.
2. Cables to deliver the 6-20 kV power from the substation to the port terminal.
3. Power conversion, where necessary. (Frequency transformer).
4. Cables to distribute electricity to the terminal. These might be installed underground within existing or new conduits.
5. A cable 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 high voltage electricity to 400 V.
8. The electricity is distributed around the ship and the auxiliary engines are switched off.

This configuration which is proposed by European Commission is a form of decentralized topology as the frequency converter is installed really close to the berthing place of the vessel. Due to this fact, this solution has a significant drawback. When designing and dimensioning the frequency converter, the engineer has to make sure that the equipment can accommodate the vessel which has the highest power demand. For example, if this solution was to be adopted for Piraeus coastal shipping terminal, every frequency converter should have a power output of 2800 kW in order to provide electricity to the vessel with the highest power demand. Therefore, this configuration will not be able to make use of the overcapacity of the frequency converter when a vessel with a lower power demand is connected to the system.

Another important issue is that of galvanic isolation. Galvanic isolation is the principle of isolating functional sections of electrical systems to prevent unwanted current flow. No direct conduction path is permitted but energy and information can still be exchanged between the sections of the electrical system by other means such as electromagnetic induction. With the proposed configuration of the European Commission there is a chance that a vessel uses the same voltage as the supplied from the shore. In this case, the lack of the transformer leads to a total lack of galvanic isolation between the vessel and the electric system on land.

Of course, the fact that each berthing place is equipped with a frequency converter can be seen as an advantage if a fault occurs at the system. If one of the frequency converters is damaged, it can be disconnected from the system so that other berths can operate separately. Moreover, maintenance planning and servicing are easier this way.

4.1.2 Centrally placed frequency converter

In order to surpass the two significant drawbacks of this configurations, a different one will be proposed. This configuration was proposed by Patrik Ericsson and Ismir Fazlagic' in their Master of Science Thesis in Chalmers University of Technology[8]. This model consists of a main, centrally placed installation for the frequency converter with matching switchgears and double busbars. The frequency converter is coupled via a transformer to the one of the busbars and in order to enable simultaneous connection of 50 Hz and 60 Hz vessels, the second busbar is connected to the national grid. In this way, each berth place can be fed via a breaker and a change-over switch with current of the desired frequency. A voltage transformer is installed in each berthing place in order to decrease voltage to 6600 V e.g. Also, the voltage transformer provides the necessary galvanic isolation between the vessel and the shore electrical system and it acts as the last link between the two electrical systems. If a fault occurs onboard a vessel, there is good chance that the transformer will reduce the fault current and decrease the risk of a potentially fatal propagation of the fault.

With this configuration, it is possible to take advantage of the frequency transformer's power capacity in a more efficient way. When there is need for 60 Hz current, the frequency converter is used but when 50 Hz current is needed, the frequency converter can be bypassed via the double busbar configuration. That results in higher efficiency as the converter is not burdened by the 50 Hz vessels. Also, this method allows for a better space allocation inside the port as far less space is required for equipment installation. Moreover, this configuration allows for future expansion of the system-if power demand at port increases- with an addition of another frequency converter parallel connected to the existing one. The disadvantage of this configuration is that in case of a fault or damage to the frequency converter, the 60 Hz frequency will not be available in neither berth although the 50 Hz frequency current should be available via the 50 Hz busbar which is directly connected to the national grid.

4.2 Basic design for Piraeus port

The goal of this section is to present a preliminary design of a possible shore-side electrical installation in Piraeus port. The configuration which will be proposed can be divided into three parts. Shore-side power for coastal shipping vessels, cruise vessels and container vessels. Given that the ferry and the cruise terminal are located close to each other, their case can be examined together.

In general, electricity in the port of Piraeus is provided via the electrical grid of IPTO (Independent Power Transmission Operator) which distributes electricity produced by various companies in Greece. For both the passenger and the cargo terminal in Piraeus port, the provided electricity is of medium voltage at 20 kV / 50 Hz. Given that most cruise ships and deep sea container vessels use current of 60 Hz frequency, a frequency converter needed in both cases. The design principle for both (passenger and container) terminals is the same. Electricity is provided to the facility through a busbar at 20kV/50Hz. Voltage transformers are used so that the 20kV current is stepped down to the frequency converter's operating voltage. Depending on the power demand it is possible that more than one frequency converters are connected in parallel. Voltage transformers are used to step up the 60 Hz current to 20kV for distribution. A double busbar system which is provided with 20kV/50Hz current directly from the national grid and 20kV/60Hz current from the frequency converters via the voltage transformers ensures that the option of 50 or 60 Hz is available at every quay. The system that includes the busbars, the voltage transformers and the frequency converters is located in a centrally placed building called main substation. Each berth is provided with a transformer that reduces current voltage from 20 kV to 11/6.6 kV in case of cruise ships and containerships and 20/6.6 kV in case of ferries. The final connection socket is located in a junction box which is watertight. The cable that connects the vessel to the junction box should be provided by the vessel and in the case where the vessel's voltage is different than 11/6.6kV, an onboard transformer will be required.

4.2.1 Preliminary design of shore-side installations for passenger port of Piraeus

This subsection will focus on the preliminary design of the shore-side installation in the Ro-Ro passengers ferry terminal and the Cruise terminal in Piraeus port. Based on information found in port's schedule and www.marinetraffic.com, the number of simultaneously berthed ferries varies from 5 to 7 and as shown in 3.2.2, the number of simultaneously berthed cruise vessels is 2.8 during peak season but decreases significantly from October to March.

Ferries

As shown in chapter 3.1.2 of this report, the power demand for Ro-Ro passenger ferries in Piraeus port varies from 1100 kW for smaller ferries to 2800 kW for the bigger ones. Given that ferries berth in different times during the day, it is safe to assume that the shore-side electricity equipment will be possibly be used by more than one vessel. Therefore, dimensioning of the equipment shall be done for the ships with the higher power demand.

According to this study, only 3 of the ferries have a power demand greater than 2000 kW (2200-2800 kW) while all other ferries require 1100 to 1900 kW. However, these ferries that require 2800 kW each, are sister ships which operate between Piraeus and Crete and never berth at Piraeus port at the same time. Therefore, only one berthing place should be dimensioned for 2800 kW. Assuming a power factor of 0.8, the worst case scenario for power demand is shown in table 37.

Table 37 – Maximum power demand per ferry slot

Berthing place	kW	MVA
1	2800	3.5
2	2300	2.875
3	2000	2.5
4	1600	2
5	1600	2
Total	11900	14.875

Cruise vessels

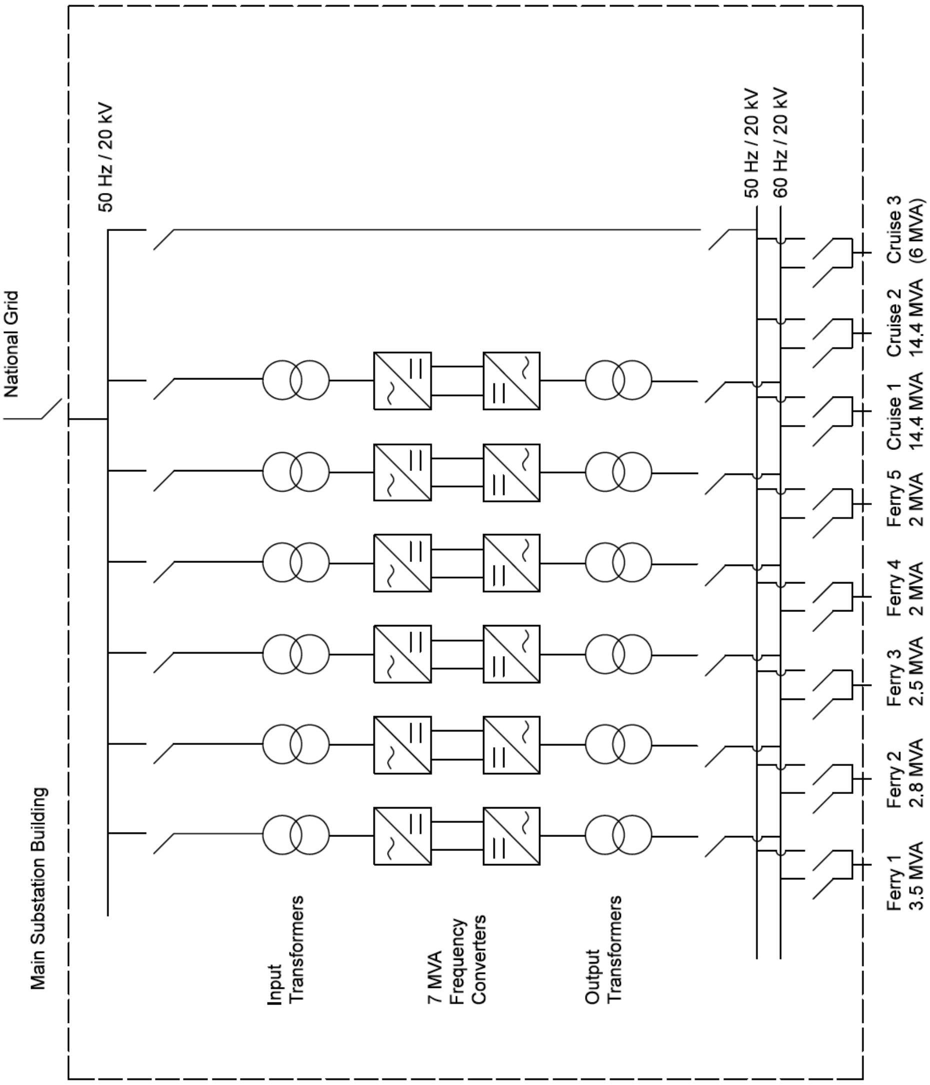
According to 3.2.3, the peak demand for cruise ships is found to be 11500 kW. The cold ironing installation should be capable of meeting the worst-case power demand scenario and also should be able to handle a possible increase in hotelling needs of cruise ships in the future. For that reason, dimensioning of the equipment should be done for a power demand of 11500 kW per vessel. However, many cruise ships that often visit Piraeus port, such as Mein Schiff 2, require significantly less power than the maximum of 11500 kW. The installation of a third berthing place that would provide electricity to cruise ships with smaller hotelling load when there is excess power would be beneficial.

Table 38 – Maximum power demand per cruise ship slot

Berthing place	kW	MVA
1	11500	14.375
2	11500	14.375
Total	23000	28.75

Main substation building

A total power output of 41.6 MVA is required in the worst-case scenario, if all berths are occupied and providing the maximum electrical power to the vessels. The most suitable equipment for our case is the ABB PCS 6000 SFC-7000[13] frequency converter with a maximum power output of 7 MVA. By using 6 of these converters in parallel connection, the nominal power output is of 42 MVA. The dimensions of each indoor cabinet are 2.5 X 4.9 X 1.2(m). Considering that voltage transformers, busbars, circuit breakers, switchgears and safety appliances also occupy a fair amount of space, the area needed for the main substation building is around 300 m^2. A schematic electrical drawing of the main substation can be found in picture 9.



Picture 9 – Schematic electrical drawing of the main substation

Power distribution

Power distribution from the main substation to all shore-side transformers should be preferably done via underground cables of medium voltage (20 kV) so that transfer losses are minimized.

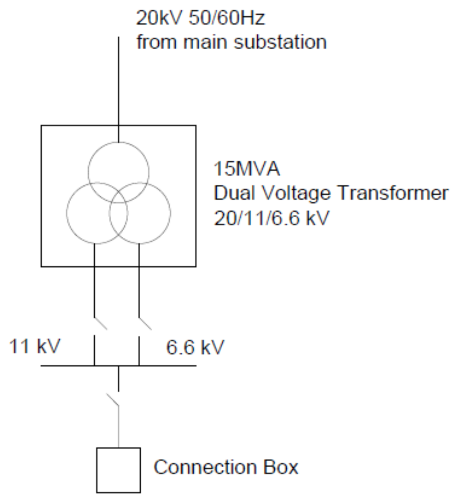
Shore-side station

Every berthing place that will be provided with shore power, will be equipped with a transformer station where the 20kV distribution current will be stepped down to 11 or 6.6 kV. Ferries' berthing places will be equipped with 20/6.6kV transformers while cruise vessels berthing places will be equipped with 20/11/6.6kV Dual Voltage transformers and voltage selection switchgears (Table 39).

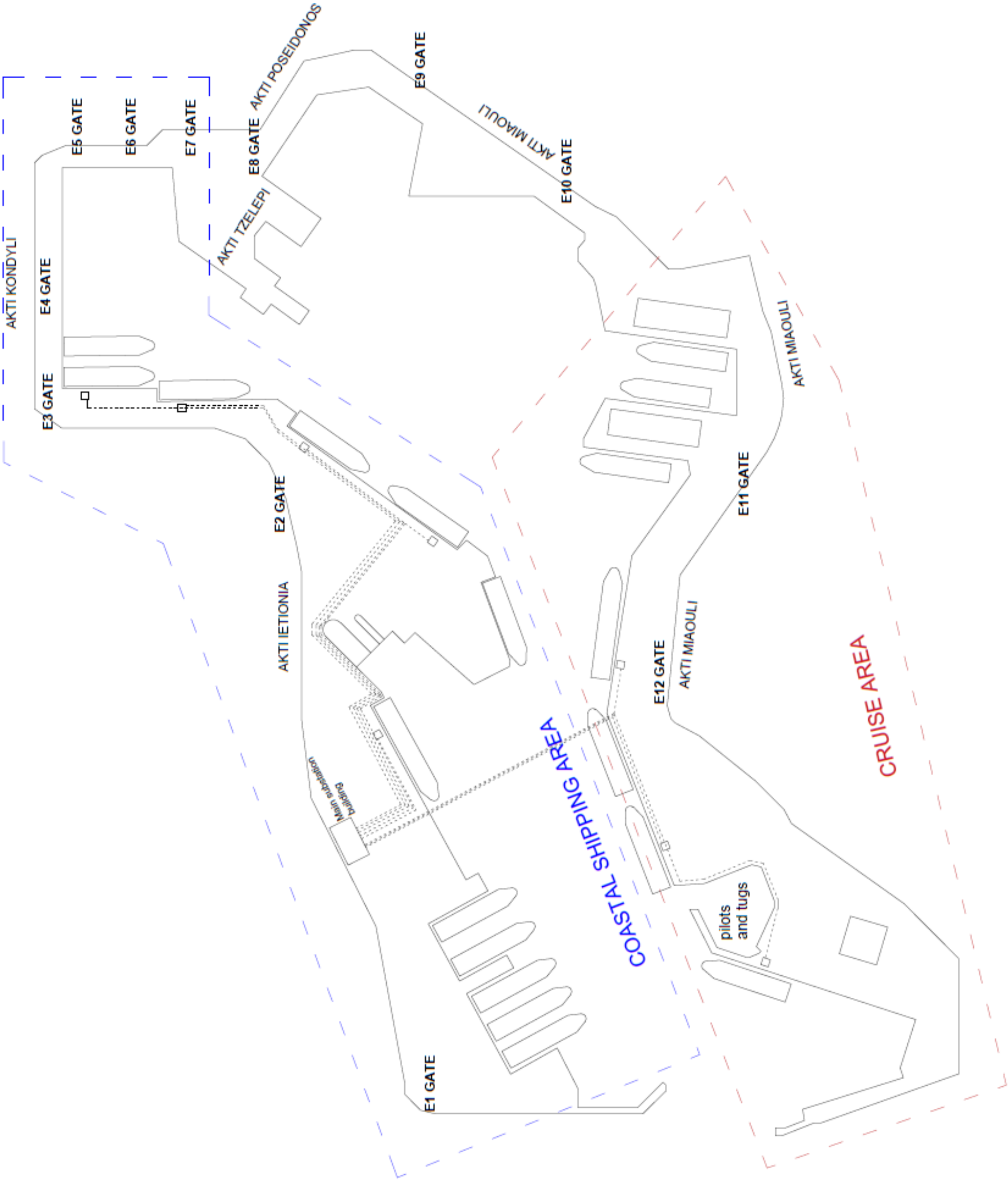
Except from stepping down voltage, the transformer also acts as a safety device. Because no direct conduction path is established in a transformer, galvanic isolation between the ship and the national grid is achieved.

Table 39 – Shore-Side transformer specifications

Berthing Place	MVA	Shore-Side Transformer	kV
Ferry 1	3.5	Single Voltage	20/6.6
Ferry 2	3	Single Voltage	20/6.6
Ferry 3	2.5	Single Voltage	20/6.6
Ferry 4	2	Single Voltage	20/6.6
Ferry 5	2	Single Voltage	20/6.6
Cruise 1	15	Dual Voltage	20/11/6.6
Cruise 2	15	Dual Voltage	20/11/6.6
Cruise 3	6	Dual Voltage	20/11/6.6



Picture 10 – Schematic electrical drawing of shore-side transformer



Picture 11 – Schematic drawing of Piraeus passenger port Cold Ironing network

4.2.2 Preliminary design of shore-side installations for Piraeus container terminal

As shown in 3.3.2, almost 190 vessels per month call at Piraeus container terminal. Considering that the average berth time is around 24 hours, it is safe to assume that on average, 6 vessels are being berthed simultaneously. Hoteling power demand of these vessels was calculated in 3.3.3 and based on the Port of Rotterdam[4] study as well on the 12 container vessel dataset, the conclusion about power demand is:

- The average power demand for container vessels of 1500-2500 TEU is 400 kW
- The average power demand for deep sea container vessels is 1500 kW
- Peak load for a feeder vessel can be up to 900 kW
- Peak load for a deep sea vessel can be up to 7000 kW
- The average peak load for deep sea vessels is 2000 kW
- Around 23% of the vessels use 50 Hz current while the rest 77% uses 60 Hz current

Main substation

Because of the difference in ship's frequency (50 or 60 Hz) it can be assumed that five out of six berths that are to be supplied with shore-side power are to be connected to ships that use 60 Hz frequency.

Due to the fact that only 2 out of 36 deep sea vessels had a peak load of 6000-8000 kW, it is not logical to dimension the shore-side equipment based on this power demand as this method would lead to an unwanted overcapacity of the system. Instead, the frequency converter installation should be capable of handling 6 vessels with a power demand of 2000 kW each, which is the average peak demand. Also, the system should be able to handle an increased power demand, for example 5 vessels with 2000 kW power demand each and one vessel with 7000 kW power demand. Assuming a 0.8 power factor, the frequency converter facility should have a nominal power output of 21250 MVA. Using 3 frequency converters ABB PCS 6000 SFC-7000[13] in a parallel connection, a 21MVA power output is achieved. The space needed for the frequency converter and supporting equipment is around 150 square meters (12 x 12m building). Because a container terminal is packed with TEU's, occupied with crane rails and truck roads, finding space for the installation of such equipment is difficult.

Shore-side Station

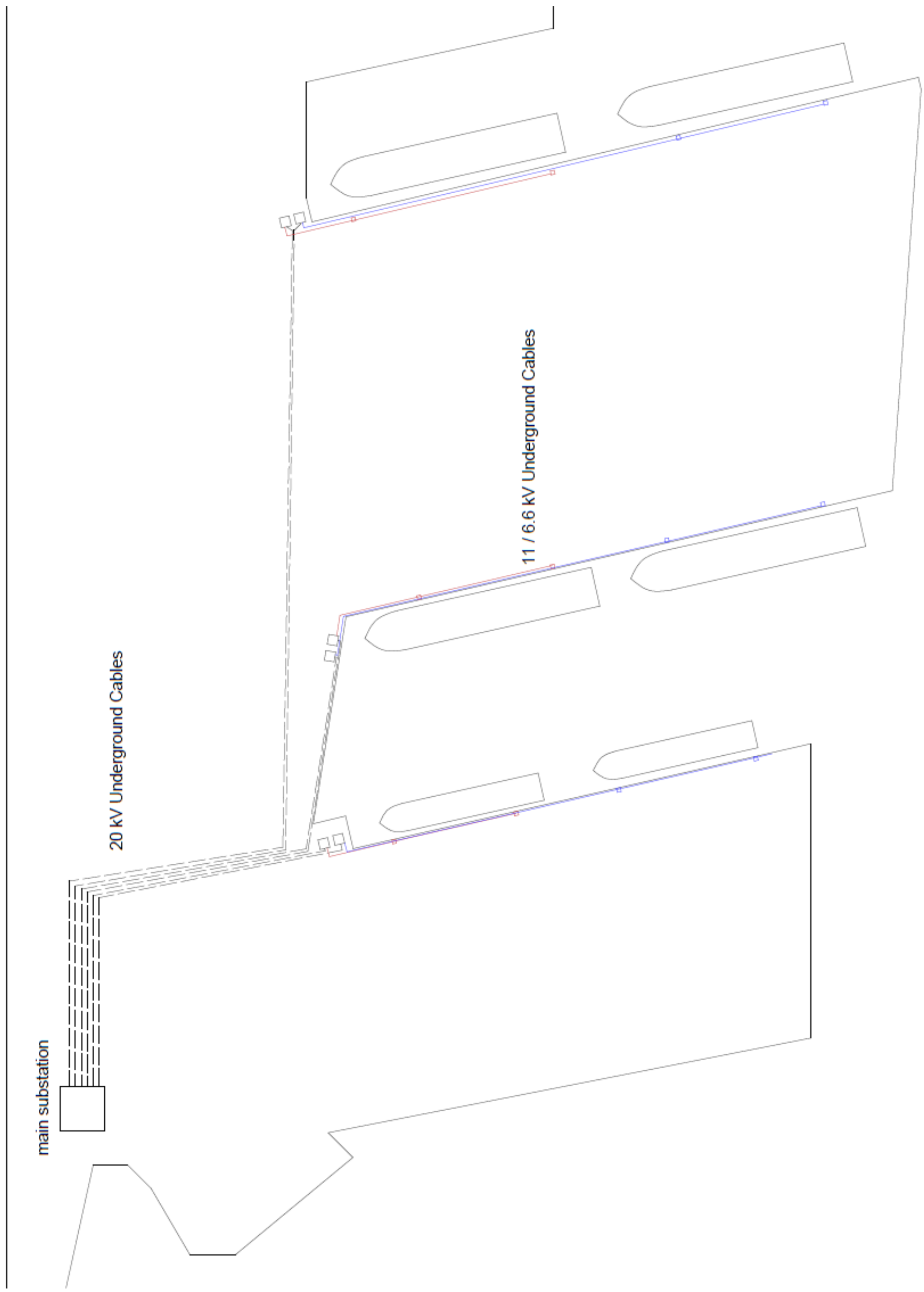
Shore-side equipment like the final transformer, cables, switchgears and circuit breakers should be dimensioned for a greater power output. In that way, it will be possible to accommodate ships with a higher power demand and take advantage of the overcapacity of the frequency converter when power output is low. Furthermore, a greater dimensioning of shore-side equipment is advantageous in the case where a vessel with increased power demand and 50 Hz current needs to be connected to shore power. In that case, the frequency converter is bypassed but the shore-side equipment should be able to carry the increased power load.

The shore-side station contains the transformer, which is the case of the container vessels is a single voltage transformer 20/6.6kV, a switchgear and a secondary circuit breaker.

Table 40 – Shore-side transformers specifications

Berthing Place	MVA	Shore-Side Transformer	kV
Container 1	4	Single Voltage	20/6.6
Container 2	4	Single Voltage	20/6.6
Container 3	4	Single Voltage	20/6.6
Container 4	4	Single Voltage	20/6.6
Container 5	4	Single Voltage	20/6.6
Container 6	9	Single Voltage	20/6.6

Due to crane rails, shore-side stations cannot be placed right next to the berthing place. In addition to that, shore-side stations must be installed in a place that does not affect container stacking or their transportation with port's trucks. To overcome this problem, one solution is to place the final transformers at the end of the quay and then distribute current of 6.6 kV to connection boxes via underground cables. These underground cables will be installed in the available space (1 meter approximately) between the crane rails and the edge of the quay.



Picture 12 – Schematic drawing of Cold Ironing installation in Piraeus Container terminal

5. Economic analysis

5.1 Cold-Ironing economics for Piraeus port

5.1.1 Infrastructure Cost

Despite the environmental advantages of applying cold-ironing for vessels which berth at Piraeus port, cost is the key factor to determine whether this method would be chosen as an alternative solution to cut down emissions at port and whether there are chances of an implementation of shore-side power in a bigger scale worldwide.

The largest financial burden of a cold ironing installation lies to the port authority. That is because the elements included in the main power station, such as the frequency converters and the voltage transformers are particularly expensive. The cost of frequency converters is equal to the 1/3 of the total cost while cost of cables, switchgears, circuit breakers, construction of buildings or safety equipment is high but represents only 15% of the total cost of the investment.

In order to estimate the cost of equipment for passenger and container terminal of Piraeus port, this report was based on the financial analysis for cold-ironing in Port of Valletta[17], Port of Rotterdam[4] and Port of Oslo[14]. The shore-side solution of a centrally placed frequency converter that was proposed in 4.2.1 and 4.2.2 is currently the best way to reduce equipment cost because dimensioning is based on the total actual power demands and not on the maximum power demands at each berthing place. The cost estimation showed that the price for installing cold-ironing equipment of 42 MVA power output to the passenger terminal of Piraeus port would be 15 million Euros. The cost of a 21 MVA system with 6 berthing places for the container terminal at Piraeus port is estimated to be 7.6 million Euros.

There is no doubt that in order to allow for a competitive solution, the high equipment and installations cost must be reduced. On the other hand, this kind of investment should not be strictly assessed from an economic perspective as the primary objectives of shore-side power are the reduction of emissions and the improvement of air quality near ports. It is a fact that cost, profit and risk are the fundamental evaluating parameters for every investment but there is a time when protection of the environment and urban areas near ports is of greater importance.

Table 41 – Infrastructure costs for Piraeus port

	Passenger Terminal		Container Terminal	
System size	42 MVA		21 MVA	
		Cost in Euro €		Cost in Euro €
Main Substation				
Building		70,000.00 €		40,000.00 €
Frequency Converters	6 X 7 MVA	5,200,000.00 €	3 X 7 MVA	2,600,000.00 €
Converter's supply transformers	6 X 7 MVA	2,000,000.00 €	3 X 7 MVA	1,000,000.00 €
Converter's output transformers	6 X 7 MVA	2,000,000.00 €	3 X 7 MVA	1,000,000.00 €
Double Busbar		450,000.00 €		300,000.00 €
Circuit breakers, switchboards, cables		500,000.00 €		300,000.00 €
Cooling, ventilation, fire detection, lighting, alarm		170,000.00 €		80,000.00 €
Power distribution				
20 kV Cables	7300 m	330,000.00 €	5300 m	240,000.00 €
11 kV Cables	600 m	24,000.00 €		
6.6 kV Cables	1200 m	42,000.00 €	2700 m	94,500.00 €
Shore-Side Station				
Building	8 X 4000	32,000.00 €	6 X 4000	24,000.00 €
Transformers	2X15MVA & 6MVA & 3.5MVA & 3MVA & 2.5MVA & 2X2MVA	2,900,000.00 €	9MVA & 5X4MVA	1,560,000.00 €
Connection boxes	16	750,000.00 €	8	375,000.00 €
Switchgear, circuit breakers, cables		550,000.00 €		400,000.00 €
Total		**15,018,000.00 €**		**7,613,500.00 €**

5.1.2 Operating and Maintenance Costs

Apart from the investment cost, operating and maintenance costs must also be considered. Each cold-ironing facility requires full time presence of a qualified electrician/engineer who will supervise and monitor system activity. Moreover, there is need for technicians who will coordinate, monitor and check the connection and disconnection procedures of the vessels. Maintenance cost can be assumed to be at 3% of the total installation cost of the cold ironing facility. Total annual operating costs are 204,000.00 € and 156,000.00 € for passenger and container terminal respectively while maintenance cost are 450,540.00 € and 228,405.00 € respectively.

Table 42 – Operating costs for Cold Ironing in Piraeus port

	Passenger Terminal		Container Terminal	
Personnel	Persons	Annual Wage/person	Persons	Annual Wage/person
Qualified Electrician/Engineer	3	20,000.00 €	3	20,000.00 €
Technicians	9	16,000.00 €	6	16,000.00 €
		Annual Cost		Annual Cost
Total Annual Operating Cost		204,000.00 €		156,000.00 €
		Annual Cost		Annual Cost
Maintenance		450,540.00 €		228,405.00 €
Total annual cost	**654,540.00 €**		**384,405.00 €**	

5.1.3 Economic benefits for Piraeus

A shore power installation may not have direct economic benefits for the administration of Piraeus port, nevertheless the indirect economic benefit which comes from the amelioration of human health or the reduction of pollution to the ecosystem is huge. To further understand that economic advantage, it is useful to introduce the term of shadow price or shadow cost.

Shadow price of emissions

Shadow prices are in general artificial monetary values which are assigned to goods or productions factors that are not traded. Shadow cost or shadow price of emissions refers to the monetary value which is assigned in order to quantify the effect of these emissions in human health, ecosystems and constructions. In order to evaluate the economic impact of cold ironing, these shadow prices of CO_2, SO_X, NO_X and PM must be taken into account. A report which was conducted by CE Delft in 2010[12], provides an estimation for these shadow prices which can be found in the following table 43. In general terms, this report covers the effect of emissions on human health (cost of cure and cost of life), on the ecosystem (cost of restoration process), on buildings (cost of loss of material degradation and cost of restoration) and on agriculture. It is important to say that the estimation of shadow price is based on methodologies may produce variable results according to the assumptions that have been made. There are no scientifically precise methods in order to estimate shadow prices and therefore these prices may change over time.

Table 43 – CE Delft calculation of emissions shadow prices

Pollutant	Damage Cost (€/kg)
CO_2	0.00487
SO_2	8.73
NO_X	7.87
PM	28.2

The maximum economic benefit for human health, which results from the reduction in ship's emissions when all ships at berth use shore power can be found in the following table. The use of shore power leads to a significant decrease in all major pollutants (CO_2, SO_X, NO_X, PM) and the annual indirect economic benefit for human health is calculated to be 29.5 million € for the urban area around Piraeus port.

Table 44 – Health Maximum Annual Valuated economic benefit resulting from the use of shore power

	CO_2	SO_X	NO_X	PM	Total
Reduction In Emissions (t/year)	35015	1705	1652	52	
Economic Benefit	170,523.05 €	14,884,650.00 €	13,001,240.00 €	1,466,400.00 €	**29,522,813.05 €**

Of course, this economic benefit refers to the case in which every ship that berths to Piraeus port is switching off its diesel generators and receives shore power. Until now, the vast majority of vessels is not ready to receive shore power and a few ports around the world offer the possibility of Cold-Ironing. Because of the small amount of ports providing shore power, cruise ship and container ship operators are less eager to retrofit their vessels. The environmental benefits may be important but ship operators are not likely to invest in cold-ironing equipment if the investment is not going to pay off. Ferries, which berth daily at Piraeus for many hours per day, are more likely to be retrofitted in the near future because the investment will pay off. From that point, it is useful to present the indirect economic benefit to human health when only 50% of the cruise and container vessels and 100% of the ferries in Piraeus port are connected to shore power. In that case, the emissions saved and the economic results can be found in the following table 45.

Table 45 – Health Annual Valuated economic benefit in the second case

	CO_2	SO_X	NO_X	PM	Total
Reduction In Emissions (t/year)	20831	1015	983	31	
Economic Benefit	101,448.49 €	8,855,511.08 €	7,736,094.32 €	867,656.82 €	**17,560,710.71 €**

5.2 Cold Ironing economics for berthing vessels

Retrofitting cost

Based on the 2005 Shore-Side electricity report which was conducted by ENTEC for the Directorate General Environment of European Commission[3], the cost of installing a cold ironing system onboard an existing ship is much higher than installing the same equipment on a new ship. The cost estimation for a 0.5-4 MW transformer is 40,000.00 € – 110,000.00 €, while the retrofitting installation is estimated at 150% of the equipment cost (60,000.00 € - 165,000.00 €). The onboard cable reel system that needs to be installed has an estimated cost of 150,000.00 € (including the cable). This system is used to handle the high voltage cable that provides electricity from the junction box at the quay to the vessel. Because this cost estimation refers to 0.5-4 MW equipment, the actual cost for cruise ships or mega containerships is expected to be higher.

Vessels that use the same voltage as the one provided from the shore-side facilities (6.6/11 kV) are not required to be equipped with a transformer and will have a reduced retrofitting cost.

Table 46 – Average cost for newbuildings and retrofitting of existing vessels

	Newbuildings	Existing Vessels
Onboard Transformer	75,000.00 €	75,000.00 €
Installation	56,250.00 €	112,500.00 €
Cable Reel System	150,000.00 €	150,000.00 €
Total Cost	281,250.00 €	337,500.00 €

Fuel Prices

As not all ships buy fuel from Piraeus based bunker traders, fuel price used for calculations will be based on fuel prices in European major ports.

Table 47 – Fuel prices in major European ports (May 2016)

Fuel Prices	$/mt	€/mt
	MGO	
Piraeus	420.00	382.91
Hamburg	407.00	371.06
Rotterdam	379.00	345.53
Genoa	447.00	407.53
Algeciras	424.00	386.56
Las Palmas	417.50	380.63
Lisbon	429.00	391.12
Istanbul	430.50	392.49
Gothenburg	600.00	547.02
AVERAGE	439.33	400.54

Based on our previous calculations about ship fuel oil consumption at berth, it is easy to calculate the cost of onboard electricity production in €/h. The cost of onboard power generation will be calculated with MGO prices according to European legislation which obliges member states to ensure that marine fuels with more than 3.5% sulphur content are not being used in their territorial seas. So for the three hypothetical ships of each type (ferries, cruise ships, container vessels) that were used in 3.2.5 the fuel cost per kWh and per hour at berth can be found in the table below.

Table 48 – Fuel cost for 3 ferries while at berth

Vessel Name	Hotelling Load (kW)	Fuel Consumption (kg/h)	Fuel Cost €/h
FESTOS PALACE	2553	467	205.30
BLUE STAR DELOS	1465.2	268	117.82
NISSOS RODOS	1110	203	89.26

Table 49 – Fuel cost for 3 cruise ships while at berth

Vessel	Capacity (Pass)	Hotel Load (kW)	Fuel Consumption (mt/h)	Fuel Cost (€/h)
Cruise Ship 1	2000	6234	1.22	537.06
Cruise Ship 2	2500	7793	1.53	671.33
Cruise Ship 3	3000	9351	1.83	805.60

Table 50 – Fuel cost for 3 container vessels while at berth

Vessel	TEU	Hotelling Load (kW)	Fuel Consumption (kg/h)	Fuel Cost (€/h)
Container Ship 2	4500	910	178.37	78.36
Container Ship 3	9660	1238	242.85	106.69
Container Ship 4	10500	1331	260.95	114.64

The average cost of fuel per kWh is calculated to be 0.0861 €/kWh

Maintenance and Operational cost of diesel generators

For 4-stroke auxiliary engines and diesel generators, a cost of 0.003€/kWh for maintenance and repairs can be assumed.

Moreover, lubricant oil consumption must be considered in an economic analysis. Lubricant oil has a cost of approximately 4000€/ton and marine 4-stroke diesel generators have an oil consumption of 0.35 gr/ kWh.

Therefore, a diesel generator producing 1000kW for 10 hours will have a cost of approximately € 30 for maintenance and repairs and 14€ for lubricant oil.

Maintenance of Cold-Ironing equipment

We can assume that maintenance of the onboard cold-ironing equipment will be performed every two years with a cost of 5% of the acquisition price. Therefore, the annual maintenance cost will be 2.5% of the acquisition price.

Electricity cost in Greece

On the website of the Public Power Corporation S.A. (DEH) one can find information about electricity pricing for large industries and businesses. Different pricing is applied based on the time and the days the consumer is using the provided power. Ships should be provided with electricity via the shore-side facility at every time, every day, so for this report an average electricity cost of 0.063905 €/kWh is taken. Power fee is 5.5€/kW/month and for 50000 kW per month this power fee is 275,000.00 €. This power fee could either be totally or partially absorbed by Piraeus port so that shore power could stand as a competitive alternative to diesel generators or it could be transferred to ship operators as an increase to the €/kWh price. There is always a chance that the Public Power Corporation would make a special deal with port of Piraeus in order to decrease that power fee and increase the demand for shore power.

Table 51 – Price rates of shore electricity in Greece for businesses and industries

Low Usage Factor		
Zone	Power fee (€/kW/month)	Energy Cost (€/kWh)
7:00-23:00 on working days	5.5	
7:00-23:00 on working days		0.07124
23:00-7:00 on working days		0.05657
Weekends and holidays		0.05657

5.3 Feasibility of the investment

As we know, cruise vessels and containerships do not usually have a fixed schedule. Unlike ferries, which may operate between two ports for throughout their lives, cruise vessels and containerships visit many ports, may have different routes and destinations from year to year and so on. Given that only a few ports around the globe offer shore-power connection, one should know the exact operational schedule of such a vessel in order to decide whether it would be worthy or profitable to install a cold-ironing equipment onboard. Due to that reasons, this chapter will focus on assessment of this kind of investment on ferries which operate between Piraeus port and the Aegean Sea islands. Also, a table with the estimated annual costs and incomes from the port aspect will be given.

5.3.1 Feasibility of the investment for the average ferry

Feasibility of the investment will be examined for one hypothetical ferry which operates in the Aegean Sea and uses Piraeus as home port. In order to create that hypothetical ferry, we used average values for hoteling load, annual berth time, fuel consumption and emissions. The characteristics of this vessel can be found in table 52.

Table 52 – Power, energy and emissions characteristics of a hypothetical ferry

Hoteling Load (kW)	1544
Annual Berth Time (h)	1420
Fuel (t/year)	402.8
CO_2 (t/year)	1298.5
SO_X (t/year)	22.0
NO_X (t/year)	21.3
PM (t/year)	1.3

For a ship-owner, the basic income which comes from retrofitting the vessel is that of fuel economy and it is calculated to be 46745 €/year using equation 4. Also, money is saved as lubricating oil consumption is reduced and generator's maintenance is less frequent. Lubricating oil and maintenance costs were analyzed in chapter 5.2 and for this hypothetical ferry, savings from maintenance and Lubricating Oil is 9265 €/year. However, apart from the initial investment, ship-owners have to consider maintenance costs for the cold-ironing equipment which are estimated at 8440 €/year for this vessel.

$$FuelSaving\ (€) = \left(Fuel\left(\frac{€}{kWh}\right) - ShorePower\left(\frac{€}{kWh}\right)\right) * BerthTime(h) * Load(kW) \quad (4)$$

The annual savings are estimated to be around 56,000.00 € while maintenance costs of the equipment are to be around 8,437.5 €/year. The investment cannot be profitable for the ship-owner in the case where the total power fee has to be absorbed by the owner. With the actual Public Power Corporation prices, as shown in table 51, the power fee for each ferry is around 47,000.00 €/year. The scenario which is proposed in this report, includes a 45% participation of the ship owner in power fee while port administration is responsible for the rest 55%. Of course, as mentioned before there can be a special pricing arrangement between the Public Power Corporation and Port authorities so that more ship-owners will be interested in Cold-

Ironing. Profit is always the driving force in every kind of industry, therefore it is necessary that the retrofitting investment pays off so that more and more vessels will be equipped with cold-ironing equipment.

Assuming a discount rate of 4% and a 20-year lifetime of the onboard equipment (transformer, cable reel system, switches etc.), the profitability of the investment can be measured using the net present value method (NPV) (equation 5). Net cash flow is calculated using the incomes and expenses mentioned above. Results from this method are shown in table 53.

$$NPV(i,N) = \sum_{t=0}^{20} \frac{Net\ Cash\ Flow}{(1+i)^t} \quad (5)$$

Table 53 - NPV calculation for hypothetical ferry

Year	Annual Savings (fuel, maintenance)	Maintenance of cold-ironing equipment	Usage fee	Investment (Retrofit)	
0				-337,500.00 €	-337,500.00 €
1	56,009.92 €	-6,750.00 €	-23,718.75 €		24,558.82 €
2	56,009.92 €	-6,750.00 €	-23,718.75 €		23,614.25 €
3	56,009.92 €	-6,750.00 €	-23,718.75 €		22,706.01 €
4	56,009.92 €	-6,750.00 €	-23,718.75 €		21,832.70 €
5	56,009.92 €	-6,750.00 €	-23,718.75 €		20,992.98 €
6	56,009.92 €	-6,750.00 €	-23,718.75 €		20,185.56 €
7	56,009.92 €	-6,750.00 €	-23,718.75 €		19,409.19 €
8	56,009.92 €	-6,750.00 €	-23,718.75 €		18,662.68 €
9	56,009.92 €	-6,750.00 €	-23,718.75 €		17,944.89 €
10	56,009.92 €	-6,750.00 €	-23,718.75 €		17,254.70 €
11	56,009.92 €	-6,750.00 €	-23,718.75 €		16,591.06 €
12	56,009.92 €	-6,750.00 €	-23,718.75 €		15,952.94 €
13	56,009.92 €	-6,750.00 €	-23,718.75 €		15,339.36 €
14	56,009.92 €	-6,750.00 €	-23,718.75 €		14,749.39 €
15	56,009.92 €	-6,750.00 €	-23,718.75 €		14,182.10 €
16	56,009.92 €	-6,750.00 €	-23,718.75 €		13,636.64 €
17	56,009.92 €	-6,750.00 €	-23,718.75 €		13,112.15 €
18	56,009.92 €	-6,750.00 €	-23,718.75 €		12,607.84 €
19	56,009.92 €	-6,750.00 €	-23,718.75 €		12,122.92 €
20	56,009.92 €	-6,750.00 €	-23,718.75 €		11,656.66 €
NPV					9,612.81 €

5.3.2 Costs and benefits for port

Summary of annual cost and income which was given in 5.1.3 is presented in table 54. Of course, annual savings from emissions cannot be considered as cash flow since they represent the indirect valuated health benefit which results from the use of shore-power instead of onboard diesel generators.

Table 54 - Annual cost and income for port

Annual Savings (Valuated Health Cost)	Operation and Maintenance	Power fee	Investment
			22,631,500.00 €
€29,522,813.05	-€1,038,945.00	-2,236,080.00 €	

Following the example of Los Angeles port, Piraeus port authority could also introduce a special regulation which would require that diesel generators are shut down for specified percentages of fleet visits. These percentages should rise each year so that in a decade from now more than 80% of the berthing vessels should be ready to connect to shore power. Cruise and container vessels traffic is rather high in Piraeus and it is expected to further increase in the next decade. An appropriate regulation which would require a specific percentage of cold-ironed vessels per year would be extremely beneficial for public health and the environment but would also boost the implementation of Cold-Ironing.

6. Summary and Conclusions

6.1 Summary

This report mainly focused on the implementation of Cold-Ironing in passenger and cargo terminal of Piraeus port. Because of the rapid growth of the Piraeus Container Terminal in the past few years, Greece's position as a popular holiday destination but also Greece's insular morphology, container carriers, cruise vessels and ferries are the most frequent visitors in Piraeus port. As a result, these types of vessels were studied in terms of power demand at berth, fuel consumption and emissions so that the possibility of shore power could be examined. The comparison of the emissions between onboard and shore power generation, the estimation of cost of the installation for the port and the ship-owners as well as the direct and indirect benefits for nearby urban areas were among the scopes of this study.

The main results of this study are:

Ferries

1. Berth time per year varies between 770 and 3860 hours and the average berth time is around 1500 h/year per vessel. One single berth lasts 5-7 hours for most of the vessels, so a shore-power connection is feasible. The number of simultaneously berthed ferries at Piraeus is between 5 and 6 vessels.
2. Average power demand at berth is 1500 kW. Minimum power demand is 1100 kW and maximum power demand is 2500 kW.
3. Estimation for the 16 ferries which were included in this study showed that fuel consumption for one year is around 6500 tons and diesel generators emissions are around: 21000 tons of CO_2, 350 tons of SO_X, 340 tons of NO_X and 21 tons of PM.

Cruise vessels

1. In average, 650 cruise ships visit Piraeus port on an annual base, carrying 1.8 million passengers from all around the world.
2. Average berth time is 15 hours. Peak season occurs from April to October and most of this time there are 3 simultaneously berthed cruise ships.
3. Average power demand is 7500 kW. Power demand depends on vessel size, passenger capacity, level of comfort and may vary from 4000 to 11000 kW.

4. The majority of cruise vessels use 6600V / 60Hz current.
5. Estimation showed that 16500 tons of fuel/year are consumed for hoteling power needs in Piraeus port and 54000 tons of CO_2, 910 tons of SO_X, 880 tons of NO_X and 54 tons of PM are emitted each year. This estimation does not cover fuel consumption or emissions during maneuvering which may be significant especially for large cruise ships.

Container vessels

1. In average, 2000 container vessels of various sizes visit Piraeus each year. Average berth time is around 19 hours and 5-6 vessels are berthed at the same time.
2. Average power demand is 2000 kW for deep sea vessels and 200 kW for small feeders with a capacity of less than 800 TEU. In general, vessels of such capacity are a rare sight in Piraeus. Peak power demand may be up to 7000 kW. Power demand of container vessels is highly volatile and depends highly on the number of reefers onboard.
3. Large container vessels mainly use 440V / 60Hz current but high voltage systems of 6600V / 60Hz are constantly gaining ground due to various advantages.
4. Estimation showed that 11850 tons of fuel were consumed for electricity generation in 2015 while 35000 tons of CO_2, 593 tons of SO_X, 574 tons of NO_X and 35 tons of PM were emitted.

Emissions

Even in Greece, where lignite is still the major fuel source for electricity production, shore power emissions are far lower compared to those of diesel generators even when the latter are running on MGO. This study shows that a reduction of 32% in CO_2, 92% in SO_X and NO_X and 47% in PM emissions is achieved when a vessel is connected to Greece's national grid instead of using its diesel generators. Further increase is the use of renewable sources like sun and wind for shore power generation would lead to even lower emissions.

Port infrastructure

The model which is proposed in this study is based on the basis of a centrally placed frequency converter. This solution is the most advantageous in terms of power management, space arrangement and cost. A centrally placed frequency converter installation with a capacity of 42MVA which will serve ferries and cruise ships is proposed for passenger terminal of Piraeus port, while a smaller similar installation of 21MVA is proposed in order to handle the power demand of the containership terminal. This arrangement provides 5 power slots for ferries, 3 slots for cruise ships and 6 slots for container vessels.

Economics

The total cost of the investment for the port authority is around 22,500,000.00 €. Frequency converters and voltage transformers cover almost 75% of the total cost. Cost for retrofitting a vessel depends on power demand, primary voltage and varies from 250,000.00 to 425,000.00 €. Vessels with the same primary voltage as the one provided by the shore-side installation will have a significantly reduced cost. With current MGO prices and electricity pricing in Greece, cold ironing can be profitable for ship-owners in the case where 45% of the power fee (€/kW/month) is paid by the ship-owner and 55% is subsidized by the state or the port. A possible special arrangement between Piraeus port and the Power Corporation would make Cold-Ironing even more appealing to ship operators.

An important but hidden economic aspect of Cold-Ironing lies upon the shadow prices of emissions. Based on the results of the Shadow Prices Handbook by CE Delft, if all vessels at Piraeus port were connected to shore-power the reduction of emissions would lead to an estimated valuated health benefit of 29,500,000.00 €.

6.2 Conclusions

The benefits of implementing Cold-Ironing in Piraeus port are numerous and significant. Because of Piraeus's port proximity to dense urban areas, ship emissions really affect quality of life, human health and the ecosystem. As shown in 1.1.2, ship emissions such as SO_X, NO_X and PM have negative effects on human health, flora and fauna. The implementation of Cold-Ironing provides a solution to that important issue as it is the only method that drastically cuts down emissions with direct and measurable positive effects to air quality and accordingly, to quality of life of the surrounding residents. Cold-Ironing not only allows for ships to be electrified in a greener way but also, allows for harmful emissions to be carried away from major cities and urban areas. Additionally, noise levels near major harbors could significantly decrease once the diesel generators are shut down.

From a strictly economic point of view, Cold-Ironing is a rather expensive method of cutting down emissions, because it requires significant modifications and investments both at port and onboard the vessels. Although, facing the new strict IMO environmental rules, the rising oil prices (especially those of low-sulphur content) and pressures from local governments and port authorities, ship-owners may consider Cold-Ironing as an appealing alternative. Anyway, as shown in 5.3.1, Cold-Ironing can be profitable for ship-owners in some cases. Introducing shadow price of emissions and valuating the induced health damage, one may find that Cold-Ironing is far from expensive. It is true that profit is the driving force of every investment but there is a time when people should place health, ecosystem or environment in a higher priority.

A future increase in the percentage of electricity which derives from renewable sources, would further strengthen Cold-Ironing position as the greenest alternative to other means of cutting down emissions but could also render shore-power more competitive than marine fuels in an economic basis.

To sum up, the strengths of shore-power are the drastic cut down in emissions, the decrease of noise levels near busy harbors as well as the potential ship-owner savings from fuel and maintenance. Weaknesses of this method are the direct dependence between oil prices and the profitability of the investment as well as the high investment cost for both ship-owners and ports. Moreover, compared to other air pollution control methods or LNG as fuel, Cold-Ironing is only offered at berth and therefore emissions during maneuvering or coastal sailing cannot be reduced. The possibility of an even greener electrification of ships as renewable sources gain ground but also the potential increase of profit as oil prices rise are the great opportunities of the method. Other means of reducing ship emissions such as scrubbers, filters or the use of LNG as fuel are the possible threats against Cold-Ironing.

Further research could focus in a comparison between Cold-Ironing and other means of air pollution control or exhaust after treatment systems from an economic and ecological point of view. Furthermore, future work could examine the possibilities of a green Cold-Ironing system at popular cruise destinations around Greece such as Mykonos and Santorini, using only renewable energy from wind farms or solar panels. For Piraeus port, because of the increasing car imports –mainly for other European markets- future studies on Cold-Ironing should also include car carriers and Ro-Ro vessels.

Appendix I

Table 9 – Specific fuel oil consumption for MAN and Wärtsilä engines (Source: MAN and Wärtsilä project guides)

MAN L16/24						**Wärtsilä 6L20**					
% Load	100	85	75	50	25	% Load	100	85	75	50	25
SFOC (g/kWh)	195	195	194	202	223	SFOC (g/kWh)	193	190	192	197	n/a
MAN L21/31						**Wärtsilä 6L26**					
% Load	100	85	75	50	25	% Load	100	85	75	50	25
SFOC (g/kWh)	192	189	189	193	207	SFOC (g/kWh)	187	185	189	198	n/a
MAN L32/44						**Wärtsilä 6L32**					
% Load	100	85	75	50	25	% Load	100	85	75	50	25
SFOC (g/kWh)	178.1	175.3	179.3	184.8	204.2	SFOC (g/kWh)	184	181	182	193	n/a
Wärtsilä 8L46F						Wärtsilä 12-14-16V46F					
% Load	100	85	75	50	25	% Load	100	85	75	50	25
SFOC (g/kWh)	179	175	183	189	n/a	SFOC (g/kWh)	178	174	182	188	n/a
Average						**SFOC (g/kWh)**	**186**	**183**	**186**	**193**	**n/a**

Table 55 – Manufacturer's data for marine engine emissions

Emissions			
Fuel: 2.5% w/w sulphur			
CO_2		590	g/kWh
SO_X		10	
NO_X		9.68	
PM	Soot	0.3	
	Fuel Ash	0.25	
	Lub. Oil Ash	0.04	

Table 56 – Port of Rotterdam research, Feeder container vessels

Feeders					
	Length O.A.*	TEU*	Reefers*	Average Hotelling Power	Max. hotelling power
1	100	390	30	70	120
2	100	390	50	150	
3	100	330	40	140	200
4	100	390	60	110	150
5	100	510	50	140	170
6	100	370	50	200	350
7	110	510	60	120	220
8	120	230	40	400	800
9	120	540	50	155	220
10	120	530	40	180	210
11	120	700	70	200	280
12	130	550	90	120	300
13	130	710	100	180	900
14	130	870	150	200	600
15	130	700	150	200	400
16	130	750	100	90	110
17	130	870	150	200	300
18	130	870	150	170	230
19	140	810	180	160	230

Table 57 – Port of Rotterdam research, Deep sea container vessels

Deep sea vessels					
	Length O.A.*	TEU*	Reefers*	Average Hotelling Power	Max. hotelling power
1	150	1080	160	400	400
2	160	440	0	213	200
3	160	1160	100	350	400
4	180	1740	100	350	1100
5	210	2890	400	1100	1500
6	210	2490	570	1600	2200
7	240	2580	230	700	1200
8	240	3030	260	550	650
9	240	2930	150	400	500
10	260	3840	250	700	900
11	270	5060	800	1460	1460
12	280	5300	500	700	1100
13	280	5250	500	1000	1500
14	280	3800	360	400	450
15	280	5620	1000	1400	1500
16	280	5550	0	1200	6000
17	280	5500	500	1500	2400
18	280	5610	500	2000	2400
19	280	5610	500	1400	1800
20	280	5780	500	1200	2000
21	280	5330	500	1400	8000
22	290	4020	350	700	1000
23	290	4430	350	550	900
24	290	4210	950	1800	2000
25	290	4210	950	1600	2000
26	290	4890	370	1200	1900
27	290	6350	500	2000	2500
28	290	5060	450	1000	1700
29	300	6210	500	1500	3000
30	300	6980	710	2000	3500
31	300	6420	0	2000	2220
32	330	8400	700	1600	5100
33	340	8150	700	2000	3500
34	350	7370	840	1000	2000

*Due to confidentiality reasons, the length of the vessels and the TEU and reefer capacity was rounded off.

Table 58 – Average berth time for 12 container vessels

TEU	Average time in port (h)
1810	30
2240	26
3075	24
4496	35
4496	33.91
4496	29.35
4824	26.52
8850	25.95
9662	26.76
10484	32.92
10484	28.43
Average	29

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