Universitatea Națională de Știință și Tehnologie Politehnica București

Facultatea TRANSPORTURI
ȘCOALA DOCTORALĂ TRANSPORTURI
Domeniul de doctorat
INGINERIA TRANSPORTURILOR

REZUMAT

TEZĂ DE DOCTORAT

CONTRIBUTIONS TO THE MERCHANT VESSELS' PERFORMANCE TO REDUCE THE ENVIRONMENTAL IMPACT IN PORTS

CONTRIBUȚII ASUPRA PERFORMANȚEI NAVELOR COMERCIALE ȘI IMPACTUL ASUPRA MEDIULUI ÎN PORTURI

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BUCUREȘTI 2026

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ABBREVIATIONS

AFC	*Alkaline Fuel Cell*
AIS	*Automatic Identification System*
ALB	*Allocated Berth*
AMP	*Alternative Maritime Power*
CAPEX	*CAPital EXpeditures*
CCS	*Carbon Capture and Storage*
CI	*Cold Ironing*
CIB	*Cold Ironing Berth*
CII	*Carbon Intensity Indicator*
DMFC	*Direct Methanol Fuel Cell*
DNV	*Det Norske Veritas*
ECA	*Emission Control Area*
EIAPP	*Engine International Air Pollution Prevention*
EU ETS	*European Union Emission Trading System*
EUA	*European Allowances*
FOC	*Fuel Oil Consumption*
GHG	*Greenhouse Gases*
GloMEEP	*Global Maritime Energy Efficiency Partnerships Project*
HFO	*Heavy Fuel Oil*
HVO	*Hydrotreated Vegetable Oil*
HVSC	*High Voltage Shore Connection*
IAPP	*International Air Pollution Certificate*
IEC	*International Electrotechnical Commission*
IEEE	*Institute of Electrical and Electronics Engineers*
ICE	*Internal Combustion Engine*
IMO	*International Maritime Organization*
LBG	*Liquefied BioGas*
LCA	*Life Cycle Assessment*
LNG	*Liquefied Natural Gas*
LOA	*Length OverAll*
LPG	*Liquefied Petroleum Gas*
LSFO	*Low Sulphur Fuel Oil*
LVSC	*Low Voltage Shore Connection*
MBM	*Market-Based Measures*
MCFC	*Molten Carbonate Fuel Cell*
MDO	*Marine Diesel Oil*
MGO	*Marine Gas Oil*
MSC	*Maritime Safety Committee*
MRV	*Monitoring, Reporting, and Verification*
NECA	*Nitrogen Emission Control Area*
OPEX	*OPerating EXpenses*
OPS	*Onshore Power Supply*
PAFC	*Phosphoric Acid Fuel Cell*

PEMFC	*Polymer Electrolyte Membrane Fuel Cell*
SBC	*Shore-side Battery Charging*
SCADA	*Supervisory Control and Data Acquisition*
SCP	*Shore/berth Connection Point*
SCR	*Selective Catalytic Reduction*
SCS	*Shore Connection Substation*
SECA	*Sulphur Emission Control Area*
SEEMP	*Ship Energy Efficiency Management Plan*
SOFC	*Solid Oxide Fuel Cell*
SPB	*Shoreside Power Bank*
SSE	*Shore Side Electricity*
TEN-T	*Trans-European Transport Network*
UGC	*Underground Cable*
VLSFO	*Very Low Sulphur Fuel Oil*

CHAPTER 1

INTRODUCTION

The maritime activity leads the transportation sector, with more than 12 billion tons of cargo in 2023, compared to 4.3 billion tonnes in 1990 (United Nations, 2024), being at the same time one of the most affordable and cost-effective means to transfer goods worldwide. In the last 20 years, the International Maritime Organization's (IMO) statistics have confirmed that shipping substantially contributes to pollution, especially GHG (Greenhouse Gas) pollution. Maritime transport represents approximately 3% of global CO_2 emissions.

Worldwide, more than 98% of the fuels burned in ships' engines were represented by conventional fossil fuels such as HFO (Heavy Fuel Oil), LSFO (Low Sulphur Fuel Oil), or MGO (Marine Gas Oil) (DNV, 2024).

1.2 The Necessity and Opportunity of the Research

The marine sector will need to investigate alternative fuels, remodel existing infrastructure, invest in and educate in new technology, and adapt shore and ship personnel, shipyards, specialists, and professionals. Energy-efficient ships can reduce greenhouse gas emissions in light of the current climate change conditions and the growing awareness of the need for urgent change.

Vessels are the lead component of the maritime sector, and their performance is directly linked to environmental protection. The parameters that define vessels' performance include:

- fuel oil consumption;
- identifiable voyage efficiency in terms of sailing and idle times;
- speed management;
- voyage efficiency in terms of route optimization and stability parameters;
- cargo capacity utilization;
- technological integration, technical integrity, and reliability;
- economic performance, operational costs, and return on investment;
- compliance with international standards;
- emissions quantities and control measures to decrease the pollutants, etc.

The options are limited for existing ships and focus mainly on operational measures and retrofit solutions. In addition, low-carbon fuels, such as LNG (Liquefied Natural Gas) and methanol, may be short and medium-term options. Various technologies are being developed for new ships, and research is moving in the direction of technologies based on hydrogen, ammonia, batteries, and nuclear power, depending on the vessel's type and size. The available data show that in 2024, 27% of the vessels on order will be burning alternative fuels, which is an important step forward towards cleaner fuels and efficient shipping (DNV, 2024).

Ports worldwide have the opportunity to decrease the emissions from the vessels while at berth. The operation and implementation of the Cold Ironing system on a global scale are in the initial phases, and it is an important step for port development and for the vessels' efficiency.

In addition to the facilities offered by the ports by installing a Cold Ironing system, ports can assist in increasing the vessels' performance by minimizing the costs and reducing the emissions while the vessels stay at anchor, waiting for a free berth (Park & Suh, 2019). The ports can utilize the opportunity of a shore power system to allow vessels to use a free berth fitted with Cold Ironing to wait until the designated berth becomes available, instead of waiting at anchor.

1.4 The Objectives and Structure of the Thesis

The thesis objectives are:

1. To assess the impact of vessel operation on the environment in the context of current international and European regulations.
2. To evaluate the operational and technical measures applicable for reducing fuel oil consumption and minimizing emissions generated by ships.
3. To examine the availability and challenges of future technologies and alternative fuels, as well as their capability to reduce emissions and the cost-effectiveness of decarbonization options.
4. To evaluate a Cold Ironing (shore power) system both onboard the vessels and in port facilities, with a particular focus on the Port of Constanţa, to determine its effectiveness in reducing pollution from moored vessels while ensuring compliance with environmental regulations.
5. To investigate the impact of queueing models on berth efficiency and waiting times at Port of Constanţa with the goal of identifying the methods for minimizing congestion.
6. To develop and to validate a berth allocation model that integrates Cold Ironing requirements, aiming to minimize overall costs and emissions while vessels await their designated berth.

The present thesis is organised into six chapters. Besides "Introduction", the next chapters are as follows:

Chapter 2. The author examines international and EU regulations concerning the reduction of ships' environmental impact. The IMO's ship energy efficiency indicators and EU initiatives are introduced, along with a study on CII regulation. The main factors and challenges of the decarbonization solutions are analyzed, as well as their influence on maritime activities.

Chapter 3. The author investigates actions to increase the efficiency of the vessels to meet environmental standards. New technologies and fuels are considered for the future of ships' propulsion systems, along with evaluating techno-economic and political fuel strategies. There are various energy efficiency measures, and their potential depends on each company's management plan. Some of the measures can be used together, and the potential GHG reduction can be significant. A study on the cost-effectiveness of current decarbonization options is presented.

Chapter 4 is centred on the shore-side electricity system. The Cold Ironing system in Port of Constanţa is analyzed from the cost point of view and emissions reduction feasibility. By installing shore-side electricity, the emissions would decrease substantially and would assist the vessels in improving their energy efficiency. Even if the electricity emissions are zero, by producing energy, different pollutants are released. From the green alternatives studied for the Port of Constanţa, the viable potential lies with offshore wind turbine farms and solar panels, and the evaluation and selection of the green energy option shows that solar panels are the preferred option for the port.

Chapter 5. The author proposes a Cold Ironing berth allocation model as a solution for the vessels that wait for the designated berth to become available. This chapter intends to develop an algorithm that reduces the anchor times for the vessels by allowing them to berth in a free berth that has a compatible shore-side electricity connection. Both the emissions and the costs will decrease if the vessels wait for their allocated berth in a free Cold Ironing berth. This section evaluates the berth efficiency and waiting time reduction by applying different queueing models.

Chapter 6. The author draws the final conclusions and outcome of the thesis, based on the case studies presented. The personal contributions and the directions for future research are also shown in this part.

CHAPTER 2

REGULATIONS CONCERNING THE REDUCTION OF SHIPS' ENVIRONMENTAL IMPACT

2.1 Environmental Impact of Maritime Transport

IMO aims for net-zero emissions by or around 2050, having the year 2008 as a reference (IMO, 2023). Figure 2.2 shows the IMO targets for GHG emissions reduction from shipping. In July 2021, the European Commission set the target of a 55% decrease in greenhouse gas emissions by 2030 and to achieve climate neutrality by 2050 (European Commission, 2023).

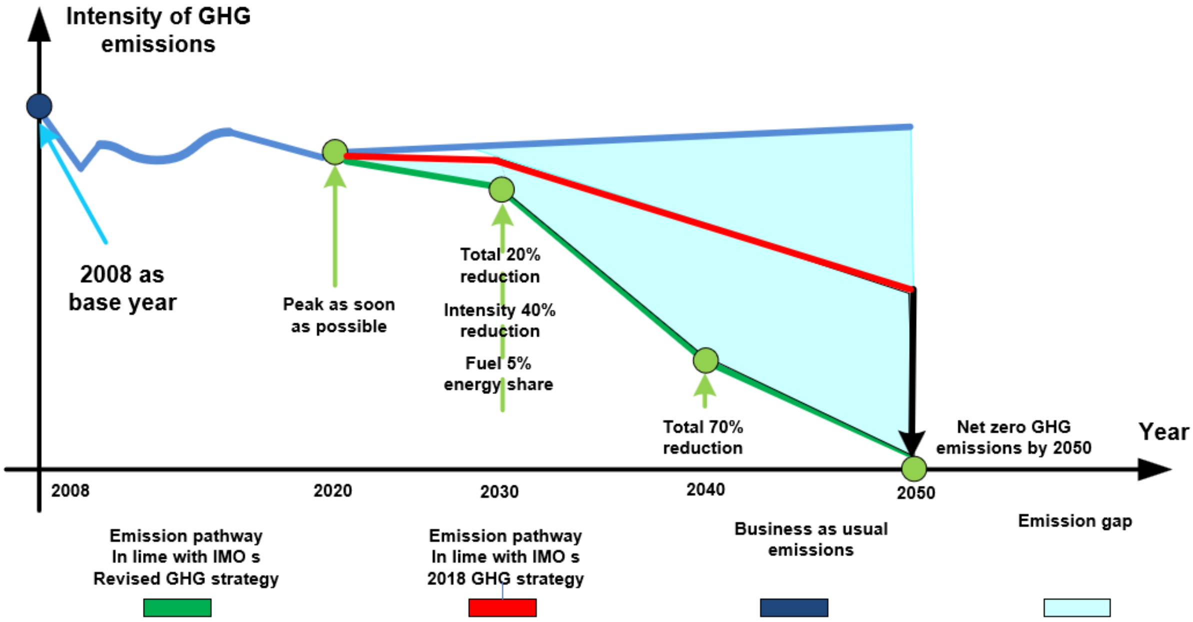


Figure 2.2 IMO targets for GHG emissions reduction from shipping

Source: (DNV, 2023)

2.2 Maritime Transport Emissions' Characteristics and Relevant Regulations

2.2.2 Maritime Transport Emissions Types and Characteristics

The main gas emissions from shipping activities are represented by greenhouse gases and pollutant emissions. The main types of pollutants, their characteristics, and their main impacts on human health and the environment are presented in Table 2.7.

Table 2.7 Maritime transport emissions' types, characteristics, and main effects

Emission	Formation/Characteristic	Main effects
Nitrogen (N_2)	Remains largely unreacted in the combustion process. A small amount will take part in the chemical reaction, resulting in nitrogen oxides. Forms 78% of the intake air	Nitrous Oxide (N_2O) is a GHG that can be converted into NO_2 and NO, which have an important effect on the stratospheric ozone layer
Oxygen (O_2)	Forms 21% of the intake air, and it is partially converted in the combustion	
Carbon Dioxide (CO_2)	It is the main component of any combustion process of fossil fuel, and the quantity is determined by the fuel's carbon content.	CO_2 is currently the main concern among all pollutants, leading to global warming and having a major impact on sea life
Nitrogen Oxides (NOx)	NOx depends on the engine type (slow-speed engines have NOx emissions higher than medium-speed engines) and the type of fuel	NOx is responsible for causing respiratory issues, it causes acid rain with harmful effects on the vegetation
Sulphur Oxides (SOx)	The generation is connected to the sulphur content of the burnt fuel. In the combustion process, the sulphur reacts with oxygen, forming SO_2. SOx reduction can be achieved by burning low sulphur content fuel or by the use of scrubbers	SOx are responsible for respiratory infections and vegetation by creating acid rain. Low concentrations can cause eye irritation, chest pain, and lung illnesses. High concentrations can even cause death
Hydrocarbons (HC)	This is formed from partially burned fuel and lubricating oil, and the main emissions will result from incomplete combustion	HC can cause health problems, from mild effects, such as eye irritation, to severe effects, such as high toxicity
Carbon monoxide (CO)	The emissions depend on the engine's load and performance, and are dependent on the combustion process that takes place, and the quantity of air supply for the combustion	CO is colourless, odourless, and tasteless, and can cause death at high concentrations
Particulate matter (PM)	Represents a combination of organic and inorganic components from non-combusted or partially combusted carbon elements of the fuel and lubricating oil	PM emissions are responsible for a considerable amount of lung cancer. The size of the PM determines the effect on human health
Ozone (O_3)	The ozone layer is affected by substances such as halogenated refrigerants and propellant gases	When the ozone layer is affected, the ultraviolet B radiation causes skin and eye damage

Source: (Kristensen, 2012)

The harmful effects of the emissions have driven international and EU institutions to impose limits on the GHG emissions from maritime transport. Therefore, maritime organizations set ambitious goals for the emissions generated from ship operations (Figure 2.2).

2.3 International and EU Requirements for Emissions Reduction from Maritime Transport

2.3.1 IMO Approach to GHG Emission Reduction

The IMO short, mid, and long-term measures are shown in Table 2.8.

Table 2.8 Short, mid, and long-term IMO measures

Plan	Measures
Short-Term	Improvement of energy efficiency (EEDI and SEEMP) Development of technical and operational energy efficiency solutions Use of speed optimization tools and speed reduction Developments of port activities and logistics to encourage GHG reduction from shipping Start the research on alternative technologies and fuels
Mid-Term	Development of different technologies for low-carbon and zero-carbon fuels Enhance operational and technical energy efficiency initiatives
Long-Term	Progress the studies and use of neutral fuels to take into account the full decarbonization of shipping around 2050 Advance and accelerate the adoption of innovative technologies for emission reduction

Source: (IMO, 2020)

To achieve the ambitious goals, IMO is emphasizing the necessity of technical innovation for the medium- and long-term targets, and novelty and the development of alternative fuels and alternative resources for powering and running the vessels.

2.3.2 EU Environmental Regulations

The EU environmental regulations that impact maritime transportation are:

a) The *EU Emission Trading System (EU ETS)*. The regulation works in a 'cap and trade' approach, a 'cap' representing a limit of the GHG emissions that can be released by an installation.

b) *FuelEU Maritime* belongs to the 'Fit for 55' package and intends to reduce emissions from maritime transport by using renewable and low-carbon fuels.

c) *Low sulphur fuel*. As per (European Union, 2005), from 1st January 2010, vessels should burn fuels with a sulphur content less than 0.1% in the inland waterways and while at berth in the European ports.

d) *Shore-side electricity.* Among the solutions for reducing pollution and limiting global warming, (European Union, 2016) accentuates the use of shore-side electricity while the ships are docked.

CHAPTER 3

METHODS AND TECHNOLOGIES TO ENHANCE SHIPS' EFFICIENCY

3.2 Energy Efficiency Measures

3.2.1 Energy Management Measures and Implementation

Table 3.2 shows the potential operational and technical solutions that can be applied onboard the vessel.

Table 3.2 Energy efficiency measures and their potential savings

Area	Category	Measures	Potential energy efficiency gain	Potential GHG reduction
Operational measures	Voyage management	Voyage planning	1-10%	1-10%
		Weather routing		1-10%
		Trim and draft optimization		1-10%
		Auto-pilot optimization		1-10%
		Hull biofouling management		5-25%
		High-performance coating		2-20%
		Energy management		1-10%
		High-efficiency propeller		5-15%
	Fleet strategies	Vessel deployment and schedule	1-15%	2-50%
		Fleet portfolio optimization		5-50%
		Fleet management, logistics		5-50%
		Speed optimization		Up to 75%
Technical measures	Hull and propeller efficiency	Hull design optimization	1-8%	2-20%
		Propeller design		5-15%
		Anti-fouling systems		5-25%
		Propulsion improving devices		5-15%
		Air lubrication		1-10%
	Propulsion systems	Optimized cooling system	1-5%	5-15%
		Exhaust scrubber		SOx-98%
		Exhaust gas recirculation		NOx-35%
		Selective catalytic reduction		NOx-35%
		Waste heat recovery		1-10%
		Engine technology		1-10%
	Alternative fuels	LNG, LPG	1-15%	35%
		Hydrogen, Ammonia, Methanol		80-100%
		Biofuel		90%
		E-fuels		100%
	Alternative power systems	Full electric	1-8%	50-90%
		Solar-sail system		50-90%
		Wind assisted propulsion		50-90%
		Nuclear power		50-90%

Source: (IMO, 2022b)

3.3 Future Technologies

Currently, most of the fuels used in maritime transport consist of fossil fuels, which are responsible for 1,036 t of CO_2 per year (Law et al., 2022). One of the most viable solutions is the use of alternative fuels, either with low-carbon content or carbon neutral. Figure 3.3 shows the number of ships in operation and on order, as per the fuel used.

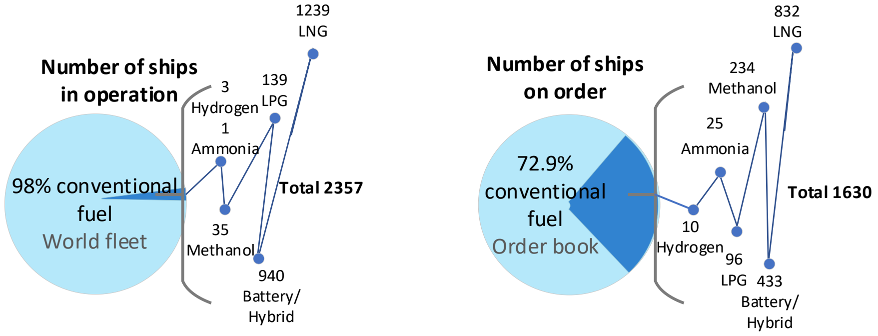


Figure 3.3 Alternative fuel uptake by number of vessels, as of June 2024

Source: (DNV, 2024)

3.3.1 Technologies for Zero-emissions Vessels

Renewable energy can be used directly for the ship's propulsion or can be used to produce green fuels (Mallouppas & Yfantis, 2021). Renewable technologies are (Issa et al., 2022; Mallouppas & Yfantis, 2021):

1. Wind – sails, rotors, kites, wind turbines.
2. Solar energies – solar photovoltaics.
3. Nuclear power.
4. Carbon Capture and storage technology.
5. Fuel cells.
6. Batteries and supercapacitors.

3.3.2 Evaluation of Alternative Marine Fuels

As of today, 98% of the fuels used for vessels' propulsion in operation consist of conventional/fossil fuels, and only 2% alternative fuels. Maritime transport has already started to use alternative fuels, which at the moment are regarded as the most viable solution for the decarbonization strategy.

All the alternative fuels can be categorized into the following categories, based on the source of production (DNV, 2023), Figure 3.5:

- Grey fuels, alternative fuels produced from conventional sources, such as coal, do not reduce CO_2 emissions considerably;
- Blue fuels, deriving from natural gas with CCS (Carbon Capture and Storage) - importantly reduce CO_2 emissions;
- Biofuels, deriving from bioenergy sources, such as biogas, biodiesel - low on CO_2 emissions and have low sulphur content;
- Green fuels, Electro fuels, deriving from renewable electricity – technology considered with zero CO_2 emissions.

Grey	Blue	Green
Conventional / Fossil fuels (HFO, LNG, LPG, Methanol)		
Hydrogen	**Hydrogen** Produced from conventional sources gas/coal with CCS	**Hydrogen** Produced from renewable electricity
Ammonia	**Ammonia** Produced from conventional sources gas/coal with CCS	**Ammonia** Produced from renewable electricity
	e-fuels Produced with CO_2 from CCS from different combustion process	**e-fuels** Produced with CO_2 directly from the atmosphere
		Biofuels

Figure 3.5 Alternative fuel types and production sources

Source: Author

The alternative fuels specific energy and storage requirements are presented in Table 3.4.

Table 3.4 General characteristics of available alternative fuels

Alternative Fuels	Specific Energy (MJ/kg)	Storage requirement onboard	Required storage capacity (m3)
MGO	42.7	Liquid at ambient temperature	1,000
LNG	50.0	-163°C	1,602
LPG	46.4	-43°C	1,527
Methanol	22	Liquid at ambient temperature	2,272
Ethanol	26.0	Liquid at ambient temperature	1,693
Biodiesel	38-46	Liquid at ambient temperature	
Electricity	-	High energy density	-
Hydrogen	120-140	350-700 bar (gas); -253°C (liquefied)	4,223
Ammonia	18.6	21°C under 8.8 bar; -33°C atm pressure	3,121

Source: (Reusser & Osses, 2021)

It is observed that, from the alternative fuels, only methanol and biofuels are stored at ambient temperature and standard pressure. The storage of the other alternative fuels at very low temperatures implies special equipment required for storage, as well as different engine arrangements onboard. Vessels powered by low temperature storage alternative fuels need a fuel preparation room as well to prepare the fuel before being used by the engine. Cooling down the tanks as well as preparing the fuel for the main engine requires extra energy that needs to be generated onboard. An important consideration is the specific energy of alternative fuels, which means the engines have another fuel consumption than conventional fuels. It leads to an increase in fuel storage tanks onboard, which has a direct impact on the cargo lost space.

3.4 Cost-effectiveness of Current Decarbonization Options

The economic impact of alternative fuels is illustrated in two studies, as follows:

A. CAPEX, OPEX, and emissions under current conditions, when the vessel uses fossil fuels and four decarbonization alternatives.
B. The cost of lost cargo area (space) when the vessel burns methanol and ammonia.

A. The study calculates and analyzes costs and emissions in different cases (Table 3.13). The vessel's particulars are:

LENGTH OVERALL	302 m
DEADWEIGHT	95,906 t
GROSS TONNAGE	85,745
TEU	8,150
TOTAL ENGINE POWER	64,640 kW
AUX ENGINE POWER	1,416 kW
AVERAGE DAILY ENERGY CONSUMPTION (IDLE)	1,400 kWh
AVERAGE DAILY ENERGY CONSUMPTION (SAILING)	14,000 kWh

The operational vessel's summary is presented in Table 3.11.

Table 3.11 Outline of results for the vessel considered for one year, given route

AVG SPEED (knots)	HRS SEA	HRS IDLE PORT/DRIFT/ANCHOR	DISTANCE (NM)	VLSFO consumption (t)	MDO consumption (t)
15.7	6,839.5	1,992.6	107,463	21,775.7	2,910.3

Source: Author

Detailed fuel consumption based on idle and sea times and the type of fuel is in Table 3.12.

Table 3.12 Breakdown of fuel consumption based on idle/sea time and type of fuel (t)

Condition	VLSFO	MDO
Sea	21,023.4	2,412.3
Idle	752.3	498

Source: Author

The operational profile of the vessel is:

- Idle (Moored/Anchor/Drifting) 83 Days/year (23%);
- Moored only 67 Days/year (18%);
- Sailing time 282 Days/year (77%).

The report will return:

- CAPEX/OPEX breakdown;
- Emissions amount.

for the current condition, and in the following decarbonization alternatives, as in Table 3.13:

Table 3.13 Decarbonization alternatives

Alternatives	Type of Shore Decarbonization Method	Onboard preventive measure	Change to alternative fuel
1	Shore Power	Hull Coating	Methanol
2	Shore Power	Hull Coating	Biofuels
3	Shore Power	Hull Coating	Hydrogen
4		Hull Coating	Full Electric

Source: Author

CAPEX, OPEX, and emissions results are graphically illustrated in Figures 3.8, 3.9, and 3.10.

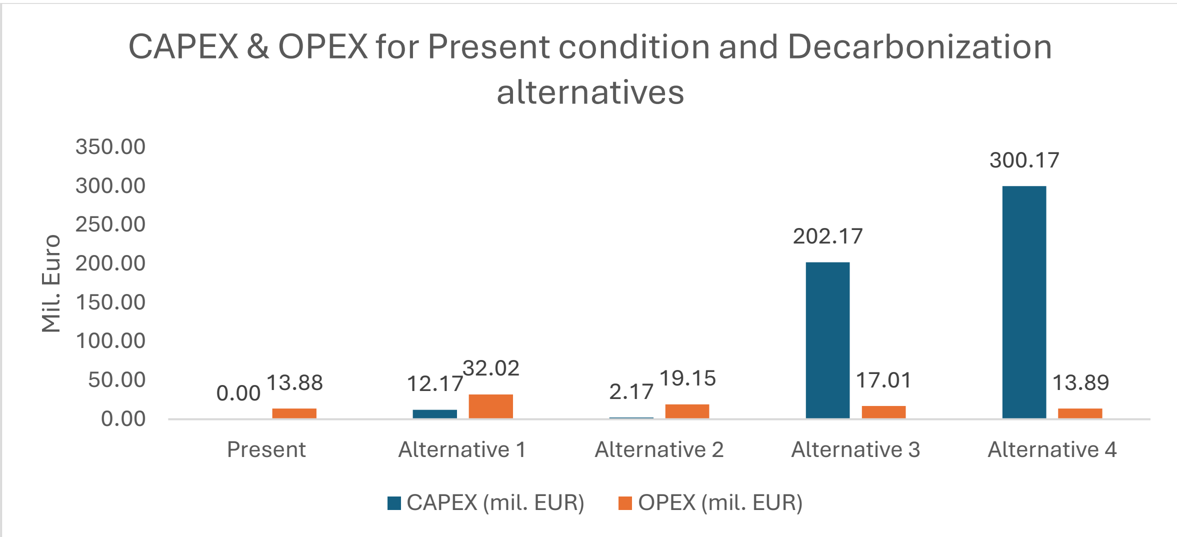


Figure 3.8 CAPEX and OPEX for present condition (fossil fuel) and decarbonization alternatives (Million EUR)

Source: Author

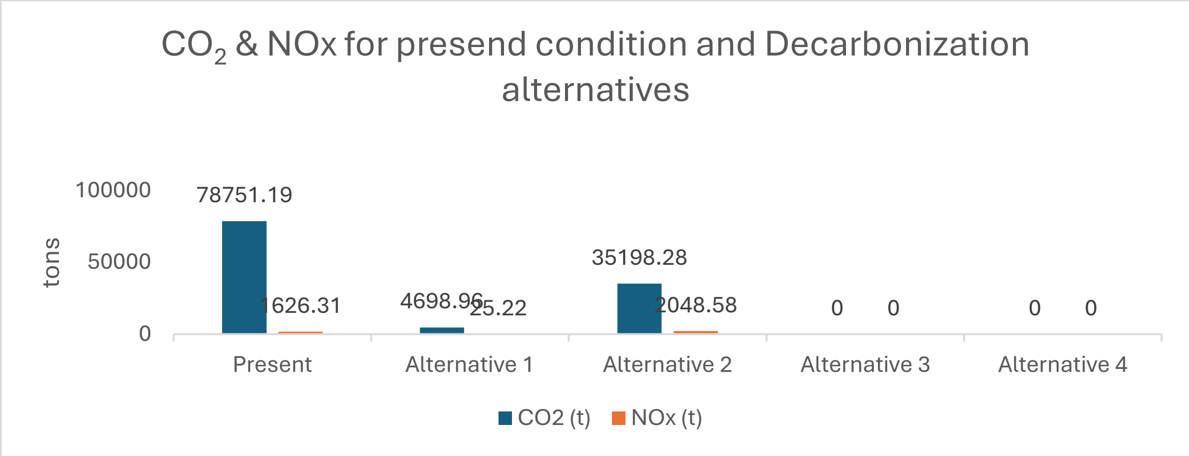


Figure 3.9 CO_2 and NOx for present condition (fossil fuel) and decarbonization alternatives (t)
Source: Author

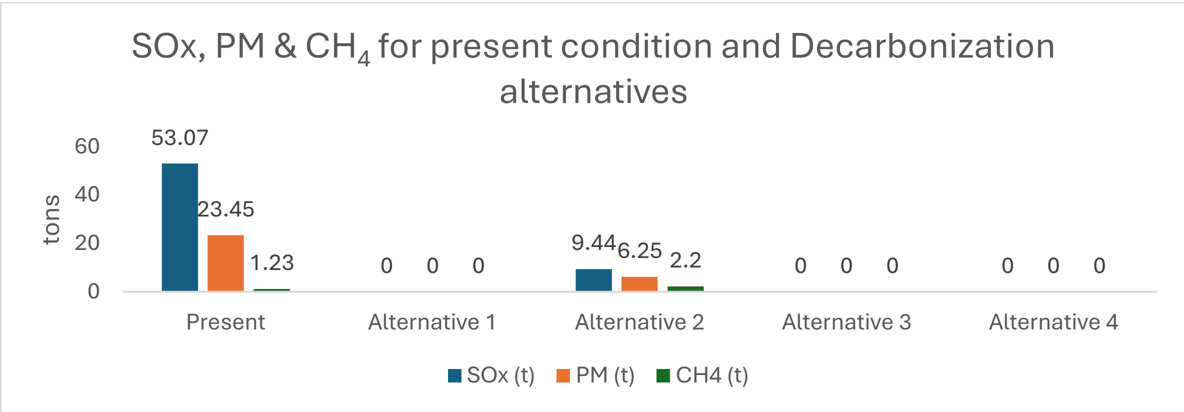


Figure 3.10 SOx, PM, and CH_4 for present condition (fossil fuel) and decarbonization alternatives (t)
Source: Author

Conclusions

Alternative fuels represent feasible and practical answers to decarbonizing maritime transport. However, the transition to alternative fuels comes with a significant cost for the Ship Owner. The conclusions that emerge from the research are:

1. Operational option applied onboard (hull coating) can reduce fuel consumption and emissions up to 20% (see Table 3.2). Cold Ironing is a mature and ready solution to be implemented for the vessels in ports, and OPEX returns important savings.
2. CAPEX - If for methanol the engine retrofit is necessary, for biofuels, no engine alterations are required, since biofuels can be blended with fossil fuels. For hydrogen and full electric, besides the new engine design, the fuel tank capacities require large design modifications in the ship's design.
3. It is noticed that the CAPEXs for hydrogen and full electric options are very high; however, OPEXs are similar to fossil fuels, and with the reduction perspectives in the next decades.
4. Even if some alternative fuels have already reached maturity in different aspects, global usage is still in the early stages, mainly because of technical incompatibilities, environmental regulations, costs, infrastructure difficulties, and seafarers' competence and training.

B. This research uses the same vessel's details as in study A. This study calculates the cost of lost cargo space when a container vessel burns methanol and ammonia. The cargo lost space has a significant impact on the earning potential of the vessel throughout its lifetime. The results are shown in Table 3.29.

Table 3.29 Cost of lost cargo area for an 8,150 TEU container vessel (EUR)

Fuel	Cost of lost cargo area (EUR)
Methanol	55,655
Ammonia	75,703

Source: (Rauca & Batrinca, 2024)

Conclusions

When it comes to alternative fuels, the lost cargo area is an issue that must be taken into account by the Ship Owner. Alternative fuels have different energy densities compared to fossil fuels; therefore, they require more fuel space. The results are:

1. The cost of lost cargo area can increase substantially with the vessel size; the amount is significantly higher for alternative fuels with lower energy density.
2. Regardless of whether the Ship Owner chooses a one-stop or two-stop approach, the Ship Owners must determine the frequency of bunkering based on the vessel's route and conduct a thorough review of the fuel tank capacity.
3. The best location for alternative fuel tanks is another factor that needs to be considered.
4. Throughout its existence, the cargo lost capacity has a major effect on the vessel's earning potential. The owners must assess all options when selecting an alternate fuel or retrofitting, depending on the following: bunkering occurrence, financial evaluation, comparing prospective cost reductions against financial losses from decreased cargo capacity, port sequence, and bunkering facilities to enable the potential for bunkering more than twice during a journey, long-term fuel accessibility, and vessel projected lifetime.

CHAPTER 4

COLD IRONING SYSTEM AS A MEASURE FOR SUSTAINABLE PORTS AND VESSEL OPERATIONS

4.1 Cold Ironing System Overview

Shoreside Electricity (SSE), Cold Ironing (CI), Onshore Power Supply (OPS), or Alternative Maritime Power (AMP) provide electrical power to the vessels while made fast alongside, using onshore facilities.

While the vessels are moored, the energy necessary for the running of auxiliary engines is provided by the shore power supply. The engines, normally burning fuel to provide the electricity required for all the operational activities, are now connected to shore power. This is an essential facility provided by the ports as it eliminates the harmful GHG emissions from the vessels while at berth. Besides the emissions reduction, other advantages include noise and vibration reductions, improving the visibility in the port, and, in the end, increasing the safety of the port personnel.

4.4 Assessment of Cold Ironing in Port of Constanţa

The examination will focus on the Cold Ironing system in the Port of Constanţa, and it analyzes the implementation of this project from the emissions perspective. The following berths will be investigated (Figure 4.4):

114 – Bulk terminal;

121&123 – Container terminal.

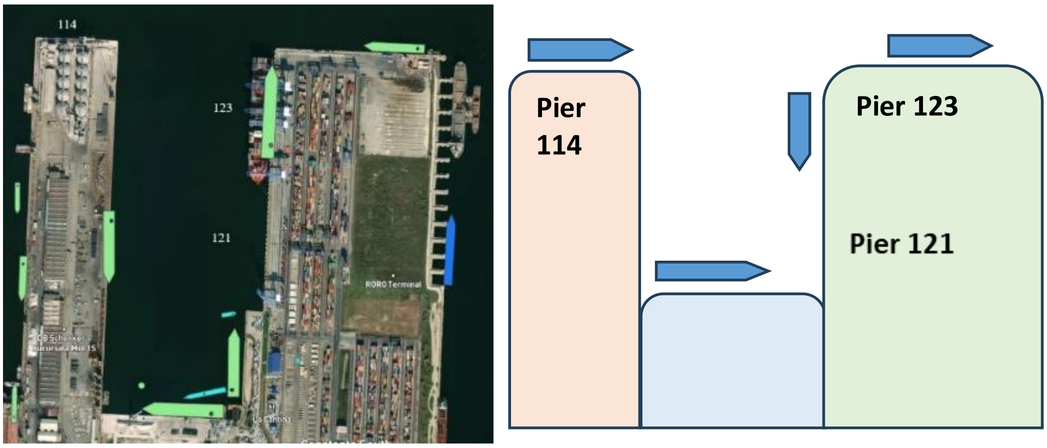


Figure 4.4 Berths 114, 121&123 in Port of Constanţa

Source: Marine Traffic; Author

4.4.1 Assessment of Emissions, Fuel, and Electricity Costs

4.4.1.1 Evaluation of Vessels' Air Pollution

This study compares the emissions of ships burning fossil fuels vs emissions generated by the energy production for the Cold Ironing technology. It analyzes the vessels that called at the berths 114 – Bulk Terminal and berths 121&123 from the Container terminal, between the years 2021-2023. Figures 4.5 and 4.6 show the emissions quantities and fuel oil consumption from ships docked at berths 114, 121&123 in the period 2021-2023.

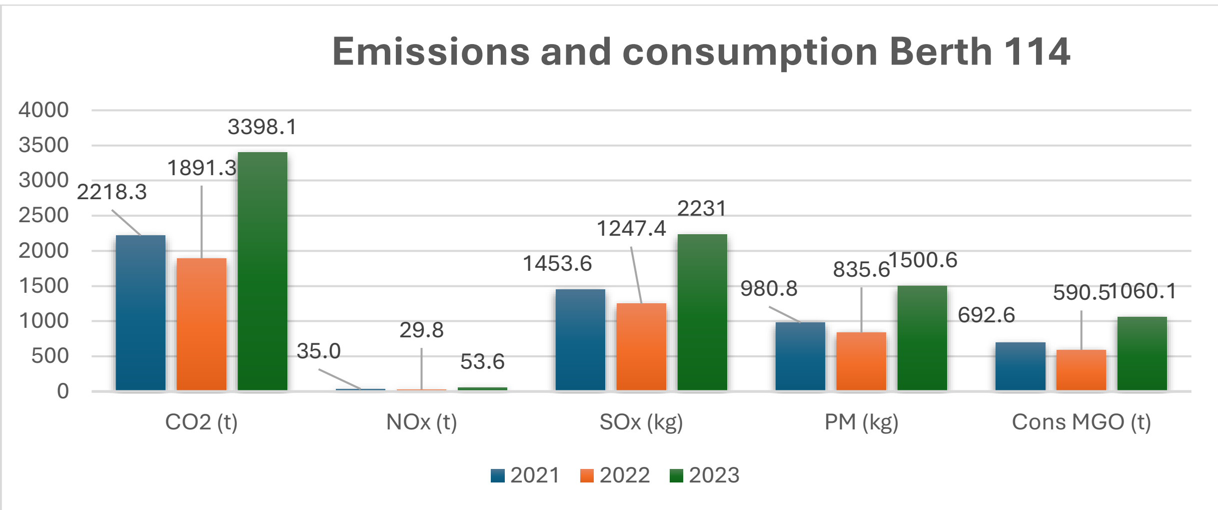


Figure 4.5 Emissions and fuel consumption at berth 114, 2021-2023

Source: Author

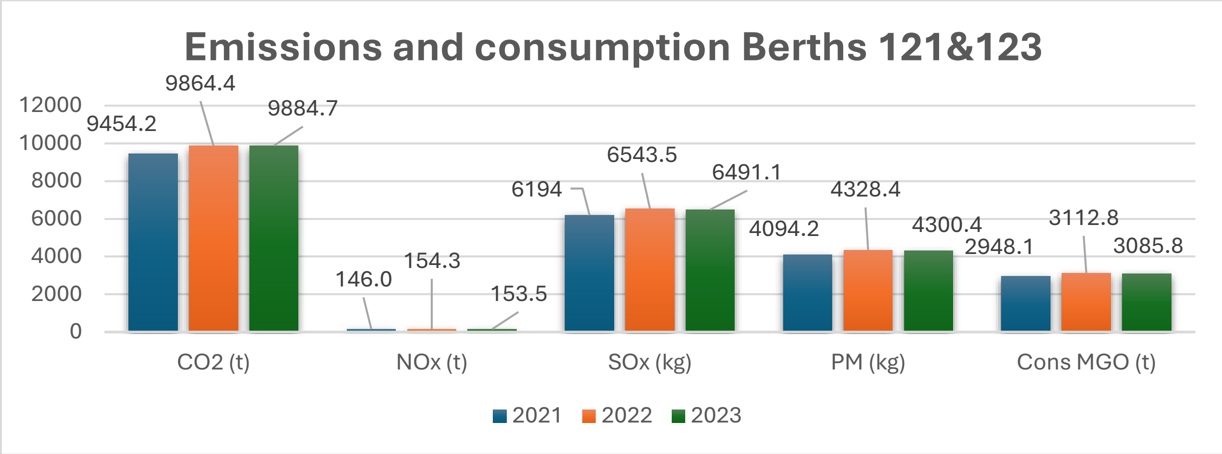


Figure 4.6 Emissions and fuel consumption at berths 121&123, 2021-2023
Source: Author

Next, the emission will be calculated when the shore-side electricity is used. Even if electricity itself does not generate any pollution, there will be emissions generated by the electricity production. The emissions reduction by using onshore power supply in Port of Constanţa in the berths 114, 121&123 for the years 2021-2023 is shown in Figures 4.7 and 4.8.

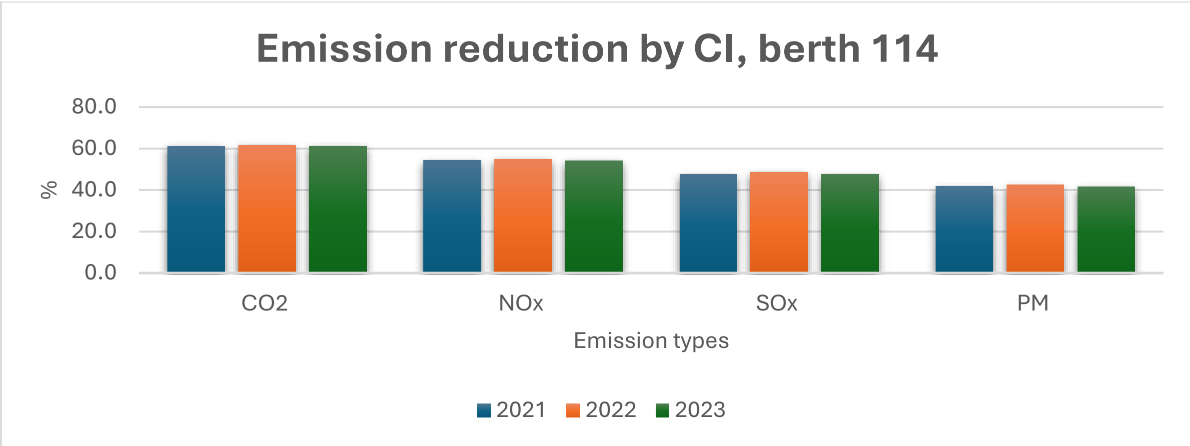


Figure 4.7 Emission reduction from Cold Ironing at berth 114, 2021-2023 (%)
Source: Author

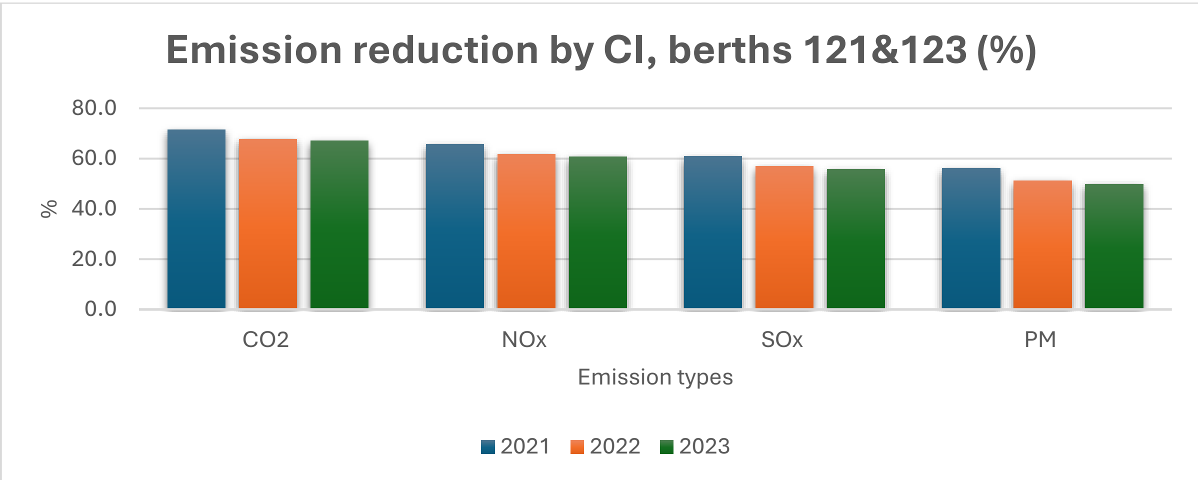


Figure 4.8 Emission reduction from Cold Ironing at berths 121&123, 2021-2023 (%)
Source: Author

Conclusions

Vessel traffic increased significantly in both terminals in 2023 compared to previous years. The tendencies are showing that vessel numbers will increase, the fact that will lead to an increase in fuel oil consumption during port stay, therefore the emissions will increase with harmful effects on the population. The average amount of CO_2 emissions is 12,000 tonnes per year, and fuel consumption during port stay only is more than 3,700 tonnes each year.

The Cold Ironing system offers the possibility of using a shore power alternative in the Port of Constanţa. The berths studied will allow the vessels moored to be connected to shoreside electricity; therefore, to use the electricity to power the vessels, instead of burning fossil fuel. The benefits of CI are numerous; however, the most important advantage will be the absence of pollution in the terminals and berths where it is installed. This fact will lead to an increase in the air quality in the port area and port vicinity, and an increase in working quality for both the port and ship personnel.

Even though the electricity has zero emissions when used for powering the vessels, the production of the electricity is not free of pollutants. The calculations show a substantial decrease in well-to-wake emissions, with an average of 60%. The amount of emissions can be further decreased if the electricity is produced from renewable sources.

4.4.2 Cold Ironing Implementation Costs

4.4.2.3 Cost Assessment of Vessels Under Different Operational Profiles

The following study assesses the cost of a given route for Vessel B (bulk carrier) and Vessel D (container vessel), having similar cargo capacities (Vessel B – 114,000 DWT and Vessel D – 101,000 DWT). The study focuses on analyzing the fuel oil cost if the vessels burn fuel oil only vs the costs when the vessels are connected to shore power in EU ports. The study calculates the EU ETS and FuelEU Maritime of both vessels on a yearly basis, then it calculates the total costs in different configurations, taking into account the retrofit costs. Comparing a container ship and a bulk carrier of similar size or cargo capacity highlights how vessel type and operational profile (engine design, speed, and energy demand) influence emissions, even when the transport capacity is comparable.

The vessels' consumption and operational profiles are presented in Tables 4.25 and 4.26.

Table 4.25 Breakdown of fuel consumption based on idle/sea time and type of fuel for Vessel B (t)

Condition	HFO	VLSFO	MGO
Sea	4,255	1,537	458
Idle	0	388	422

Source: Author

The operational profile of the Vessel B is:

- Idle (Moored/Anchor/Drifting) 148 Days/year (41%);
- Moored only 44 Days/year (12%);
- Sailing time 217 Days/year (59%).

Table 4.26 Breakdown of fuel consumption based on idle/sea time and type of fuel for Vessel D (t)

Condition	VLSFO	MGO
Sea	21,023.4	2,412.3
Idle	752.3	804

Source: Author

The operational profile of the Vessel D is:

- Idle (Moored/Anchor/Drifting)	83 Days/year (23%);
- Moored only	67 Days/year (18%);
- Sailing time	282 Days/year (77%).

Assuming half of the time the vessel is moored in EU ports, it means the fuel oil consumption while moored is (Table 4.27):

Table 4.27 Duration of port stay and fuel oil consumption for Vessel B and Vessel D while moored in EU ports

Vessel	Port stay (days)	MGO consumption while moored (t)
Vessel B	22	110
Vessel D	34	306

Source: Author

The results are illustrated in Figure 4.11 and Figure 4.12.

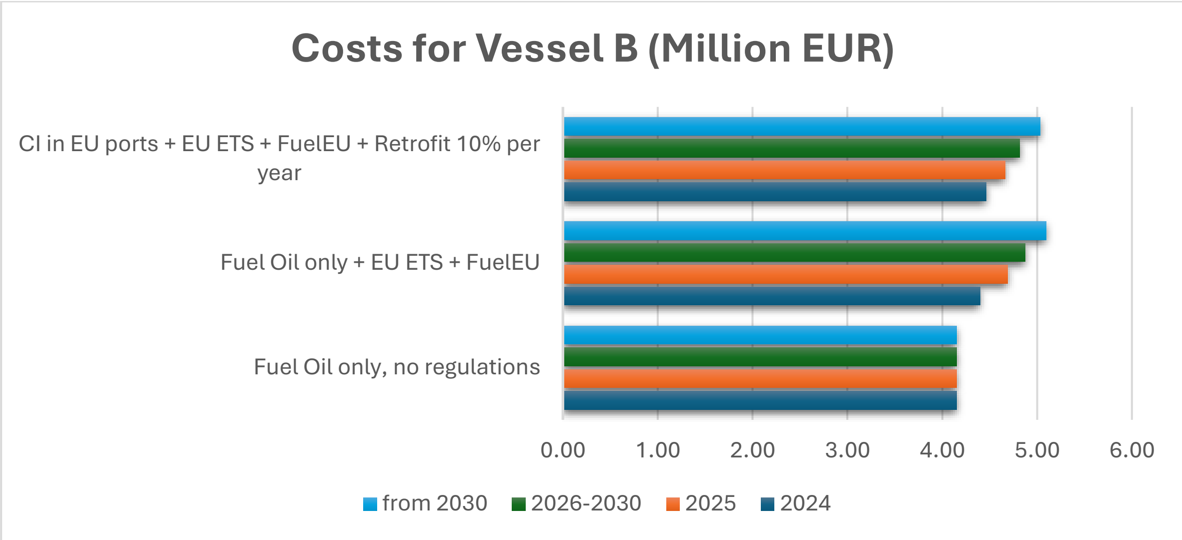


Figure 4.11 Costs for Vessel B (Million EUR)

Source: Author

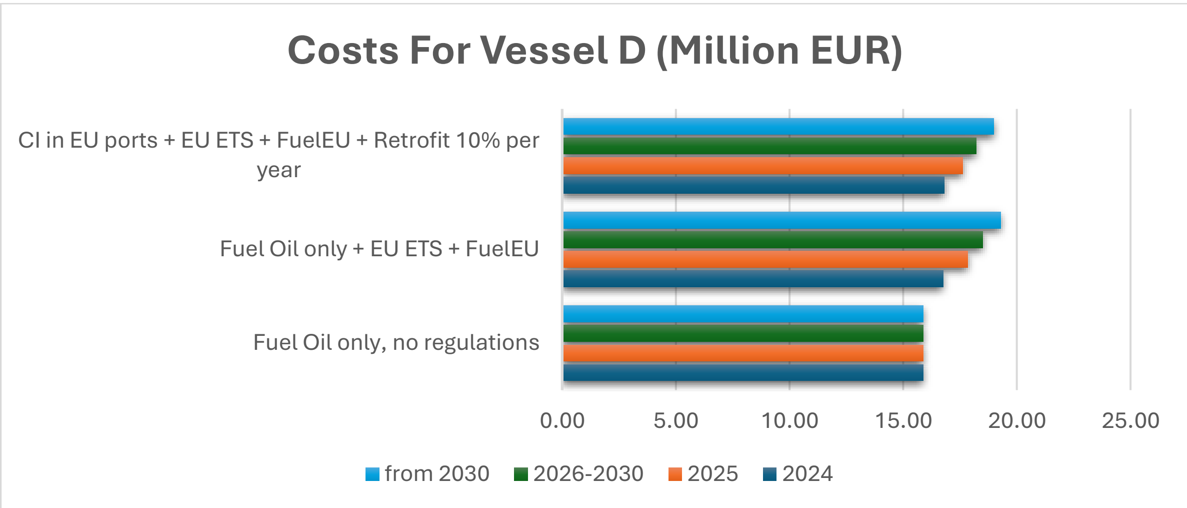


Figure 4.12 Costs for Vessel D (Million EUR)

Source: Author

Conclusions

The study analyzed a one-year route from the perspective of two vessels, one container vessel and the other a bulk carrier, both having similar cargo capacities. The vessels have different operational profiles; bulk carrier has longer idle/service times, both at anchor and at berth, compared to container vessels, due to different types of cargo operations and necessary equipment at port. Assuming that the vessels are moored in EU ports for half of the total moored time in a year, the fuel oil used in EU ports is MGO, with a sulphur content of 0.1%. In addition to EU ETS and FuelEU Maritime costs, the Ship Owners will cover the vessel retrofit costs for installing the Cold Ironing system. The study considered that the CI retrofit costs will be amortized over a 10-year period. The conclusions of these findings are:

1. From 2025, the Ship Owners have more costs associated with the new EU ETS and FuelEU Maritime regulations. Cold Ironing could be a solution, but the emission reduction is in the port only when the vessels are moored.
2. In order to use the CI system in the ports, existing vessels have to be retrofitted. Depending on the vessel type and size, the retrofit costs are significant. Assuming that the retrofit costs will be amortized over a 10-year period, that will increase the total operational costs by more than 13%.
3. The CO_2 emissions will decrease by less than 3% for each vessel when using CI in EU ports, while the total costs will increase by 17% on average compared to the situation when no regulations are in place.
4. The CI technology can lower the costs and reduce emissions; however, port container vessels, by the nature of their cargo operation and port infrastructure, have a short port stay, one day on average. For the other type of vessels, such as bulk carriers, where the port stay is longer, the CI technology can have a higher impact on the final operational costs.
5. New EU regulations and a significant increase in the costs in EU waters could prompt Ship Owners and charterers to seek more convenient ports outside the EU to operate their vessels. That can have a significant impact on the European economy, as the cargo could be shifted to other means of transportation, increasing the transfer time, costs, and pollution.
6. The calculations show that the costs increase substantially; however, the emissions in the port are reduced to zero, since the electricity has no emissions. This fact will lead to an increase in air quality in the port area.

CHAPTER 5

PORT EFFICIENCY AND ITS IMPACT ON VESSEL PERFORMANCE AND ENVIRONMENT

5.1 Introduction

The berth allocation problem is of utmost importance in port activity. It relates to the proper allocation of berths to arriving ships, in order to reduce the waiting times and delays, and most importantly, reduce the costs and emissions. A typical berth allocation problem can be adapted and remodelled into a Cold Ironing berth allocation problem. It means that vessels, instead of staying at anchor awaiting a free berth, can dock at a free berth that has implemented shore-side electricity, with the condition that both the vessel and the Cold Ironing free berth are compatible. The algorithm developed from the berth allocation problem shows important savings in terms of costs and emission release. In this way, the vessels properly use the port facilities and comply with environmental regulations. The advantages of utilizing a free Cold Ironing berth instead of waiting at anchor before docking at the scheduled berth are:

- Important reduction of emissions. In case the vessel waits at a Cold Ironing berth, it does not use auxiliary engines to provide electricity; it is connected to shore-side power.
- Cost savings. Depending on the price of electricity, connection to shore power can be less expensive than fuel oil.
- Compliance with EU regulations. While the vessel uses shore-side electricity instead of using fuel oil, the vessel will be FuelEU compliant.
- Decrease the penalties imposed by EU legislation. The regulations establish a cost on GHG (Greenhouse Gas); therefore, the costs will be reduced.
- Improving CII rating. By reducing the CO_2 emissions, the rating will improve, and the vessel will be more attractive to potential charterers.
- Improving the port air quality and improving the working quality conditions for all the parties involved in the ship operations, from the vessel personnel to terminal workers.

5.2 Cold Ironing Berth Allocation Model

5.2.1 Description and Objectives of the Proposed Model

A Cold Ironing allocation berth model could be a solution to take advantage of the shore-side power facilities that the ports must provide starting from 2030, as required under the EU regulations. Considering the high number of waiting days for a vessel before docking, waiting at a free berth equipped with Cold Ironing is an important opportunity for both the vessel and the port.

Firstly, the berth efficiency is assessed to identify methods to reduce congestion. Thereafter, a berth allocation model that integrates Cold Ironing requirements is applied to minimize costs and emissions. In this way, the vessels will use the engines only for manoeuvering purposes, from the port roadstead to the Cold Ironing berth and when moving from the Cold Ironing berth to the allocated berth. For the time the vessel waits at a Cold Ironing berth, the vessel is connected to shore-side electricity; therefore, the auxiliary motors will be shut off, and the vessel will use shore electricity instead of burning fuel oil.

The model aims to determine the efficiency of vessel port call operations, having two main objectives:

1. To analyze the efficiency of berth utilization with the purpose of reducing vessel waiting times. Within the model, the operational efficiency of berths is analyzed in terms of waiting times and utilization rate. The duration of loading/unloading operations is included; however, the analysis focuses on ways to reduce waiting times through the application of queuing models.

2. To maximize the utilization of berths equipped with Cold Ironing (CI) to reduce costs and emissions.

The model characteristics are:

a) The assessment of system performance parameters is needed to analyze the resources and capacity limits and evaluate the ships' waiting time to optimize the port activities and to use port resources efficiently in conditions of various requirements (Raicu et al., 2023).

b) The model refers to a discrete berthing layout, meaning that a vessel can dock at one berth at a time and cannot use more than one berth. While at berth, only one vessel can be connected to the pier's shore power. For the same reason, double berthing is excluded.

c) For a vessel to be able to berth at a Cold Ironing berth (CIB), the compatibility between the shore-ship voltage connection is deemed necessary. In addition to the compatibility restrictions, the length of the pier and the water depth at the Cold Ironing berth should align with the length and draft of the vessel.

d) The model considers the weather conditions. In case of unfavourable conditions and the port is closed, the ship traffic inside the port area is suspended. It will further advantage the vessels that are already waiting at CIB (Cold Ironing Berth) to use electricity instead of remaining at anchor and burning fuel, waiting for the hydro-meteorological conditions to improve. CIB is the berth fitted with Cold Ironing technology.

e) In the situation where the port is congested, and the number of vessels queued at the port roadstead is higher than a limit imposed by port authorities, the incoming vessels are instructed to adjust their speed to arrive later in the port area. The new speed will permit vessels to a later arrival so that the waiting time is minimized. Thus, vessels slow down and consume less fuel, which has a direct influence on the costs and emissions.

The adjusted speed should be above the economic speed of the vessels (see subchapter 1.3 for the economical speed definition). In case the adjusted speed falls below the economic speed, vessels are either instructed to anchor at an outer designated anchorage for cargo operation by barges, to proceed to another/alternative berth if permitted, or, ultimately, to proceed to another port, mostly the case of liner vessels.

f) The service discipline at ALB (Allocated Berth) can be either FIFO or priority-based - according to the type of goods transported (grain cargo has priority over other types of cargo, due to their perishable nature). That priority does not apply to CIB; the vessels enter at the Cold Ironing berth on a first-come, first-served basis, as the vessels don't operate at CIB. ALB is the specific berth allocated/designated for loading/unloading cargo.

g) This model aims to find the minimum costs associated with the most feasible arrangements based on the available Cold Ironing berth, subject to defined constraints. Once arrived in the port area, instead of waiting at anchor, the vessels are instructed to proceed to a free berth fitted with a shore electricity system. In this way, the ships will wait at a berth equipped with Cold Ironing until the designated/allocated berth becomes available.

The model will calculate the costs and the ship emissions under the solution found, indicating the duration of waiting time at anchor, manoeuvring time from anchor to Cold Ironing berth, duration of stay at Cold Ironing berth, manoeuvring time from Cold Ironing berth to designated berth, and duration of handling time – operational time at allocated berth. The model considers a safety entrance time between two successive vessels, for the docking purpose, to avoid two vessels coming across at the same berth.

Figure 5.3 illustrates the Cold Ironing berth allocation model.

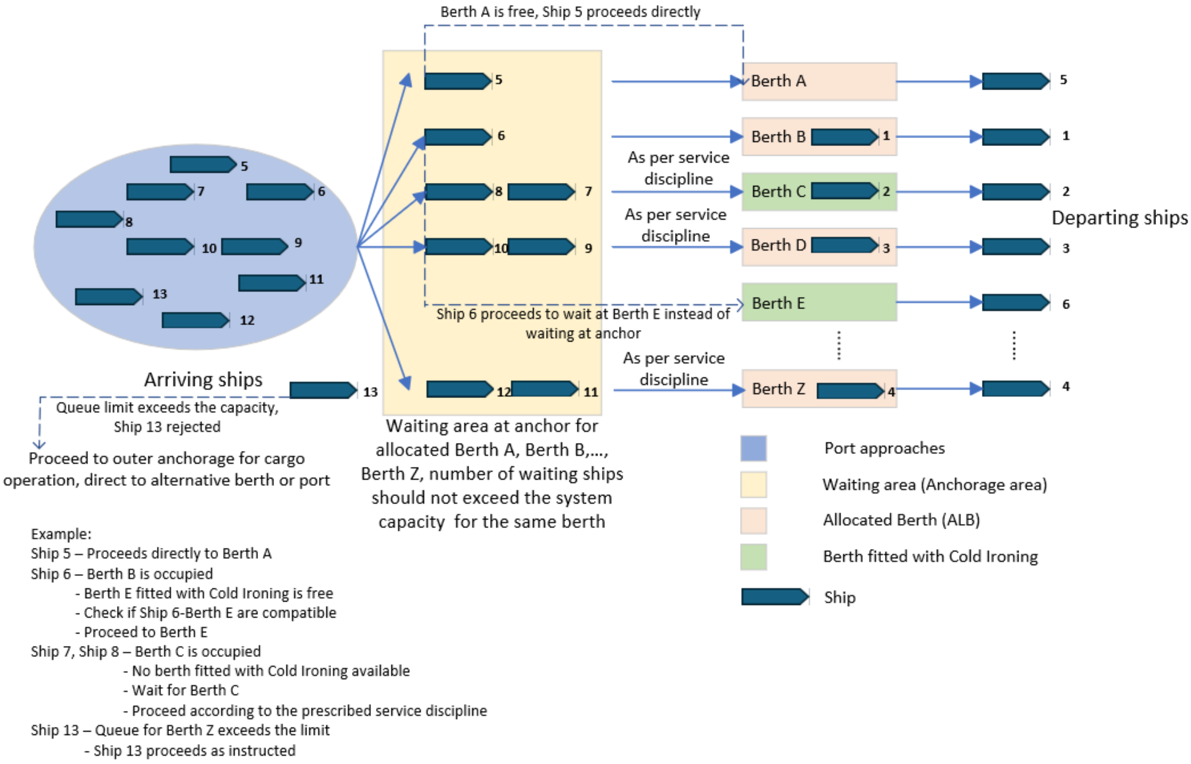


Figure 5.3 Cold Ironing berth allocation model

Source: Author

5.2.2 Methodology

The Cold Ironing berth allocation model is divided into three main sections:

I) Queuing system models;

II) Speed adjustment from the previous port to the current port;

III) CI Berth allocation model costs and emissions.

I) Queuing system models

Queuing system models are used for an accurate illustration of port activities/operations. The queuing system models applied are M/G/1/b/∞/FIFO, M/G/1/b/∞/PQ(NP), and M/G/1/b/∞/PQ(P) to determine the terminal/berths workload and efficiency. Queueing models enable more efficient traffic in the port; otherwise, ports experience congestion and prolonged waiting times, which, in the end, result in higher fuel consumption and pollution.

Due to the complexity of the finite-capacity system, there isn't a simple, specific formula to calculate the blocking probability and average time in the queue. Due to the irregularity of arrivals, the variation in service times, and the finite capacity of the system, the blocking probability and the waiting time at anchor were determined through simulation by tracking the system's evolution over time. Based on the input parameters — arrival time at the port, priority, service time at berth, and system capacity — relevant information regarding the overall behaviour of the system can subsequently be obtained.

The summary of formulas for the M/G/1/b/∞/FIFO, M/G/1/b/∞/PQ(NP), and M/G/1/b/∞/PQ(P) queueing models is illustrated in Table 5.1.

Table 5.1 Summary of formulas for the M/G/1/b/∞/FIFO, M/G/1/b/∞/PQ(NP), M/G/1/b/∞/PQ(P) queueing models

Parameter	M/G/1/b/∞/FIFO	M/G/1/b/∞/PQ(NP)	M/G/1/b/∞/PQ(P)
Total utilization for priority class *j* (ψ_j)	-	$\psi_j = \frac{\lambda_j}{\mu_j}$	$\psi_j = \frac{\lambda_j}{\mu_j}$
Total utilization (ψ)	$\psi = \frac{\lambda}{\mu}$	$\psi = \sum_{i=1}^{j} \psi_i$	$\psi = \sum_{i=1}^{j} \psi_i$
Blocking probability total $P_{block,total}$	Through simulation	Through simulation	Through simulation
Blocking probability per class ($P_{block,j}$)	-	Through simulation	Through simulation
Effective arrival rate (λ_{eff})	$\lambda_{eff} = \lambda \times (1 - P_{block})$	$\lambda_{eff,j} = \lambda_j \times (1 - P_{block,j})$	$\lambda_{eff,j} = \lambda_j \times (1 - P_{block,j})$
Average waiting time (ω_Q)	Through simulation	Through simulation	Through simulation
Average time in the system (ω)	$\omega = \omega_Q + \frac{1}{\mu}$	$\omega_j = \omega_{Q,j} + \frac{1}{\mu_j}$	$\omega_j = \omega_{Q,j} + \frac{1}{\mu_j}$
Average queue length (l_Q)	$l_Q = \lambda \times \omega_Q \times (1 - P_{block})$	$l_{Q,j} = \lambda_j \times \omega_{Q,j,PQ(NP)} \times (1 - P_{block,j})$	$l_{Q,j} = \lambda_j \times \omega_{Q,j,PQ(NP)} \times (1 - P_{block,j})$
Average number of ships in the system (l)	$l = \lambda_{eff} \times \omega$	$l_j = l_{Q,j} + \lambda_{eff,j} \times E(S_j)$	$l_j = l_{Q,j} + \lambda_{eff,j} \times E(S_j)$
Rejection rate (R)	$R = \lambda \times P_{block}$	$R_j = \lambda_j \times P_{block,j}$	$R_j = \lambda_j \times P_{block,j}$

Source: Author

where:

λ - arrival rate of ships for FIFO discipline;

λ_j - arrival rate of class j ships for priority disciplines;

λ_{eff} - effective arrival rate for FIFO discipline;

$\lambda_{eff,j}$ - effective arrival rate of class j ships for priority disciplines;

μ - service rate of ships for FIFO discipline;

μ_j - service rate of class j ships for priority disciplines;

ψ_j - berth utilization of class j ships for priority disciplines;

ψ - total berth utilization;

$E(S)$ - mean service time of ships for FIFO discipline;

$E(S_j)$ - mean service time of class j ships for priority disciplines;

l_Q - average queue length, average number of ships in waiting area for FIFO discipline;

$l_{Q,j}$ - average queue length, average number of class j ships in waiting area for priority disciplines;

l $-$ average number of ships in waiting area and at berth ALB for FIFO discipline;

l_j $-$ average number of class j ships in waiting area and at berth ALB for priority disciplines;

ω_Q - average queuing time of ships in waiting area prior to docking (hrs) for FIFO discipline;

$\omega_{Q,j}$ - average queuing time of class j ships in waiting area prior to docking (hrs) for priority disciplines;
ω $-$ average time of ships' stay in waiting area and at berth ALB (hrs) for FIFO discipline;
ω_j $-$ average time of class j ships' stay in waiting area and at berth ALB (hrs) for priority disciplines;
$P_{block,total}$ - blocking probability when number of vessels exceeds the limit for FIFO discipline and total blocking probability for priority disciplines;
$P_{block,j}$ - blocking probability when number of vessels exceeds the limit for class j ships for priority disciplines;
R - rejection rate of ships for FIFO discipline;
R_j - rejection rate of class j ships for priority disciplines;
j - priority class $j \in \{1, 2\}$, where class 1 ships are high priority, class 2 ships are low priority.

II) Speed adjustment from the previous port to the current port

An effective way to reduce port congestion is to adjust sailing speed between ports. After leaving the previous port, the vessel reports its estimated arrival time to the destination authorities. If the port is congested and the capacity is exceeded, the vessel is instructed to reduce its speed, without sailing below its economical speed. The formulas used are from (5.15) to (5.19).

$$\tau_s = ETA_s - ETD_s \quad [hr] \tag{5.15}$$

$$v_s = \frac{D_s}{\tau_s} \quad [knots] \tag{5.16}$$

$$v_{adj_s} = \begin{cases} \frac{D_s}{\tau_s + [(t_k + t_{1_k} + t_{2_k} + t_{3_k} + t_{4_k} + t_{5_k}) - t_s]} & \text{if } N > (b-1) \text{ and ALB is occupied} \\ v_s & \text{otherwise} \end{cases} \quad [knots] \tag{5.17}$$

$$n\tau_s = \begin{cases} \frac{D_s}{v_{adj_s}} & \text{if } v_{eco_s} \leq v_{adj_s} < v_s \\ 0 & \text{otherwise} \end{cases} \quad [hr] \tag{5.18}$$

$$nETA_s = ETD_s + n\tau_s \tag{5.19}$$

where:
s - vessel checked;
ETA_s - expected arrival time of ship s;
$nETA_s$ - new expected arrival time of ship s;
ETD_s - departure time of ship s from the previous port;
τ_s - sailing time between previous port and actual port (hrs) of ship s;
$n\tau_s$ - new sailing time between previous port and actual port (hrs) of ship s;
v_s - required speed between previous and actual port (knots) of ship s;
v_{eco_s} - economical speed between previous and actual port (knots) of ship s;
v_{adj_s} - adjusted speed between previous and actual port (knots) of ship s;
D_s - distance between previous port and actual port (nautical miles) of ship s;

N - number of ships being in the port area for a specific ALB simultaneously;
b - system capacity;
$t_{1_k}, t_{2_k}, t_{3_k}, t_{4_k}, t_{5_k}$ - time components - at anchor, manoeuvering anchor-CIB, CIB stay, manoeuvering CIB-ALB, ALB stay, for the vessel *k*;
$t_s,\ t_k$ - expected arrival times of ship *s* and ship *k* relative to the first ship arrived from an initial set of ships *S*;
k - vessel currently at ALB.

III) CI Berth allocation model costs and emissions

Starting from the berth allocation model – based on discrete berth layout – elements specific to the Cold Ironing system are integrated in order to develop a model aimed at reducing operational costs and minimizing vessel emissions throughout the entire ship port call, from arrival to departure. For the CI Berth allocation model costs and emissions, the mathematical model is shown below. It aims to find the minimum costs associated with the most feasible arrangements based on the available Cold Ironing berth, subject to defined constraints. Once arrived in the port area, instead of waiting at anchor, the vessels are instructed to proceed to a free berth fitted with a shore electricity system. The mathematical formulation is:

$$\begin{cases} \min\limits_{\substack{t\in T\\ q_{CIB}\in Q}} \sum\limits_{s\in S} Cost\left(s, q_{CIB}, q_{ALB}, t\right) \qquad \forall\, s \in S, \forall\, q \in Q, \forall\, t \in T,\ T \subset \mathbb{N}^5 \\ t_{3_s} \geq 36\ hours \\ compat\left(s, q_{CIB}\right) = \begin{cases} 1 & \text{if } compat\left(s_{SC}, q_{CIB_{SC}}\right) = 1, L_s \leq L_{q_{CIB}}, d_s \leq d_{q_{CIB}} \\ 0 & \text{otherwise} \end{cases} \\ compat\left(s_{SC}, q_{CIB_{SC}}\right) = \begin{cases} 1 & \text{if} s_{SC}\ LVSC = q_{CIB_{SC}}\ LVSC\ or\ s_{SC}\ HVSC = q_{CIB_{SC}}\ HVSC \\ 0 & \text{otherwise} \end{cases} \\ \left(\sum\limits_{\substack{k\in S\\ k\neq s}} \sum\limits_{t=\alpha_s}^{\alpha_s+t_{3_s}+ST} x_{kq_{CIB_s}t}\right) = 0 \qquad compat\left(s, q_{CIB}\right) = 1, \forall\, s \in S \text{ fixed} \\ \left(\sum_{t=\alpha_s}^{\alpha_s+t_{3_s}+ST} w_t\right) = 0 \qquad \forall\, s \in S \text{ fixed} \\ \left(\sum\limits_{\substack{k\in S\\ k\neq s}} \sum\limits_{t=\alpha_s+t_{3_s}+t_{4_s}}^{\alpha_s+t_{3_s}+t_{4_s}+t_{5_s}+ST} x_{kq_{ALB_s}t}\right) = 0 \qquad \forall\, s \in S \text{ fixed} \\ \left(\sum_{t=\alpha_s+t_{3_s}+t_{4_s}}^{\alpha_s+t_{3_s}+t_{4_s}+t_{5_s}+ST} w_t\right) = 0 \qquad \forall\, s \in S \text{ fixed} \\ j_s \in \{1,2\} \text{ order of priorities } 1, 2 \\ x_{sqt} \in \{0,1\}, w_t \in \{0,1\}, q \in Q, t \in T, T \subset \mathbb{N}^5 \end{cases}$$

where:
$s \in S$ - ship *s* from a set of arriving ships *S*;
$q \in Q$ - quay q from a set of quays *Q*;
$t \in T$ - time interval (period of time) *t* from a set of time intervals *T*;
$T = (t_1,\ t_2,\ t_3,\ t_4,\ t_5),\quad T \in \mathbb{N}^5$;

q_{ALB_s} - berthing quay of ship s at ALB;
q_{CIB_s} - berthing quay of ship s at CIB;
s_{SC} - type of CI shore connection at ship s, LVSC or HVSC;
d_q - depth of water at quay q (m);
d_s - draft of ship s (m);
L_q - length of a berth/quay q (m);
L_s - length of a ship s (m);
ST - Safety Time between two ships during berthing (hrs), either CIB or ALB;
w - weather condition, the value is 1 if the port is closed due to hydro-meteorological conditions, otherwise 0;
x_{sqt} - decision variable, which takes the value 0 if the ship s can dock at quay q, otherwise 1;
α_s - duration of time from ship s arrival until departure from CIB (hrs); $\alpha_s = t_s + t_{1_s} + t_{2_s}$ and it is used to simplify the formulas;
j_s - priority of ship s, based on the type and characteristics of cargo transported; $j \in \{1, 2\}$, where class 1 ships are high priority, class 2 ships are low priority.

5.2.4 Model Application at the Port of Constanţa

The Cold Ironing berth allocation model was applied to a limited number of berths in the Port of Constanţa. The berths/terminals considered for this study are dedicated to dry cargoes in bulk.

The first part of the model calculates the berths' efficiency. Queueing models M/G/1/b/∞/FIFO, M/G/1/b/∞/PQ(NP), and M/G/1/b/∞/PQ(P) are applied to the berths considered. The models analyzed 2,487 ships that arrived in the period 2021 to 2024 in the Port of Constanţa. The study considered 20 berths (Berth A to Berth T). From all of them, 4 berths are scheduled to be part of the Cold Ironing implementation project (Berths I, J, N, and S).

Next, the CI Berth allocation model (speed adjustment between ports and costs and emissions) is accomplished for 100 ships (Ship 1 to Ship 100) that arrived in the port in the first two months of 2024 and are scheduled to dock at the berths considered for the study. In case the ships had to wait at anchor until their allocated berth became available, the model checked for any available Cold Ironing berth to be used instead of waiting at anchor.

5.3 Results and Conclusions

The queuing system models M/G/1/b/∞/FIFO, M/G/1/b/∞/PQ(NP), and M/G/1/b/∞/PQ(P) determined the berths' workload and capacity employment. The results show that the berths can currently acceptably fulfil operational demands of the ships docked; therefore, there is no need to employ additional berths to satisfy the number of incoming vessels. The results are:

- the ships' schedule shows there is no uniformity in arrivals; therefore, there are periods of time with busy traffic and periods with no arrivals;
- occasionally, the system exceeds the capacity limit imposed, and the incoming ships are blocked;
- the highest blocking probability is observed for the model with non preemptive priority, while the smallest blocking probability is observed for FIFO discipline;

- the average waiting time across all berths for the period studied (2021-2024) is 65 hours per ship for FIFO, 58 hours per ship for non preemptive discipline, and 53 hours per ship for preemptive discipline.

The analysis of berth efficiency across the queueing models was based on a comparative value assigned to each berth, evaluated for every year and each model studied. This study applies a multi-criteria performance scoring model. Standardization and weighted aggregation are based on multi-criteria decision analysis.

The parameters considered for the efficiency score are:

- Total system utilization (ψ);
- Effective arrival rate (λ_{eff});
- Average waiting time in queue (ω_Q).

The berth efficiency score parameters, weights, and objectives are presented in Table 5.4.

Table 5.4 Berth efficiency score parameters, weights, and objectives

Parameter	Weight (u)	Objective
ψ_{std}	0.4	Based on ideal utilization, 0.7
$\lambda_{eff\,std}$	0.3	Maximize
$\omega_{Q\,std}$	0.3	Minimize

Source: Author

From the results obtained on the efficiency scores, the following are observed:

a) The most efficient queueing model is M/G/1/b/∞/PQ(P) with an average score 0.691, followed by M/G/1/b/∞/PQ(NP) with 0.682, and M/G/1/b/∞/FIFO with 0.671.

b) The most efficient berths have a high effective arrival rate and low waiting times, while the least effective berths have a high blocking probability. Figure 5.9 shows the efficiency scores for the most and least efficient berth, by components.

c) From the berths fitted with the Cold Ironing system, Berth I is highly performant, while Berth J is the least efficient. Figure 5.10 shows the berths fitted with Cold Ironing average utilization compared with the average utilization of all other berths. It is observed that Berth I and Berth N are underutilized; therefore, the idle time can be explored by the vessels waiting at anchor to use the Cold Ironing facility. Figure 5.11 illustrates the relationship between the available capacity in hours of the Cold Ironing berths and the total waiting time at anchor of vessels for the other berths, highlighting their underutilization.

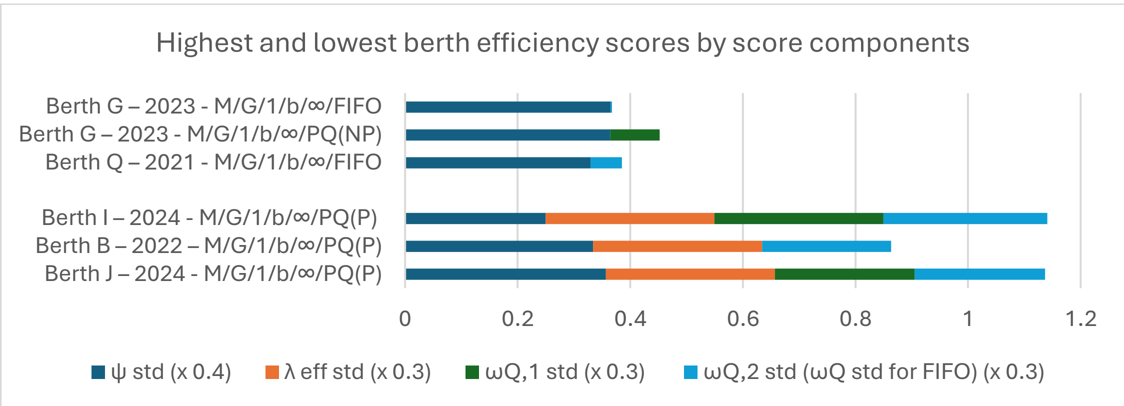
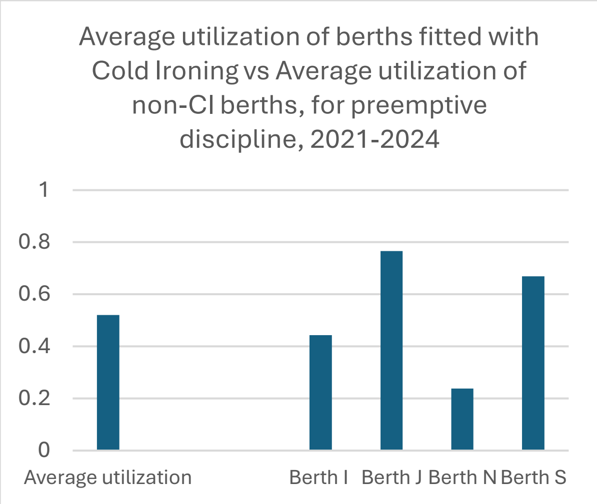


Figure 5.9 Berth efficiency scores for the most efficient and least efficient berths, by score components, 2021-2024

Source: Author



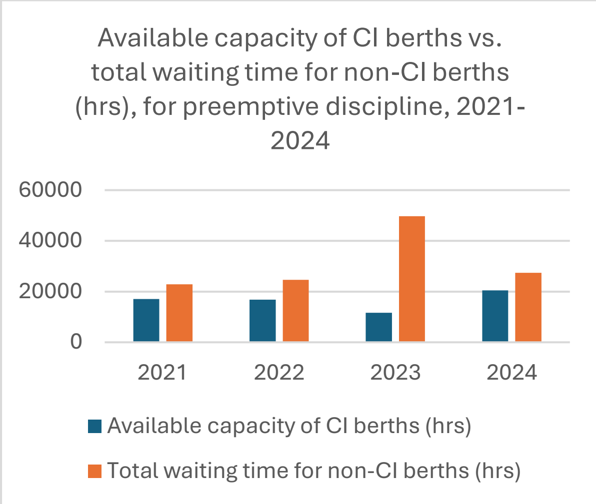


Figure 5.10 Average utilization of berths fitted with Cold Ironing compared with the average utilization of non-CI berths, for PQ(P), 2021-2024

Figure 5.11 Available capacity of berths fitted with Cold Ironing and total waiting time of non-CI berths, for PQ(P), 2021-2024 (hrs)

Source: Author

Next, the model calculates the minimum costs and emissions based on identified time components for each vessel. There are three distinct configurations analyzed, as shown in Table 5.7. Once the times are identified, the model calculates the costs and emissions.

Table 5.7 Configurations analyzed

Configuration	Description
1	Verification for scheduled ALB – no Cold Ironing operational – current status
2	Verification for scheduled ALB – Cold Ironing operational at ALB, if fitted and operational, as per current strategy; vessels wait at anchor only until the scheduled ALB becomes available
3	Model application/Algorithm verification – waiting at CIB instead of waiting at anchor, and then proceed to scheduled ALB. Port has CI installed, as per the project

Source: Author

For the 100 ships analyzed, the results showed that the average waiting time at anchor was reduced by 38% (from 45 hours average to 28 hours average) when using the Cold Ironing berth allocation model. The final costs and emissions for the above three configurations for the vessels and berths studied are presented in Figures 5.13, 5.14, 5.15, and 5.16.

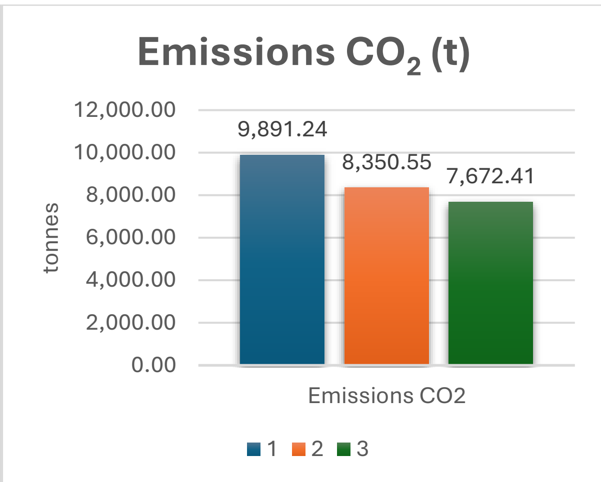


Figure 5.13 Costs under configurations analyzed (Million EUR)

Figure 5.14 CO_2 emissions under configurations analyzed (t)

Source: Author

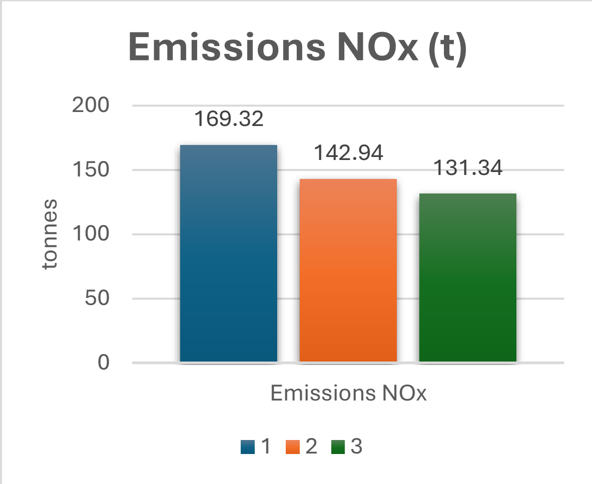


Figure 5.15 NOx emissions under configurations analyzed (t)

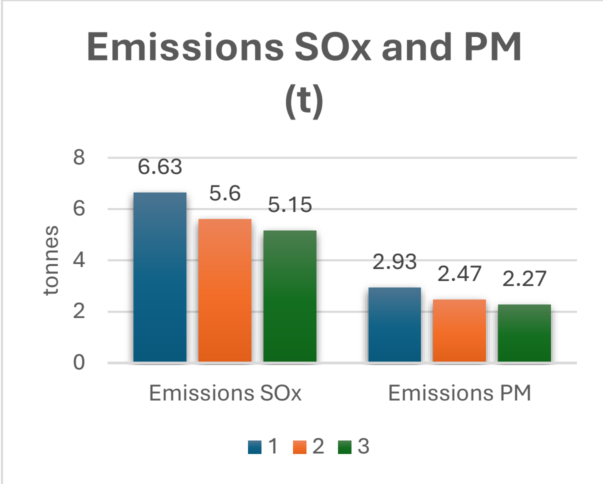


Figure 5.16 SOx and PM emissions under configurations analyzed (t)

Source: Author

Conclusions

The Cold Ironing berth allocation model application conclusions are:

1. First part determined the berth efficiency for 20 berths of the Port of Constanţa for a period of four years, 2021-2024. From all the berths, 4 are scheduled to be part of the Cold Ironing project. The calculations show that the queueing model M/G/1/b/∞/PQ(P) has the highest efficiency score. This suggests that dynamic, priority-based berth allocation is the most efficient operating strategy for the berths in the Port of Constanța, compared to the simple FIFO principle. The results show the port is occasionally congested, and waiting times at anchor are sometimes high. Waiting times are directly related to pollution; therefore, minimizing waiting times should be the objective of the ports under environmental regulations. The results determined that Cold Ironing Berths are underutilized; therefore, they can accommodate the vessels that wait at anchor until allocated berths become available.
2. Further, the model calculates the best berthing solution for a set of 100 vessels that called at the studied berths. The configurations analyzed are:

   1 Verification for scheduled ALB – no Cold Ironing operational in the port – current status;

   2 Verification for scheduled ALB – Cold Ironing operational at ALB, if fitted and operational, as per the current plan of installation; vessels wait at anchor only until the scheduled ALB becomes available;

   3 Model application/Algorithm verification – waiting at CIB instead of waiting at anchor, and then proceeding to the scheduled ALB. Port has CI installed, as per the project.

   From a total of 100 vessels, the model found a favourable solution for 20 vessels to wait at CIB instead of waiting at anchor. For the rest of the vessels, the model couldn't find advantageous solutions, so the vessels continued to wait at anchor only for their designated berth to become available. Some of the vessels proceeded directly to their designated berth ALB upon arrival. The model considered only the solution that indicated a time at CIB (t_3) greater than 36 hours, as the calculations showed that a time interval greater than 36 hours would be advantageous in terms of costs for the Ship Owner.

The solution resulting from applying the model is preferable since both the total costs and the emissions will decrease, the costs will be reduced by 9%, and the emissions by 23% on average, compared to the current configuration when Cold Ironing isn't functional. Additionally, vessels are FuelEU Maritime compliant, so they won't be subject to penalties. Furthermore, the vessels will have a surplus that can be either used for banking or pooling under FuelEU regulations. Similarly, the EU ETS will decrease due to emission reduction.

Presently, the number of ports that are offering Cold Ironing facility is limited, thus most of the vessels will encounter configuration 1 (waiting at anchor and burning fuel oil only) when visiting a port for cargo operation. The case study shows that other alternatives, 2 or 3, are more advantageous in terms of costs and emissions quantities. Cold Ironing is an efficient technical measure that will increase vessels' performance and minimize the effect on the environment.

CHAPTER 6

CONCLUSIONS

6.1 Final Considerations and Outcome

Performance is a measure of the vessel's achievement of all the criteria that define its energy efficiency, safety parameters, integrity, cost-effectiveness, profitability, regulation compliance, and environmental impact. Vessels' environmental performance is governed by the IMO strategies and EU regulations, which are challenging the industry to find efficient solutions for the progress and integration of innovative energy efficiency developments.

Decarbonization of shipping is a real concern for all parties involved. It is notorious that maritime transport is a significant contributor to global greenhouse gas emissions, and now it faces important pressure to search for solutions to run more efficiently, more sustainably, and to reduce the negative effect it has on the environment and human health.

The options include both operational and technical solutions. Although operational solutions can decrease emissions in the short and medium term, the realistic achievements of IMO 2050 targets will rely on alternative fuels.

There are several options available; however, for some alternative fuels, the technology hasn't yet reached maturity. There are pilot projects ongoing, but it can take many years until the technology is mature enough to be used extensively.

Ports can promote and stimulate the reduction of emissions and increase in vessels' performance by installing shore electricity or Cold Ironing facilities for the vessels visiting the ports.

A mix of policies, incentives, and measures can substantially motivate the companies and participants involved in shipping to adopt new technologies that can increase the vessels' performance and reduce the impact on the environment. The implementation of these measures can be difficult across the fleets, and they might shift the transportation of goods from sea to land transportation. In this case, a higher number of transportation means will be used, and finally, the total amount of emissions can increase substantially.

Outcome of the thesis

1. Certain operational measures can be implemented and applied at minimum budgets and costs and can have good results on the vessels' performance. Operational measures, such as speed reduction and minimizing the idle times (anchoring, drifting, berthing), could improve the CII (Carbon Intensity Indicator) rating.
2. New technologies, including wind-assisted propulsion systems, solar energy systems, nuclear power, carbon capture and storage technologies, fuel cells, batteries, and supercapacitors, can be successfully implemented on the vessels either by modifying the ship itself (retrofit) or by redesigning a new vessel. Some innovative technologies are immature, and their use on a large scale is limited.
3. Maritime transport has already started to use alternative fuels, which at the moment are regarded as the most viable long-term solution for the decarbonization strategy. When analyzing the ships on order, as per June 2024 data, 73% of the vessels are ordered to be built on conventional fuels, while 27% will be built on burning alternative fuels.
4. CAPEX and OPEX are both important aspects. If for methanol the engine retrofit is required, for biofuels, no engine alterations are required, since biofuels can be blended with fossil fuels. For hydrogen and full electric, besides the new engine design, the fuel tank capacities require large design modifications in the ship's design.
5. The cost associated with lost cargo capacity due to fuel tank requirements represents another important consideration; the amount is significantly higher for alternative fuels with lower energy density. Regardless of whether they choose a one-stop or two-stop approach, the owners must determine the frequency of bunkering based on the vessel's route and conduct a thorough review of the fuel tank capacity. Over the course of its existence, the cargo lost capacity has a major effect on the vessel's earning potential.
6. Shoreside electricity is a good alternative to cut emissions while the vessels are moored alongside in the port. Using this port facility will enable vessels to cut down to zero all pollutants while berthed. In addition to harmful emissions, the noise and vibrations are eliminated, increasing the quality of working conditions for the ship personnel and port workers. Also, the population living in the proximity of the port will benefit from the advantages of Cold Ironing.
7. Even if the electricity used in the port is free of pollution, the electricity production in Romania is based on both fossil and renewable sources. The calculations show that well-to-wake GHG emissions will be cut by 60% on average when using shore electricity vs burning conventional fuel.
8. The application and evaluation of queueing models on berth efficiency and waiting times is an important tool to identify further actions to avoid port congestion and assess alternative scheduling or priority rules to reduce delays. Slow steaming or Just-in-time arrivals can be employed by the ports to avoid an increase in waiting times prior to berthing.
9. A Cold Ironing allocation berth model could be a solution to take advantage of the shore-side power facilities that the ports must provide starting from 2030, as required under the EU regulations. Considering the high number of waiting days for a vessel before docking, waiting at a free berth equipped with Cold Ironing is an important opportunity for the vessels and the port. Vessels' performance can be increased by reducing pollution and, therefore, complying with IMO and EU regulations. In addition to complying with

the emission rules, vessels decrease the penalties imposed by the EU ETS and FuelEU Maritime and improve their CII rating.

6.2 Original Contributions

The thesis 'CONTRIBUTIONS TO THE MERCHANT VESSELS' PERFORMANCE TO REDUCE THE ENVIRONMENTAL IMPACT IN PORTS' focuses on the interconnection between the vessels' performance and environmental protection, and in what manner performant, efficient, and sustainable shipping can control and prevent greenhouse gas emissions. It analyzes the influence of maritime activities on the environment and life quality and investigates viable approaches for the decarbonization of maritime transport.

The research enhances vessel performance by analyzing ship- and port-side measures that jointly influence its efficiency. On the ship level, it examines alternative technologies and fuels, emphasizing Cold Ironing systems to reduce fuel use and emissions during port stays. From the port perspective, it explores measures to reduce waiting times and congestion, enable Just-in-time arrivals, and provide shore power. By addressing these dimensions, the study demonstrates how coordinated actions between ship and shore can improve efficiency, reduce operational costs, and contribute to a significant reduction of emissions within port areas.

Personal contributions are:

1. Practical approach and evaluation of the influence of the ships' operation on the environment, assessment of the factors that influence ship decarbonization, together with the challenges to decarbonization options.
2. Case studies on the applicability of the regulations, both operational and technical. Identification of operational and technical measures relevant to the research based on the case study findings.
3. Investigation on the future technologies and analysis of alternative fuels, in conjunction with techno-economic and political evaluation of fuel strategy.
4. Analysis of the design implications and cost-effectiveness of decarbonization options – CAPEX and OPEX for different operational methods, preventive measures, and alternative fuels. Examination of the lost cargo space when changing to alternative fuels. Investigation of the CII indicator for different vessels under different operational profiles.
5. Study on a Cold Ironing system implementation in Port of Constanţa, emissions assessment, fuel, and electricity costs for vessels calling at the Port of Constanţa. Berths 114, 121 &123 were analyzed between the years 2021-2023.
6. Evaluation of cost for both Cold Ironing installation in the port and vessel retrofit; evaluation of vessel costs associated with burning fossil fuel versus using shore electricity while berthed.
7. Evaluation and selection of the best green energy option in Port of Constanţa, to increase sustainability and to assist emissions reductions for the vessels that call at the port. The study utilized decision-making techniques for single- and group-level decision-making.
8. Assessment of the employment capacity of a specific berth by applying the queuing models M/G/1/b/∞/FIFO, M/G/1/b/∞/PQ(NP), and M/G/1/b/∞/PQ(P). At the same time, to decide the berth workload for the planning of the ships' berthing, to estimate

the vessel waiting time before docking, to assess how the high-priority class affects the low-priority class, and to decide further actions in case of port congestion.

9. Completion of the activity scheduling for the proposed Cold Ironing Berth Allocation Model, aimed at optimizing planning, determining the minimum project duration, and identifying the activities that can be delayed without affecting the overall timeline.
10. Development of a Cold Ironing berth allocation model, as a solution to reduce the waiting times for the vessels by allowing them to wait in a free berth fitted with Cold Ironing, instead of waiting at anchor until the designated berth becomes available.

6.3 Future Research

Decarbonization of maritime transport aligns with the interests of numerous countries, governments, institutional bodies, classification societies, academia, Ship Owners, and many sectors involved in shipping activities.

Future research of the thesis:

1. Further investigation on the operational and technical measures to enhance vessels' efficiency and performance, with a direct impact on the environment.
2. Deeper analysis of novel fuels neutral in carbon, including ammonia and hydrogen, and e-fuels that can be obtained from renewable electricity - development of the regulations, logistics (production, availability, bunkering, maintenance, etc.), advancement on the study of safety procedures, safe practices, and competence requirements.
3. Broaden the single-berth M/G/1 queuing system to a multi-berth framework (M/G/c) to overcome a limitation of this thesis and improve its relevance to extra-challenging port scenarios. An M/G/c configuration would reflect interactions across various berths, providing a thorough overview of congestion issues, particularly with unpredictable vessel traffic.
4. Further improvement of the model involves incorporating Automatic Identification System (AIS) data, enabling support for dynamic queuing predictions, traffic perspectives, in addition to adaptive berth planning in line with Just-in-time (JIT) arrival principles.

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