Integration of an Energy Storage System to support Cruise Ships Cold Ironing in the Port of Civitavecchia

Giulio Caprara

Thesis to obtain the Master of Science Degree in

Energy Engineering and Management

Supervisors: Prof. Duarte de Mesquita e Sousa
Dr. Valeria Armas

Examination Committee

Chairperson: Prof. Edgar Caetano Fernandes
Supervisor: Prof. Duarte de Mesquita e Sousa
Member of the Committee: Prof. Mostafa Kermani

June 2022

Integration of an Energy Storage System to support Cruise Ships Cold Ironing in the Port of Civitavecchia

Giulio Caprara

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

ACKNOWLEDGEMENTS:

I consider myself extremely lucky and could have not desired for a better support than what I have received through the elaboration and writing of this thesis.

First, I would like to thank my supervisors Professor Duarte de Mesquita e Sousa and Valeria Armas for their guidance and support. Professor Duarte de Mesquita e Sousa has been the ideal supervisor, guiding and encouraging me through the whole process of realisation of this work especially when difficulties occurred. At the same time, I am extremely grateful to Valeria Armas for the time she has dedicated to me in our several long videocalls and for the knowledge and the inspiration she gave me.

I want to thank Falck Renewables - Next Solution for the opportunity they gave me to use their in-house developed Energy Management Simulation Software. Special thanks to Riccardo Barilli and his colleagues for assisting me in the simulation process and all their teachings.

I sincerely thank Professor Luigi Martirano from Università di Roma La Sapienza for his support and for putting me in contact with Valeria Armas, laying the foundations to develop this research.

I am very grateful to Dr. Mostafa Kermani for sharing with me his strong knowledge on this topic and for his assistance.

This thesis work represents a very important achievement in my academic career and personal growth, I want to thank all the people that made it possible.

To conclude, I cannot forget to thank my parents, family and friends for all the unconditional support in this very intense year.

ABSTRACT:

Cold Ironing (CI) is increasingly becoming more practiced to reduce air pollutions emissions of ships at ports. Large Cruise Ships represent the most energy requiring ship type that a commercial port can host, powering them from shore represent so a great challenge. The port of Civitavecchia is one of the world's most visited by Cruise Ships and soon will be requiring a CI infrastructure. Cruise Ships CI may need power up to 14 MW and the port's grid can only supply a max of 6 MW coming from its mocccccst powerful Point of Delivery (POD). To avoid the installation of another substation the possibility of installing a high power and high energy ESS is researched. The first part of this thesis exposes a literature review and exposes the state of the art of the CI technology. The second part aims to determine and size the main characteristics of an Energy Storage System (ESS) that can be installed in the Port of Civitavecchia to power Cruise Ships Cold Ironing. The port's grid will be studied with the introduction of the new ESS the existing and additional Renewable Energy Sources (RES) and its performance will be analysed with the help of an Energy Management Simulation Software (EMSS) developed by Falck Renewables – Next Solutions.

Keywords: Cold Ironing, Energy Storage Systems, Energy Management, Renewable Energy, Cruise Ship, Port.

RESUMO:

O Sistema “Cold Ironing” (CI) está cada vez mais a ser utilizado para reduzir as emissões de poluição atmosférica dos navios nos portos. Os grandes navios de cruzeiro representam o tipo de navio que requer mais energia que um porto comercial pode atualmente acolher alimentando-os a partir de terra, o que constitui um desafio tecnológico. O porto de Civitavecchia é um dos mais visitados do mundo pelos navios de cruzeiro e em breve necessitará de uma infraestrutura de CI. Os navios de cruzeiro podem necessitar de potência até 14 MW e a rede do porto só pode fornecer um máximo de 6 MW a partir do seu ponto de entrega com a pot^encia mais elevada disponível (POD). Para evitar a instalação de outra subestação, é estudada a possibilidade de instalar uma ESS de maior potência. A primeira parte desta dissertação descreve uma revisão bibliográfica e mostra o estado da arte da tecnologia do CI. A segunda parte visa determinar e dimensionar as principais características de um Sistema de Armazenamento de Energia que pode ser instalado no Porto de Civitavecchia para alimentar navios de cruzeiro que recorrem ao CI. A rede do porto será projetada para introdução de um novo Armazenamento de Energia associado às fontes de energia renováveis instaladas. 0 desempenho da solução proposta é analisada com a ajuda de um *software* (Energy Management Simulation Software (EMSS)) desenvolvido pela Falck Renewables - Next Solutions.

Palavras-chave: Energia renovável, Armazenamento de Energia, Gestão de energia, Navios de cruzeiro, Porto.

TABLE OF CONTENTS:

LIST OF FIGURES:

LIST OF TABLES:

1 INTRODUCTION

1.1 Background and Motivation

Climate change and consequential environmental degradation are one of the most threatening issues mankind has to face for its preservation. The rising levels of air pollution for instance exemplifies the unignorable footprint that humans are living on planet earth. Over the past decade, to navigate the threats which are being posed by such an increase of pollution, attention on the topic has increased. Noticeably, Air pollution was first subject to debate during the **Montreal Protocol** in 1987 and was the first United Nations Protocol ratified by every country on earth. The protocol is a landmark multilateral environmental Agreement. It regulates the production and consumption of ozone depleting substances. A further protocol which tackles ait pollution related issues is the **Kyoto Protocol** adopted in 1997 and entered in force in 2005. The latter commits to a 5 % greenhouse gas (GHG) reduction compared to 1990 levels. The Convention itself asks UN countries to adopt policies and measures on mitigation and to report periodically. It also introduces the emission trading system between countries [1]. Finally in 2016, the **Paris Agreement** was stimulated with the goal of aiming for the goal of limiting **global warming to well below 2°C**, preferably to 1.5 degrees Celsius, compared to pre-industrial levels. Nevertheless, despite all these regulations and action, the earth still seems to be in a continuously deteriorating state. Noticeably, the transportation and the industry sector who rely on traditional combustion fuels are one of the primary causes of air pollution.

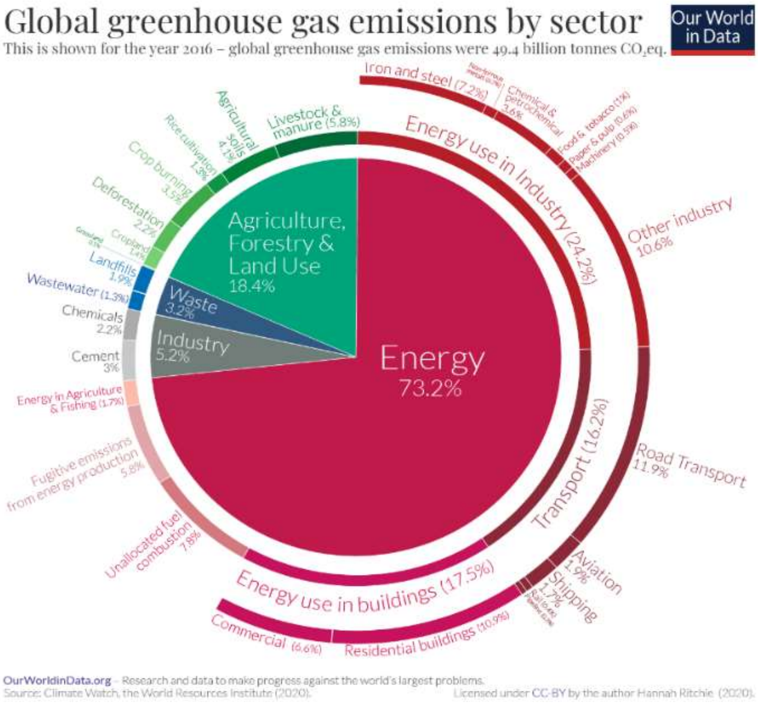

Figure 1 GHG emissions by sector [2]

Their emissions significantly have an impact on the greenhouse gasses effect, therefore negatively increasing global warming as well as causing severe health implications both for humans and animals. Hydrocarbon’s combustion is used to transform thermal energy into mechanical or electric energy. On the other hand, electricity, if produced from renewable energy sources, is the most promising energy vector to reduce greenhouse gases emissions. Figure 1 shows how the majority of greenhouse gasses 73.2% are produced from energy generation.

As for the above-mentioned reasons, it is pivotal to address climate change and investigate how harmful emissions and hydrocarbon combustion can be reduced. This study deems as necessary steps to undertake for a “greener future”, the increase of energy efficiency (obtained by decreasing the need of traditional fuels as primary source) and the optimization of the existing systems. Also, this study sheds light on the importance of substituting the hydrocarbon’s combustion by the production of electricity through renewable energy sources (RES) [3]. Past research has already been conducted to address issues emerging from air pollution, both within the industrial and transportation field. For instance, The International Maritime Organization (IMO), has conducted a study from which it emerged that emissions caused by maritime transportation are expected to grow between 50% to 250% by 2050. If these data prove to be correct, the causes of these emissions may also significantly impact the Paris agreement, ultimately ruining it. Moreover, as the maritime sector is responsible for 2.5 % of greenhouse gas emissions, regulations have been enforced. In 2005 for instance, the MARPOL Convention Annex VI, the first agreement which focused on the prevention of air pollution from ships, entered into force [4].

The first international regulation on ship emissions entered into force in 2005 as the MARPOL Convention Annex VI that focuses on the prevention of air pollution from ships. However, emissions caused by ships are still increasing and air pollutants are emitted every day for example from cruising, manoeuvring, and at berths to power their on-board facilities.

The above-mentioned results clearly highlight how ships, more specifically cruise ships significantly contribute air pollution and hence solutions should be investigated. Hence, to address the above-mentioned issue, this study looks into the Cold Ironing (CI) technique.

Cold Ironing (CI) consists in providing electricity from shore to ships which can hence power onboard utilities without keeping auxiliary engines on. Doing so, allows to cut off in port emissions allowing for a better air quality within the surrounding area.

For a deeper analysis of the CI technique and to analyse its implementation implications, this project takes as a case study the port of Civitavecchia. As a matter of fact, the latter is one of the world’s most visited ports from Cruise Ships in Italy hence also being one of the major generators of pollution within its surroundings. Powering Cruise Ships from shore is a great engineering challenge due to the high power requested while at berth. According to the existing standard the infrastructure needs to be capable of providing at least 16 MVA. Nonetheless, regardless the challenges posed, the Civitavecchia case study will show how sustainable techniques to support ships Cold Ironing can be implemented to significantly cut off air pollutants from cruise ship.

1.2 Objectives

Over the last years, the port of Civitavecchia has become one of Italy’s most visited from cruise ships. With the increase of cruises calling at the harbour inevitably also the emissions of air pollutants increased, harming the air quality of the nearby city of Civitavecchia. With the rise of infrastructures capable of providing electricity from shore and cruise ships that can receive it, adopting a CI infrastructure has become a necessity for the port. This study investigates a solution for the port to implement it.

Nowadays, different funds are allocated to finance the high expenses of CI infrastructure hence the economic effort that port authorities must face to install it is reduced. The main issue to confront is for the port's grid to reach the sufficient electrical power capable to supply cruise vessels. To date the Civitavecchia's port can deliver only a maximum of 6 MW of power.

As such, this study investigates how the port's power capacity can be upgraded to allow the electrical connection of cruise ships. The proposed solution consists in upgrading the power capacity of the port by introducing distributed Renewable Energy Sources (RES) and a High Power and High Energy Storage System (ESS).

As such, the project will focus on the following steps:

- Analysing the existing CI infrastructure around the world and the existing standard ISO 8000-1
- Analysing the port of Civitavecchia electrical infrastructure
- Analysing the Cruise Ships Traffic of a specified year
- Research the different technologies possible to increase the power of the port grid
- Model the cruise ships energy requirements
- Choose between the existing typologies the ESS type to implement
- Size the Energy Storage System (ESS) and RES to increase the power of the Port's Grid

1.3 Structure of the Thesis

The thesis consists of **7** chapters, with relative sub-chapters and appendix. It is structured as follows:

In **Chapter 1** the topics discussed and objectives of the work are introduced including the methodology applied to complete this study.

Chapter 2 is dedicated to the state of art, giving a general indication on previous works and studies used in this work.

Chapter 3 is dedicated to the description of Cold Ironing technique focused on cruise ships.

Chapter 4 describes the port characteristics electrical system and RES available

Chapter 5 gives an overview of the existing ESS choosing the more suitable for the port's need.

Chapter 6 is dedicated to the simulations and main results of the thesis.

Chapter 7 contains the conclusion of the work.

1.4 Methodology

The following section provides an overview of the methodological components comprising the research.

The subject studied is still at an early stage of scientific research as CI for cruise ships is not a very common practice. The absence of defined methodologies to be applied to the research of CI for cruise ships required to perform an exploratory study, consulting the literature available to examine the different aspects of this topic. To redact the project's first part, a literature review of the theme mentioned has been developed. Different papers and research theses have been consulted to deepen the Cold Ironing state of the art and practices around the world. Together, international standards, policies, regulations, port's emissions inventories and port authorities and international organizations webpages have been examined to produce Chapter 2.

Chapter's 3 has been composed from information present in the consulted documents and data provided from Port Utilities S.p.A. For example, data regarding the port's electrical grid have been obtained by directly interviewing Port Utilities S.p.A. members. The POD energy consumption and PV systems production have been collected from the electricity meters measurements collected directly form the utility company. These have been analysed and organized through the software Excel and programming language Python. When PV production power curves were missing the available values of PV production were used to obtain an estimation of the missing ones, the methodology is exposed in the PV systems chapter (section 4.4.3). The same has been done to estimate the PV production of the PV systems that could be installed in addition to the existing. For what concerns the estimation of the production of the Wave Energy Converters data available in literature were used as their power curves are not available for a year. In section 4.4.4 the methodology used is exposed. To define the cruise ships power needs, in absence of real data, it has been calculated according to port emissions inventories methodologies by weighting its power needs in relation to the passenger's capacity this can be appreciated in section 4.6.1. The port's cruise ships traffic given from Port Utilities S.p.A. has been used to create the yearly power request of the CI infrastructure selecting only the vessels fitted to receive electricity form shore. Cruise traffic data have been managed and analysed with Excel.

The Energy Storage Systems chapter (Chapter 4) has been produced by consulting papers related to ESS and performing a qualitative analysis to select what is the most suitable to support cruise ships CI in the port of Civitavecchia.

The inputs for the Simulations, in Chapter 5, performed with the Energy Management Simulation Software (EMSS) developed by Falck Renewables – Next Solutions, are those retrieved in the preceding chapter. Data regarding energy contracts were given from Port Utilities S.p.A. according to the real contracts of the utility company for the analysed year. The electricity purchase price was retrieved from the Italian market operator database. Successively, the ESS sizing has been done using the EMSS and aiming to obtain the minimum power and capacity required from the designed system. To emulate the worst-case condition of operation where the only available source of power would be the national grid, the RES where not included in the simulation. Furthermore, to evaluate the performance of the port’s grid it has been decided to design 5 different scenarios where the variables where the available RES. This variation among the simulations was done to allow the comparison of the different RES technologies and combination. The simulations results analysed in Chapter 5 are all obtained through the EMSS. The analysis of the simulation results consisted of a quantitative comparison of the different scenarios numerical results, such as operation cost, expenses, revenues, NPV, energy consumption, power curves, BESS SOC, monthly energy production and consumption and other relevant values.

2 LITERATURE REVIEW

To expand upon the reasoning behind this study, the following section is dedicated to the evaluation of the existing body of literature with regard to the Cold Ironing technique.

Cold Ironing is a polyhedric theme that can be analysed in different approaches:

i. **The economical point of view:**

Its costs and revenues, the incentives available, the price of the energy sold to shipowners etc.

ii. **The environmental point of view:**

The emission reduction opportunity by adopting this technology in harbours, the impact the adoption of such an infrastructure can bring to the surrounding environment etc.

iii. **The technical point of view:**

Type of infrastructure, electrical power supply infrastructure, the power and energy required from ships, the sources used to supply energy from shore.

Before this project, different studies have been consulted each offering a different perspective about CI.

For instance, one of the landmark studies on CI comes from the Master of Science Thesis of *Patrick Ericsson* and *Ismir Fazlagic* titled ***Shore-Side Power Supply*** [5] produced for the Chalmers University of Technology in collaboration with ABB. The Master Thesis offers a clear overview of the technologies existing all over the world by 2008. The project helped the diffusion of knowledge about CI around the world and especially in Europe. It has been written before the emission of the ISO 80005-1 (produced in 2012) and so shows how CI was practised before the introduction of the international standard. The work is divided in 6 parts. The introduction is followed by a market review of the existing technologies and incoming new ones in 2008, highlighting the actors in the market. It follows a technical survey where the power generation on board and demand is analysed by ship type. This section has been referenced in many other studies as it is unique in its genre. Indeed, it shows detailed data about ships consumption, power, voltages, and frequency requirements obtained from a survey of different existing ships. The chapter ends mentioning the few standards existing in that year underlining the necessity of an international standard. It follows a section on the technical design of the CI infrastructure that highlights the requirement of frequency conversion equipment when the ships and land frequency do not match. The work ends with simulations on the implementation of the CI infrastructure in a typical harbour.

Also, the scientific paper called ***Prospects of Cold Ironing as an Emission Reduction Option*** [6] written by *Thalis P.V. Zis* has been used for the scope of this project. It starts with a deep literature review focused on different aspects of CI: its impact on port vicinity, port emissions inventories, how it can be an emission reduction option and its historical roots. It presents the status of CI in the world and successively highlights its challenges and opportunities. This paper provides an overview of the impact CI infrastructure can have economically and environmentally and it also analyses the problem with three different scenarios varying the fuel price. The scenarios are studied from the point of view of the port authority to the point of view of the ship owner. Cash Flows are analysed in three different scenarios for the shipowner: high, medium, low price of Marine Gas Oil (MGO). For the Port authority the scenarios vary depending on the price at which the electricity is sold to the ship and if the CI service includes incentives. Results show that CI is highly convenient to ship owners when fuel prices are high and interest rates are low. While for the port authorities' point of view CI is only convenient when electricity is sold to make a profit out of the transaction but ensuring that its price is 10% lower than electricity produced onboard through Auxiliary Engines.

Past research has also focused on the issue of estimating hotelling power demands, which is a difficult task due to the confidentiality that this information has and due to the huge variety of vessels that consume at different regimes. Typically to obtain this data port authorities interview crew members of the boat or the shipowner. But accurate data is always difficult to obtain. In literature there are so many different methods that are used to obtain such data and the document ***Current Methodologies and Best Practices for Preparing Port Emission Inventories*** [7] redacted by *Louis Browning and Kathleen Bailey* is one of the most representative which is hence taken into account in this project. It outlines the methodologies and practices that port owners should adopt to estimate the air pollutants emissions.

They are mainly divided in three approaches:

1. Detailed. Each ship is analysed and land side consumptions of the harbour.
2. Mid-Tier. Ships are averaged by ship type, gross tonnage and then the emissions are calculated.
3. Streamlined. Values of emissions are scaled from other emissions inventories.

These inventories are a medium to quantify emissions generated from port activities and assess emission reduction practices. From there it is possible to obtain the methods to estimate the hotelling power required from different types of ships. Hotelling is the time the vessel spends at the Pier/Wharf/Dock (PWD) only with auxiliary engines on or in cold ironing mode.

Typically, an emission calculation consists in:

$$E_m = P \cdot L_f \cdot A \cdot E_f \tag{1}$$

where E_m is the emission in weight; P is the boat engines rated power (kW); L_f is the load factor (% of the engines loading with respect to their rated power); A time of activity of the engines (h); E_f Emission factor (g/kWh). From this it is possible to estimate the energy consumed by the ship if the emission factor is ignored, in this case the result would give the Energy in kWh.

A further study regarding the introduction of CI into a harbour is ***Design of A Shore Power System For Barcelona's Cruise Piers: Cruise Pollution Study, Rules Analysis, Design And Simulation*** [3]. the Final Bachelor's Degree Project produced by *Sergi Espinosa Sanes* for the Universitat Politecnica de Catalunya published in 2015. The study is dedicated to the integration of the Cold Ironing infrastructure for cruise Ships in the port of Barcelona. It shares multiple similarities with our current study. Main highlights of the Bachelor's Final project of Sergi Espinosa Sanes are the description of the port cruise terminals in the port of Barcelona, a study of the cruise air pollution regulations active to date, a focus on the potential emissions reduction by adopting shore to ship power, analysis of the rules to design the electrical infrastructure, a design of a possible infrastructure in the port and the results of simulation made with MATLAB. The CI system is designed for the worst-case scenario considering the busiest day in terms of cruise calls reaching a peak of power requested of around 80 MW. The study highlights the difficulty in developing a model to estimate the ships hoteling power request due to the confidentiality of such information. It offers 3 different estimations for the cruise ship's power request and offers a good estimation made by a bottom-up method and based on ships length and gross tonnage. The model is obtained by analysing a database of cruise ships energy consumption at berth using regression models. The most reliable for the study results to be the exponential model based on the exponential tendency, which is then used to estimate the daily loads requested for CI. It is shown that the adoption of such an infrastructure can led to 96% CO_2 emission reduction as a less intense reduction of other pollutants. In the last sections the work dedicates design and simulations of the infrastructures firstly making a deep analysis of which are the existing classification rules, expressing how the ISO/IEC/IEEE 80005-1 is the only existing rule that determines the characteristics of the CI infrastructure.

Moreover, the paper ***Integration of Cold Ironing and Renewable Sources in the Barcelona Smart Port*** [8] produced by *Alejandro Rolan, Paola Manteca, Rahime Oktar, and Pierluigi Siano* looks into the case of Barcelona's port. This research first introduces CI state of the art, it then lists the regulations active in the port of Barcelona. It finally proposes to implement CI to all ship types fully powered from RES in the port of Barcelona. It sets a typical weak power curve estimated from the sum of all the ships power demand with an average of 221.9 MW. Starting from this value the number of PV panels and Wind Turbines are defined via a Matlab-Simulink simulation being 177 and 29 respectively.

Another significant paper which combines CI with Energy Storage is the ***Technical analysis and economic evaluation of a complex shore-to-ship power supply system*** [9] by *Daniele Colarossi and Paolo Principi.* The research considers the introduction of a Complex Compressed Air Energy Storage system in the harbour of Ancona to support CI to Ro-Ro ships. The system is composed of a cogeneration power plant, that allows to increase the energy production efficiency and lower the price of the energy, a compressed air energy storage system, and a CI infrastructure. It can deliver the waste heat to residential buildings next to the harbour. The system allows to reduce ships emissions and to reach up to an average of 74% of the ratio of energy supplied and the demand. In this paper it is shown how complex solutions like the one proposed can lead to environmental and economic benefits.

Furthermore, the paper ***Green Shipping in ECAs: Combining Smart Grids and Cold Ironing*** [10] by *J. Prousalidis, G. Antonopoulos, C. Patsios, A. Greig, R. Bucknall* introduces the adoption of Smart Grid in ports, considered as unique customers from the national grid point of view. As maritime transport is growing, environmental issues are increasing in ports and so the most suitable option proposed is to mix the cold ironing solution with RES local production and Smart Grids. In any case even if electricity provided from ships is not coming directly from RES the benefits of delocalizing air and noise pollution from port (more often nearby residential areas) and relying on more efficient electricity production are achieved. According to the study the integration of Smart Grids and CI facilities needs to be evaluated with their feasibility even though an efficiency and environmental benefit is expected. For what concerns CI three different distribution typologies are shown (see Figure 2):

- HV transformation with minimal conversion stages to berth, that does not offer frequency flexibility.
- HV transformation with frequency converter that allows to have constant or variable frequency links at berth.
- HV transformation with DC link to reduce losses and locate the transformers at berth, being this the most costly but flexible solution.

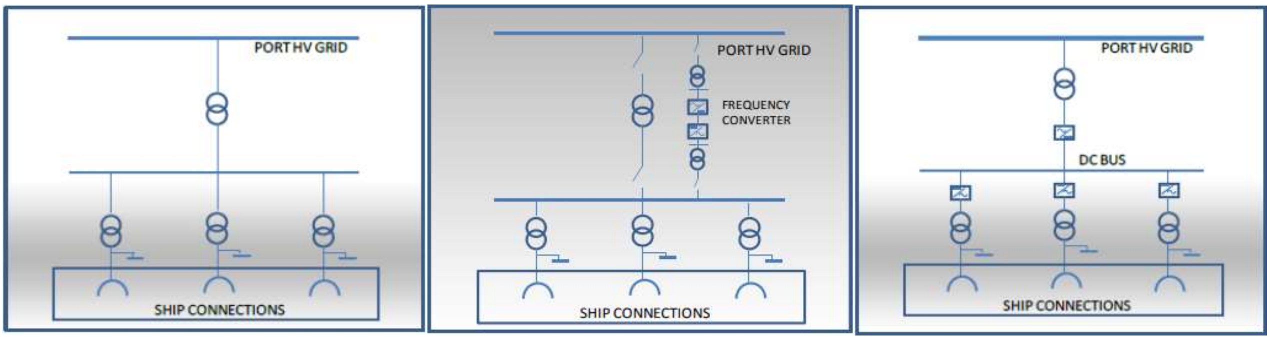

Figure 2 HV to CI infrastructure distribution typologies; Left no frequency conversion; Center Centralized frequency conversion; Right DC Bus with frequency conversion at berth

CI and Smart Grids can be associated topics into Research and Development by:

- The integration with local RES or low carbon production.
- The Requirement of Energy storage systems.
- Power Management Systems (PMS) that monitors the bidirectional power flow and studies the history trend to do the best decision making.
- Usage of power converters that can maximise the performance of interfaces.

This paper also highlights how the usage of an ESS can bring benefits to the port energy management or lead to the shift of the ship's load from day to night converting it into a smart load and smooth power demand. ESS might be of large power capacity and based on battery technology integrated with power converters. The battery typology the paper focuses on is the Flow Battery, a novel technology consisting into two cell storage tanks (positive and negative) divided by a cell stack where reactions take place. A major advantage which emerges is the possibility to perform a fast and controllable recharge of the battery by changing the electrolyte in the storing tanks. It is then delineated how the symposium of Smart grids and CI is favourable according to EU directives concerning the increase of energy efficient systems, the adoption of demand response methods by consumers etc. The paper concludes with the definition of different feasibility studies from the point of view of main actors in this new port's development challenge.

Socio-Economic benefits of Cold Ironing are investigated in the paper named ***Air Pollution from ships in ports: The socio-economic benefit of cold ironing technology*** [11] edited by *F. Ballini, R. Bozzo.* Aim of this research is to quantify the socio-economic benefits of implementing CI via a cost-benefit analysis in the case scenario of the installation of the CI facilities at the new cruise pier in Copenhagen. It begins by redacting the main regulations on air pollution emissions from seagoing ships. Continues with the methodology, that consists into the External Evaluation of Air Pollution (EVA) an advanced impact-pathway modelling system developed by the Aarhus University with the scope to calculate the external health cost form air pollutants emission. From the traffic analysis it shows that only 12% of the visiting cruise ships are fitted to receive electricity from shore, consisting in 6 ships (38 calls) for a total of 426 hours. One suggested practice is to increase the number of fitted ships to have a higher use of the infrastructure. The study shows how values of emissions are noticeably lower if electricity is produced by Nordic inland power plants rather than auxiliary engines. The case studies are two, one considering that 100% of the calling cruise ships receive CI and the second one that only 60% receive CI. The results are respectively a reduction of 65% and 39% of SO_2, 98% and 59% of NO_x, 90% and 54% of PM; 34% and 20% of CO_2. It all results in the second case (so the less optimal) into a 2.8 million euros external health cost. The capital cost of the CI infrastructure is considered to be 37 million euros resulting, from a socio-economic perspective, into 12-13 years of recovery.

A valuable perspective is provided by the research paper entitled ***Shore Side Electricity in Europe: Potential and environmental benefits*** [12] by *R. Winkel, U. Weddige, D. Johnsen, V. Hoen, S. Papaefthimiou.* This research focuses on the analysis of the economic and environmental potential of CI in Europe. The ship emissions inventory and an energy demand evaluation are created by coupling a bottom and a top-down methodology. EU ports are analysed and divided by port type depending on the ships calling at them and emissions inventory are obtained from the number of calls per year and fuel consumption in ports. The final output will be the electricity needed by the ports. A bottom-up approach is then used to zoom in on the economic, societal and environmental benefit of SSE in all the EU ports. The analysis is conducted from 2010 to 2020 and the health benefit is calculated from the difference between the marginal damage cost caused from emissions of ships and from the grid energy mix. The results show that if all seagoing ships in seaports harbours in the EU would have used SSE between 2010 and 2020 to cover their energy demand while at berth, 3.342 GWh a year would be needed around 0,1% of EU electricity consumption in 2012. The most demanding type of ships are cruise ships with an annual consumption of 260.232 tons of fuel corresponding to 1.334 GWh (39% of the total) energy consumption. In the Mediterranean Sea Cruise ports estimation of emissions reached 225.980 tons of air pollutants (6.448,9 of NO_x, SO_x, PMs and 219.531,6 tons of GHG) coming 85% of it from hotelling power needs. For the Cruise sector the seasonality plays a major role and the vicinity of ports to residential areas have high impacts on air quality and need to be regulated. The health benefits of practising CI in EU ports resulted in 2.63 and 2.94 billion € for 2010 and 2020 respectively saved. Successively, relevant EU policies are shown next to the difficulties CI is facing in its development such as the high taxation of electricity provided to ships from shore if compared to fuel prices. It is underlined how cooperation between stakeholders is required (shipping company, port operator, electricity utility company) to provide the harbour of the infrastructure but also incentives play a major Role. Results of this paper clearly outline how adopting CI infrastructure in European ports can lead to 39% of yearly emissions reduction for a total of 800.000 tons of CO_2 and health benefits of 2.94 billion euros. It is then suggested the implementation of this practice for most energy demanding ship types such as ferries and cruise ships especially for ports close to residential areas. The paper shows how Europe has huge room for improvement in this sector and can achieve high results in emissions reduction through the implementation of CI.

A further valuable source for this study is the paper ***Wise Port and Business Energy Management: Port Facilities, Electrical Power Distribution*** [13] by *Giuseppe Parise, Luigi Parise, Member, Luigi Martirano, Peniamin Ben Chavdarian, Chun-Lien Su, and Andrea Ferrante*. It gives an innovative and comprehensive view on how ports, electrical infrastructure and energy management will have to be organised. Ports are viewed as intensive energy extended areas that may require HV or multi MV power connections to the national grid in the order of tens of Megawatts. They require an Energy Master Plan, and their power systems need a comprehensive design with the criteria of “as built, as operated, as maintained”. Their electrical infrastructure must satisfy all users' demands and will continuously develop through their entire lifecycle, as the complexity will increase with the introduction of local RES production ESS and emergency sources of production. The port power system is expected to be developed towards the introduction of information and communication technologies, environmental protection and the logic of liberalisation of markets. These can be achieved through the Business Continuity Management (BCM) whose principles are an analysis of the objectives and organisation needs; implementation and operation control of energy consumption reduction; monitoring and reviewing of the same management plan. This must be assisted from data storage and computerised data management. It is thus necessary that ports develop a medium- and long-term energy master plan coordinated with the port planning scheme to achieve a more equitable energy utilisation and helped by a unified and integrated system of supervision and remote control. The study then exposes R&D points for ports which are the analysis of feasibility of CI infrastructures, introduction of RES and ESS, usage of non-traditional voltage levels, EV recharging stations, and advanced electrical architectures. This last point is key to support the increasing complexity of ports’ electrical system and allow reliability of the service for example with loop configuration of it. The port thus becomes a utilisation pole and comes naturally, from what said above, to think at ports’ electrical infrastructures organisation as an integrated network or a Microgrid, operated as a unique customer from the national grid point of view. The Microgrid can be organised as a Smart grid if it is provided with communication links, energy storage, distributed power generation, automated control systems and all the equipment working together. This allows to reduce the chaotic phenomena of utilities dispersion, allowing to optimise power flows putting together environmental needs and quality of service. Local energy production and ESS can offer high quality of energy and safe and reliable operativity. The different electrical loads (port cranes, reefers, lighting systems etc.) can be managed to obtain an ever-net load system. The paper also highlights how in the future it may be possible to have the inversion of energy flow in CI infrastructure, with a Ship to shore energy transfer requiring the port to be ready to be adaptable to this new situation. R&D on CI and the creation of new global standards may help promote its development. Energy Strategies are required to manage the high energy demanded by CI and the lack of regulatory constraints represents a curb to its success. The study finally highlights the difficulties which nowadays arise in the implementation of CI due to the high number of actors and diversity of responsibility involved.

Finally, the paper ***An Energy Storage System to support Cruise Ships Cold Ironing in the Port of Civitavecchia*** [14], proposed by *Giulio Caprara, Valeria Armas, Duarte de Mesquita, Mostafa Kermani and Luigi Martirano,* analyses what could be an innovative solution to implement cold ironing of the Port of Civitavecchia. It firstly describes the CI infrastructure for cruise ships and lists those available around the world. Successively, analyses the electrical infrastructure, energy consumption patterns of the Port of Civitavecchia, proposing to couple a large-scale ESS with RES to overcome the lack of power capacity and implement CI.

The above literature review emphasises how the CI has been already researched under different aspects as it is becoming a major practice. It emerges that the consideration of different cases of studies allows one to better understand what the bottlenecks of its implementation are, such as the high costs of investment operation and lack of power capacity in mid-size ports. Furthermore, it appears that different strategies may be applied to satisfy power requests of berthed ships, mostly depending on the port's infrastructures. In addition, it is highlighted how research on the topic remarkably helps CI development. CI has been already connected with ESS, but no academic investigation has yet been conducted on its performance in a port’s grid with RES and Battery Energy Storage System (BESS) of large capacity. Hence this study fills the existing gap in literature by undertaking the Civitavecchia Port as a case study.

3 COLD IRONING FOR CRUISE SHIPS

3.1 Definition

As it has already been briefly above-mentioned Cold Ironing (CI) consists in the provision of electrical energy from shore to berthed ships it allows to turn auxiliary engines off, used to power on-board facilities, and cut exhausts emissions. Ships that adopt this practice can rely on more efficient harbour's electrical systems and bring to zero the environmental impact of their energy consumption if the energy provided from shore is produced though renewable energy sources (RES). The expression Cold Ironing derives from the iron coal-fired engines that would cool down when in the past ships were at berth [6].

CI is also known as:

- Onshore Power Supply (OPS)
- Shore-Side Electricity (SSE)
- Alternative Marine Power (AMP)
- Shore Power
- Shore to Ship Power (S2S)
- High-Voltage Shore Connection (HVSC)

The connection from shore to the ship is performed through a specific infrastructure that varies by ship type and port design, its typical scheme shown in Figure 3 and consists in:

a. Utility supply, that usually comes from High Voltage (HV) (20-100kV) connection to the national grid.
b. Substation with step down transformer where electricity is brought at Medium Voltage (MV) level (6-20kV) (see Figure 4).
c. Power conversion system if needed when frequency needs to be changed (for example 50 Hz grid powering a 60 Hz ship).
d. Cables to bring connection to the terminal (typically underground).
e. Cable Reel System electro-mechanically controlled to avoid handling of the cables (see Figure 5).
f. Socket on board of the ship to connect the cables (see Figure 6).
g. On-board transformer to adjust voltage according to ships requirements.

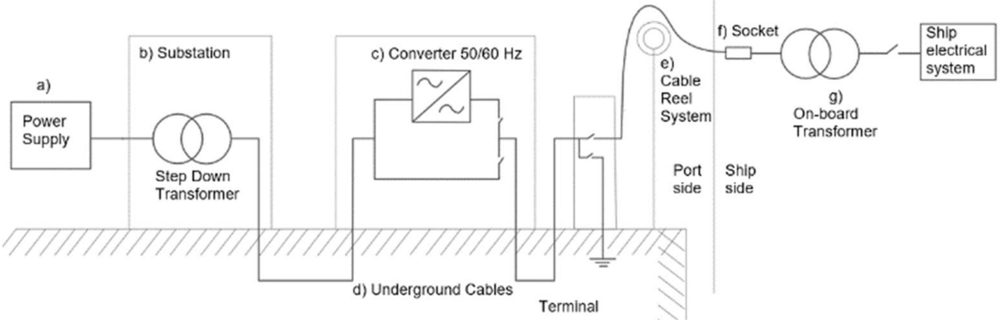

Figure 3 Cold Ironing electrical infrastructure scheme

With regards to Cruise Ships, the connection is typically performed through 4 cables and one neutral connection due to the high power requested. The shoreside connection comes from an underground connection box near the wharf from where cables are linked and through a cable management system brought to the ship switchboard.

Figure 4 Dual Voltage Transformer to step down the voltage (Port of Juneau) [5]

Figure 5 Cable Reel and movable system [15]

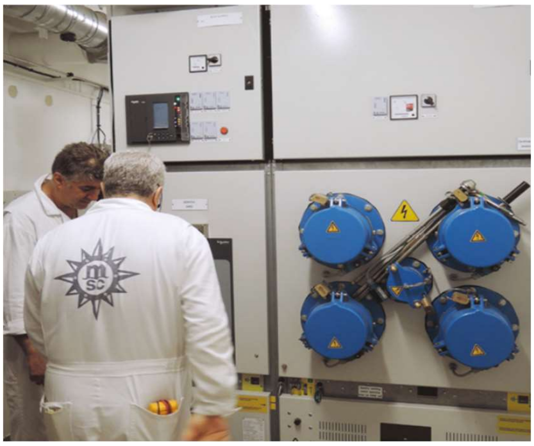

Figure 6 Ship connection point on Switchboard [15]

3.2 Benefits

As CI allows turning off engines, it cuts ships air pollutants emissions and reduces the impact of generated noise and vibrations. Hence, nearby areas, often densely populated, will have better air quality and liveability, in addition the marine fauna will be less affected from ships vibrations and noise.

Inland energy production most of the cases is more efficient than on board production (typically done by diesel generators running at partial load) so, even if RES are not used the overall energy consumed on-board impact may be significantly decreased. Having ships engines off while at berth also benefits passengers' experience on the ship (increased comfort) and the maintenance conditions for the ship operators. Also, ports and shipowners adopting this practice could increase their public perception and, in some cases, receive incentives or rewards for being environmentally friendly. For example, ships adopting this practice in some harbours may receive better treatments such as berthing priority, incentives, or port fee reductions.

3.3 Challenges

CI implementation is not straightforward, as a matter-of-fact challenges both economic and technological arise Economic-related issues are mainly caused by the high investment costs of the onshore infrastructure and of ships retrofit. For instance, feasibility studies for the U.S. and Canada’s ports have shown that the onshore infrastructure can cost from 1 to 15 million dollars [16]. Also, these values may change significantly depending on infrastructure size, capacity, closeness to suitable power supply and capability to position it in the port asset. The retrofit cost per ship can vary from \$ 400.000 to \$ 2.000.000 depending on vessel type and electrical system design [16]. To date new vessels are already being designed capable of receiving electricity from shore or to allow a cheaper retrofit when required. Hence, incentives along with private and public financing will be required to help overcome these barriers. Moreover, there is a big unbalance between the cost of electricity produced on board and the one supplied onshore. Producing a kWh on board is extremely cheaper due to absence of taxation and the low cost of marine fuels, and this restrain shipowners to buy electricity from shore connecting ships to ports infrastructures as it would increase their operational costs. The solution to this market disequilibrium could be tackled by reducing or eliminating taxes on the electricity used for this scope even though in many cases the cost of electricity remains cheaper from on-board production. Up to now, In Europe detaxation of electricity provided to ships is allowed by the Council Directive 2003/96/EC [17].

Furthermore, the installation of a Cold Ironing infrastructure most of the time is not straightforward. As a matter of fact, powering large ships requires high voltages and high-power availability, this may require the modification of the port electrical infrastructure hence leading to complex and expensive consequences. Also, when the power system of the harbour cannot sustain ships requirements, typically the first solution explored is developing a connection to the national High Voltage (HV) network. Additionally ships and harbours electrical systems do not always rely on the same frequency levels. For example, in the American continent most of harbours grids rely on 60 Hz frequency whereas in Europe and most of the countries in Africa and Asia use 50 Hz. Nearly all the global ship fleet (99%) adopts 60

Hz frequency, so when harbour and ship grid frequency do not match a frequency converter is required, hence increasing the overall cost of the infrastructure.

3.4 Diffusion of the infrastructure

The diffusion of berths electrification has grown thanks to the introduction of ISO/IEC/IEEE 80005-1:2012 that is the first standard about HVSC. It defines the technical requirements of the OPS facilities and addresses the procedures for safe operation and connection.

During the last years, what also pushed the adoption of CI was the introduction of emissions reduction policies (MARPOL Annex VI) and decarbonisation targets set by the International Maritime Organization (IMO). The shipping sector objectives are a decrease of CO2 emissions by at least 40% by 2030, 70% by 2050 and 50% of Greenhouse Gasses (GHGs) emissions by 2050. CI in fact, is encouraged by IMO and international authorities as one of the main practices to adopt to reduce ships and ports harmful environmental impact [18]. For example, OPS facilities propagation has been stimulated from regulations, within the state of California to reduce maritime transport air pollution the Ocean-Going Vessels at Berth Regulation [19] made the practice of CI an obligation under certain conditions. In Europe, similarly, different harbours are implementing OPS, to comply with Directive 2014/94/EU (article 4 paragraph 5) [20] that made the adoption of Cold Ironing mandatory in EU major harbours by 31st December 2025.

3.5 Ships Power Requirements

Vessels hotelling power requirements primarily vary by the ship's type, size, onboard facilities and performed operations. The latter characteristics will determine the necessary power ratings, voltage levels and other characteristics of the CI infrastructure. The usual power required while at berth and typical stationing time per vessel type are listed below (see Table 1).

Table 1 Vessels Power requirements and berthing time

Vessel Type	**Power Required (kW)**			**Berth time (hours)**		
	Typical	**Low**	**High**	**Typical**	**Low**	**High**
Tug	100	7.5	410	4	1	6
Bulker	200	150	300	48	-	-
Tanker	700	550	800	48	24	72
Auto/RoRo	800	700	890	24	24	36
Container	1400	500	8400	48	24	72
Reefer	3000	900	5600	60	48	72
Cruise	6000	3500	11000	10	10	12

Noticeably, cruise ships are the most requiring vessels in terms of power. This figure further highlights how they also are extremely air polluting sources when at berth. Clearly, applying cold ironing to this specific type of vessels may result in a noticeable decrease of the port impact and better air quality.

3.6 Cruise ships

Cruise Ships are the largest passenger vessels in the world, the biggest ones can host up to 5 thousand passengers crew excluded and reach a length overall of 360 metres and 200.000 gross tonnage (one of the world's largest cruise ships is shown in Figure 7).

Figure 7 Cruise Ship at berth (Symphony of the Seas length 362 m; gross tonnage 228 000)

Nowadays, modern cruise ships are usually equipped with diesel engines or gas turbines that power an electric propulsion system as shown in Figure 8. The electric drive is used as it simplifies manoeuvring especially when docking, other types of propulsion systems can include both electrical and mechanical drive for the propellers. Navigation power demand can reach up to 80 MW for modern vessels and most of the generators might be switched on.

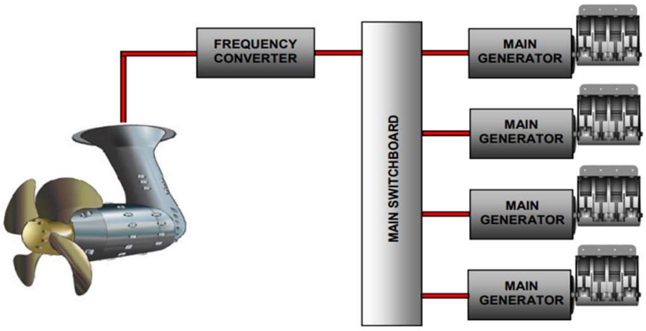

Figure 8 Cruise Ships Power Train [5]

While at berth only one or few generators are kept on satisfying hotelling power needs (as auxiliary engines). To operate at such high-power levels medium voltage is used and this can be of 6.6 or 11 kV. The totality of cruise ships of length over 200m adopts 60 Hz, while smaller types can also use 50 Hz depending on the manufacturer [5]. The above-mentioned characteristics can be visualized in figure 9. The power demand of a cruise ship can vary according to the services that it offers onboard that can vary from restaurants and bars to different kinds of entertainments such as gyms, swimming pools, waterparks, spas and even planetariums. Clearly, powering these kinds of ships from shore is a great challenge as they represent a very demanding load that can unbalance drastically ports electrical systems. It is necessary to provide ports grid of adequate power supply, transmission networks and energy management plans [11] to support cruise ships CI.

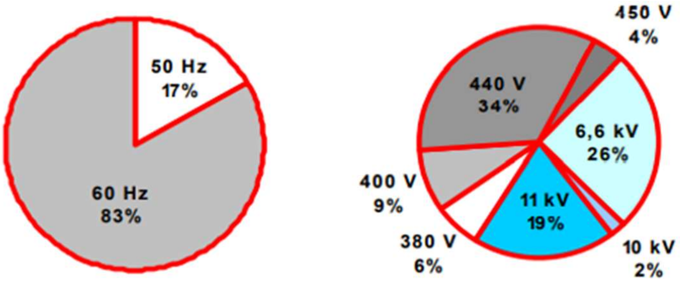

Figure 9 Cruise Ships used Frequency and Voltage [5]

3.7 Cruise Ships OPS Infrastructure Requirements

The only standard that sets the general requirements to perform High Voltage Shore Connection is the ISO/IEC/IEEE 80005-1:2012 [21] published in 2012. Hence, the following paragraphs is dedicated to outlining the requirements demanded by Cruise Ships OPS Infrastructure. According to the 2012 ISO, the shore-side infrastructure to power cruise ships should be rated at 16 MVA and, when feasible, at 20 MVA. These are not restrictive parameters, as it is allowed to adopt lower ratings only when ships with lower power demand are expected to be connected. The nominal voltages of the system are 11 kV and/or 6.6 kV in alternate current. 60 Hz frequency is suggested as the most suitable as most cruise ships rely on it. Also, if a power converter is required it is recommended installing it onshore. Moreover, cable ratings need to be sufficient to meet the maximum power that the terminal can supply to the ship. The plug type and socket type are standardised so that each ship can be powered by different ports, usually for cruise ships the connection is performed with 4 cables. The infrastructure scheme is shown below (see Figure 10).

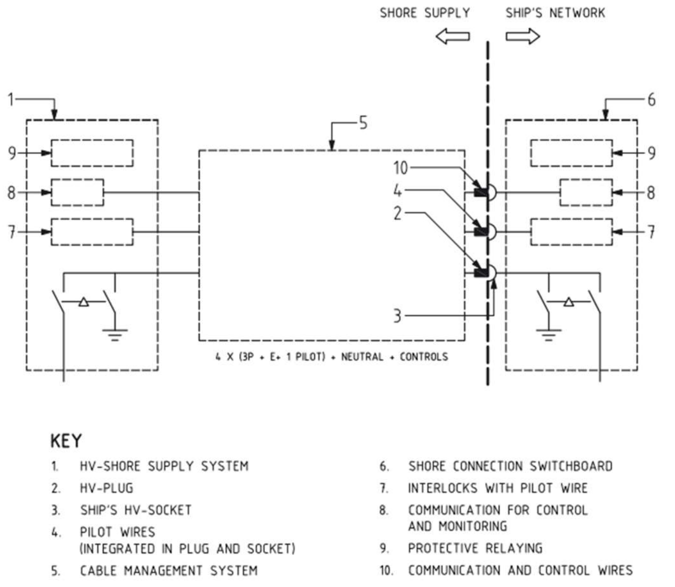

Figure 10 Cruise Ships Cold Ironing System layout [21]

3.8 Infrastructures around the World

The Cruise Line International Association (CLIA) represents 95% of the cruise ships around the world and is highly committed to reach the decarbonisation targets set by the IMO Cold Ironing is becoming a major practice which these kinds of vessels seek to introduce. However, according to data retrieved in 2020, only 68 vessels of CLIA's fleet can receive OPS and a total of 102 are going to have OPS availability between the new to be deployed and the existing to be retrofitted [22]. This means that the share of CLIA's fleet capable of being powered from shore is 32% and would increase to 57% if the deployment agenda does not change. Additionally, only a limited number of ports of the 800 frequented by cruise ships can provide them with OPS. This can be witnessed in the table below (see Table 2) which lists the major ports that are capable of powering cruise ships at berths (Source: [23], [24] and compilation of the author). This section, hence, seeks to shed light on the already existing infrastructures already existing around the world.

Table 2 Cruise Ship Cold Ironing Existing Infrastructures

Port	Country	Power (MW)	Freq. (Hz)	Voltage (kV)	Install Year
Juneau	U.S.A.	7-9	60	6.6-11	2001
Los Angeles	U.S.A.	40	60	6.6-11	2004
Seattle	U.S.A.	16	60	6.6-11	2005
Vancouver	Canada	16	60	6.6-11	2009
San Diego	U.S.A.	16	60	6.6-11	2010
S. Francisco	U.S.A.	16	60	6.6-11	2010
Long Beach	U.S.A.	16	60	6.6-11	2011
New York	U.S.A.	20	60	6.6-11	2011
Halifax	Canada	20	60	6.6-11	2014
Hamburg	Germany	12	50-60	6.6-11	2015
Livorno	Italy	12	50-60	6.6-11	2015
Ystad	Sweden	10	50-60	11	2016
Montreal	Canada	9.6	60		2017
Kristiansand	Norway	16	50-60	6.6-11	2018
Kiel	Germany	16	50-60	6.6-11	2019
Shanghai	China	-	50-60	6.6	-
Lubeck	Germany	9.8	50-60	6.6-11	2020
Genoa	Italy	10	50-60	6.6-11	2020*
Bergen	Norway	20	50-60	6.6-11	2021

* Only in shipyard

Noticeably, the harbour of Juneau in Alaska has been the first to provide electricity from shore to a large Cruise Ship, on the 24th of July 2001 by supplying for 10 hours the Princess Cruise Lines ship called Dawn Princess. The power provided from shore managed by Alaska Electric Light and Power (AEL&P) came from the excess of a hydroelectric power plant. The infrastructure was constructed at first only to provide shore power to Princess Cruises ships that also financed the project. The infrastructure also supplied steam produced from an onshore electrical boiler [5]. However, it remained the only harbour implementing this system which overall resulted in complications and inconvenience [25]. Instead, the port of Seattle, U.S.A., was the first harbour capable of providing OPS up to 2 cruise ships at the same time. In 2019, cruise ships connected 85 times to the port infrastructure for a total of 609 hours avoiding the potential emission of 2900 tons of CO^2. Also, the port of San Francisco that has one of the three cruises pier with OPS infrastructure in 2014 consumed around 7.000 MWh for this purpose, being visited from a total of 73 cruise ships [24]. However, the port which is deemed to be the world reference for CI is the one of Los Angeles. It has also participated in the establishment of the existing HVSC standard.

Finally, with regards to Europe it was the primary country to host the first HVSC infrastructure in the world, in the port of Göteborg, Sweden. Here, in 2000 a 6.6 kV, 1250 kVA, connection was used to power Ro/Ro vessels. Concerning cruise ships OPS, the first European harbour to implement it was the port of Hamburg in 2015. It adopted an innovative solution: a Liquified Natural Gas (LNG) powered barge with a max output power of 7.5 MWe which could supply cruise vessels in the harbour. It is a flexible solution as it can be moved upon necessity in the harbour and can be used also as a backup to supply electricity to the harbour grid. In addition, the harbour has one dock where cruise ships can be connected for a max of 12 MWe produced from RES. In 2018 The cruise ship Aidasol was connected to the port facility 21 times. Following Hamburg's example and Directive 2014/94/EU [20] many European harbours provided themselves with the OPS infrastructure (see Table 2). Other ports around the world are projected to have OPS facilities for cruise ships: Marseille, France; Valencia, Spain; La Valletta, Malta; Rostock, Germany; Victoria, Canada; Miami, U.S.A. Hence, given the worldwide rise of these infrastructures implementation it clearly emerges the necessity of providing also other big harbours, such as that of Civitavecchia with an appropriate infrastructure to stimulate the adoption of Cold Ironing between cruise ships.

3.9 Policies regarding CI

To more thoroughly understand and promote the installation of Cold Ironing infrastructure, it is essential to consider the already existing policies regarding CI What first attracted shipowners and ports to look at CI was the policies regarding ships air pollution and ports air emissions regulations. The first restrictions on air emissions from ships occurred in 2005 with the amendment of the sixth annex of the MARPOL Convention [26]. Further information on the MARPOL convention can be found in **ANNEX I**.

3.9.1 European Union

The interest of Cold Ironing from the EU departed from the necessity of reducing emissions generated by the maritime sector. In 2005, the EU Commission, anticipating the Annex VI (Marpol Convention) restrictions, with **DIRECTIVE 2005/33/EC** [27] imposed that from the 1st of January 2010, ships berthing in Community ports had to use only fuels with a maximum of 0.1% sulphur content by weight. This directive explicitly exempts from this restriction ships that receive electricity from shore.

Subsequently, on 8th May 2006, the **Commission Recommendation 2006/339/EC** [28] “on the promotion of shore-side electricity for use by ships at berths in Community ports” was published. It was aimed to encourage the implementation of CI and increase the awareness of member states on the technology benefits. The Recommendation expressed the necessity of addressing the issues caused by air pollution generated by ships in harbours that at that time were not adequately considered on an international level. Only one year following the entering into force of Annex VI of the MARPOL convention, it rose the necessity to take further action as IMO’s regulations were not enough to win the emissions reduction challenges proposed at that time. To tackle this issue, synergy within industries and port authorities are seen as pivotal for the development of shore-side electricity which also requires promotion within local authorities. The EU commission recommends Member States to consider economic incentives to drive the implementation of cold ironing in harbours. Hence, Actions taken to promote CI from EU states are required to be reported to the commission. The Commission Recommendation also includes an Annex that describes the technical requirements of the Shore-Side Electricity infrastructure from the HV national grid to the ships interface. Chapter 2 of the recommendation underlines the benefits of adopting CI: reduction up to 50% of CO2, 99% of CO, over 50% of NOx emissions. The document includes an economic assessment to compare benefits in implementing CI alternatively to the use of fuel oil with 0,1% sulphur content. It emerged that the monetised advantage would range between 103 and 284 million euros a year. Additional advantages of the CI implementation mentioned also are the elimination of vibration and noise (around 10-120 dB close to the ship) due to auxiliary engines operation along with an improvement of the maintenance conditions for ships engineers. Chapter 3 analyses the costs, initial investment and operational costs that are going to vary depending on the pre-existing infrastructure. The analysis is divided in two scenarios that are with or without taxes on the electricity supplied, being the second option the most convenient showing 80% reduction of the annual total system cost. This analysis already shows that the feasibility of the Shore Side Electricity for ships must consider that the higher prices of electricity produced from shore are a real bottleneck for the development of the technology and so taxes on electricity supplied from shore may be lowered or avoided.

EU commitment towards port electrification is defined by **Directive 2014/94/UE** [20] on the deployment of alternative fuels infrastructure. The Directive published on 22 October 2014, (article 4 paragraph 5) requires member states to adopt policies to promote OPS from ports and that as a priority, by 31st December 2025, Trans-European Transport Network (TEN-T) Core Network ports and other ports shall install OPS infrastructures, with the exception for cases where there is no demand of shore side electricity or benefits are not cost effective. On-shore power supply is seen as a priority from EU, being included in the TEN-T guidelines (Article 21.3 of Regulation 1315/2013 of the European Parliament and of the Council on Union guidelines for the development of the trans-European transport network and repealing Decision No 661/2010/EU).

The European Union attitude towards Cold Ironing can be summarised with the written answer from the European Commission published in October 2019 [30]. The European parliamentarian Julie Lechanteux on the 5th of September 2019 [29] submitted a question for written answer to the EU commission asking if an investment plan had already been thought of by the commission. The answer given by Ms Bulc on behalf of the European Commission showed what are the actual plans to support SSE. Ms Bulc after reminding (article 4(5) of Directive 2014/94/UE) previously mentioned, highlighted how the commission promoted the SSE as a priority for transport investment. This intent is shown in the TEN-T guidelines. Additionally, Ms Bulc reminds how shore side electricity being an alternative fuel infrastructure can be selected under the General Block Exemption Regulation (4) and funds to implement it can come from public support.

An incentive that Member states can use to install and use SSE is the reduction of the taxes on the electricity used to power ships at berth as stated from Article 19 of the directive of the **Energy Taxation Directive** [17]. The above-mentioned Directive allows to avoid taxation on “products supplied for use as fuel for the purposes of navigation within Community waters (including fishing), other than private pleasure craft, and electricity produced on board a craft”. This avoids the taxation on the energy sold to shore connected Ships. Nowadays, Germany is one of the countries that is benefiting the most from this permission due to COM(2011) 302 [31] finally obtaining a taxation reduction for the electricity provided from shore. It has been allowed to apply a reduced rate at the level of the EU minimum rate.

The European **Green Deal** [32] published in December 2019 sets the new targets of emissions reduction for the EU aiming to a 40% of GHG emissions cut a share of renewables of 32% and increase of 32.5% in energy efficiency. To reach the decarbonisation goals the transportation sector must face a reduction of at least 55% of emissions by 2030 and carbon neutrality by 2050. The direction to be taken is to reach this goal. The Sustainable and Smart Mobility Strategy published on the 9th of December 2020 in the COM(2020) 789 final [33] underlines the need to take action on reducing maritime transport and the great challenge that the sector is going to face. In the document is proposed the inclusion of the EU Emission Trading System (EU ETS) in order to boost the implementation of environmentally friendly technologies. An interesting request made is the definition of an Emission Control Area in all the EU waters and the establishment of clean ports. The document states that simplification of financing processes will be key to promote the sector transition. In this Policies context the willingness of the EU is clear, underlining how infrastructures as the SSE are going to be supported economically and are key for the sector transition.

3.9.2 Italy

Recently, Italy is shifting its attention to the adoption of CI infrastructures, including the port of Civitavecchia. The port already investigated the possibility of installing the above-mentioned infrastructure in 2006. At the time it required a High Voltage (HV) connection to the national grid due to the high power requested by the infrastructure. If all the berths available to date of the port were electrified the cost would have been of 7.8 million euros of which 1.9 million for 3 cruise ships docks and 3.8 million euros for the electrical connection to HV national grid [34]. Due to the lack of investors and the low number of ships capable of receiving the electricity from shore, the project was not continued. Furthermore, a connection to the HV national network was not easy to implement as the harbour is 6.6 km distant from it. Additionally, installing an HV/MV substation would have required adequate personnel, big areas, high costs of investment and maintenance. Hence, it may have resulted in an under usage of it when no ship would be connected.

To date the realisation of CI infrastructure in the port of Civitavecchia became more possible thanks to the allocation of 80 million euros to develop it. The funds come from the Piano Nazionale Ripresa e Resilienza (PNRR) [35] (National Plan for Recovery and Resilience) adopted from Italy to recover the economy following the Covid-19 pandemic outbreak.

4 THE PORT OF CIVITAVECCHIA

4.1 Description

The harbour of Civitavecchia is one of the main junctions of the logistics of Central Italy and the biggest harbour of the Tyrrhenian Sea. Located 70 km north of Rome (see Figure 11), it extends from the city centre of Civitavecchia to the north-west end of the city. The construction of the harbour was ordered by the emperor Traiano around 108 A.D. after the construction of the city of Civitavecchia previously named "Centumcellae". The harbour was built to host part of the military fleet and support maritime trades.

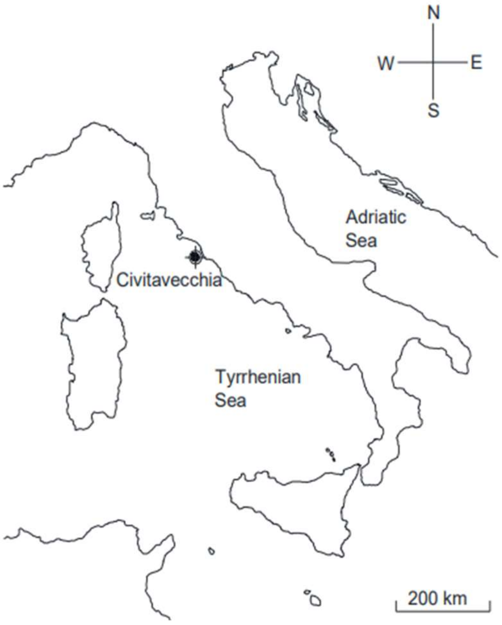

Figure 11 The Port location [36]

Nowadays, the Harbour is one of the most developed of Italy, operating in both the touristic and shipping sector. It operates under the Port Authority of the Central Northern Tyrrhenian Sea which also controls the harbours of Fiumicino and Gaeta. The company Port Utilities S.p.a which has been designated from the Port Authority to manage the electrical, water and telecommunications services of each of these harbours.

The port of Civitavecchia is divided into two major areas (see Figure 12): the south and the north one, respectively dedicated to touristic and commercial purposes. The southern side also hosts the historical harbour next to the Michelangelo Fortress, the Marina Yachting, and the Darsena Romana (Roman Dock) where the offices of Port Utilities S.p.a. are located and part of the fishing activities take place. Close to this area Port Authority buildings are located by the Molo Vespucci. The northern sector of the port, instead, is dedicated to commercial activities such as the trade of goods and logistics. It hosts a terminal for containers, docks for general cargo vessels, bulk carriers, Ro-Ro and Ro-pax vessels and a dock for the harbour services. A section is also dedicated to the Autostrade del Mare (Sea Highways), scheduled services for passengers and goods transportations around the Mediterranean

Sea done mostly with Ro-Ro and Ro-pax vessels. The renovations of the harbour will increase the whole harbour surface introducing in the northern side an area dedicated to a new container terminal and a quay dedicated to oil. This area denominated Darsena Energetica Grandi Masse (DEGM) hosts the first full scale prototype of Oscillating Water Column incorporated into a breakwater ever built in the Mediterranean Sea [37]. When the infrastructural renovations in progress will be finished the harbour will be able to host boats up to 400 metres long and 18 metres draft (originally 360m length 15 m draft). The infrastructural renovation of the harbour will bring the total surface area from 724.200 m^2 to 1.385.537 m^2 increasing noticeably the harbour capacity and traffic. The total docks length is going to be increased from 12.100 m to 14.934 m. The actual number of docks are 36, with 6 terminals for passengers, 6 docks dedicated to cruise ships, 9 for Ro-Ro and Ro-pax and 4 for commercial traffic. Figure 12 shows the architecture of the port and the different docks.

The port is mostly characterised by passenger vessels traffic and it is specialised in cruise ships. Only in 2019 it recorded 816 cruise ships calls and 1.1 million (1.111.542) transited passengers [38]. Unsurprisingly, it is one of the ten most visited harbours from cruise ships in the world, being in the Mediterranean Sea second to Barcelona only for a few calls and the first in Italy.

Figure 12 Map of the Port

The harbour develops from the city centre of Civitavecchia to the north-west end of the city where it confines with the thermal electric hub of Torrevaldaliga. The hub consists of a 1.98 GW Thermoelectric Coal Fired Powerplant and 2 Natural Gas Turbines of 800 and 400 MW. Hence, the city air quality is significantly affected by the Torrevaldaliga power plants emissions and by the consistent ship traffic.

4.2 Port’s Electrical Grid

The Civitavecchia’s Port Electrical infrastructure is connected to the national grid by 3 Medium Voltage (MV) Points of Delivery (POD) at 20 kV and 11 Low Voltage (LV) PODs at 230 V or 400 V, it works at the frequency of 50 Hz. From the MV PODs the electricity is distributed in MV and Low Voltage (LV) (400V three phase and 230V monophase) the LV network develops from 17 cabins. The port’s electrical grid users grew from 285 (5 in MV) in 2015 to 370 (7 in MV) in 2019. By April 2021, due to the Covid-19 pandemic in 2020 the number of users connected decreased to 333. The port infrastructure is continuously evolving and adapting to the user's needs, it can be considered as a microgrid whose main point of connections are the PODs from the national grid. In table 3 the power rating of each MV connection is listed.

Table 3 MV POD Power Ratings

MV POD Stations	Available Power [kW]
A (Flavio Gioia)	6 000
B (Largo della Pace)	3 000
C (Varco Nord)	300
Total Available Power	**9 300**

Also, the port electrical grid has been designed to always offer the highest quality of and most reliable service to its users. For this reason, the distribution in Medium Voltage (MV) is designed in a loop and mesh structure. The structure at the closed loop is the most reliable distribution network because when one loop is opened, automatically the power supply is allowed from the other side of the loop. The radial network instead allows the use of backup diesel generators to power non disconnectable loads. To date, the piers of the Cruise Terminal are fed by MV lines whose maximum rating is 17 MW. In the near future, the loop will be closed allowing the counter feeding of the two principal PODs A and C. Allowing in case of fault to power the loads from the not faulted POD. The port's electrical grid is continuously evolving and adapting to new users' needs or local generation. It has been designed to be capable of providing the maximum continuity of service, reason why part of the MV distribution network has a closed loop structure that allows isolating faults and increasing the continuity of the service. Now, only POD B and C are connected by loop structure and a future reconditioning will close the loop between POD A and C to enhance the reliability of the grid service. Figure 13 shows where the three MV POD are located.

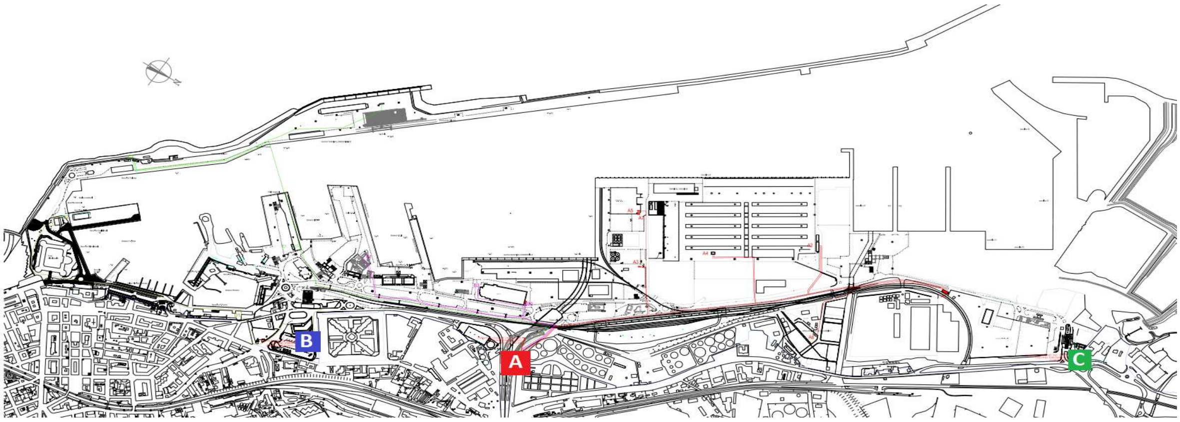

Figure 13 Port's Grid PODs (A Flavio Gioia 6 MW; B Largo della Pace 3MW; C Varco Nord 0.3MW)

From an analysis of the power curves of the PODs in MV of 2019 the data in Table 4 has been obtained.

Table 4 MV PODs Ratings, Peak Power, Average Power Requested

POD	A (Flavio Gioia)	B (Largo della Pace)	C (Varco Nord)	Total (from sum of Power Curves)
Rated (kW)	**6000**	**3000**	**300**	**9300**
Peak (kW)	2090	618	60	2386
Peak/rated	34.80%	20.60%	20%	25.70%
Day - Time of Peak	14/08/2021 21:00	10/09/2021 21:00	25/02/2021 21:00	14/08/2021 21:00
Avg (kW)	1155	168	29	1352
Avg/Rated	19.30%	5.60%	9.60%	14.50%
MWh/year	10117	1473	252	11842

It is possible to see (Table 4) that POD A, the one with higher power available, is the most used. Its power absorption never exceeded 35% of its rating, while the other 2 are the least used. The averages of their power absorption shows that most of the time a consistent amount of power is left available, and peaks of requested power occur typically at 9 PM. The Port's energy consumption is higher during summer as port activity increases, being July the most energy consuming month with 1.378 GWh, while the monthly average energy consumption is 1 GWh. The yearly consumption also including the LV PODs absorption in 2019 was 13 GWh. In Figure 14 the yearly consumption of the MV PODs is shown.

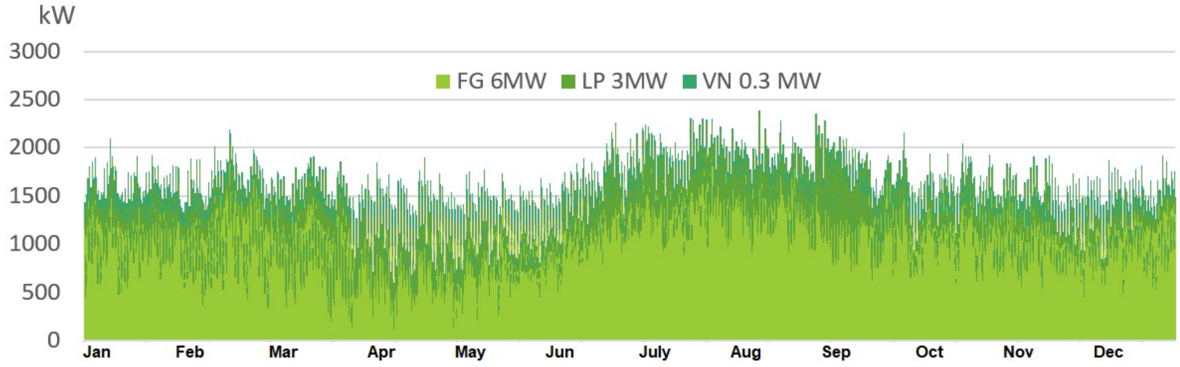

Figure 14 Hourly Power absorption at MV PODs

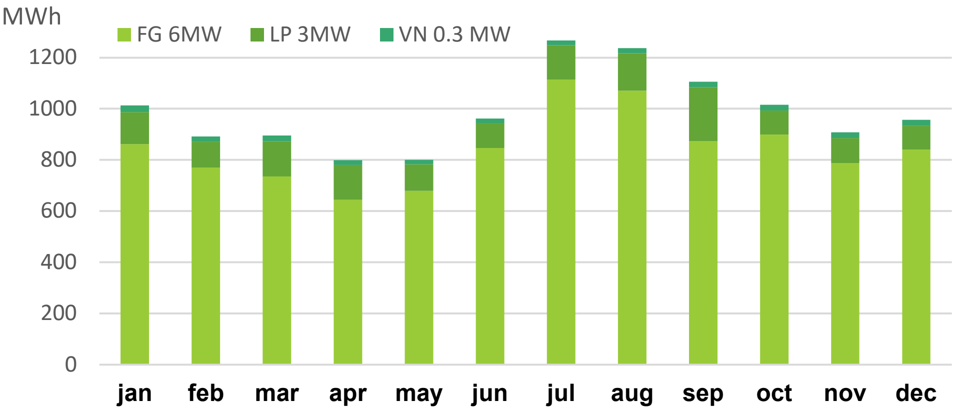

Figure 15 Monthly Energy Absorption by POD

If we analyze the average and maximum daily consumption at Mv level of the port, we obtain a bar chart (see Figure 15) that shows the max (dotted line) and average (full line) power required at MV PODs by hour of the day for a low season month (April in grey) and a high season month (July in black). The curves are obtained by summing all MV PODs Power curves.

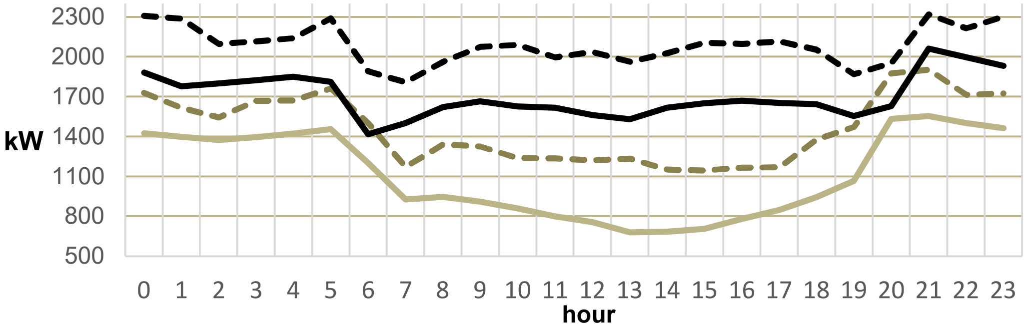

Figure 16 Daily Average Power absorption at MV
(dotted line–maximum; full line–average; Grey-low season month; Black-high season month)

From the above-mentioned figure (see Figure 16) it is possible to witness how the peaks of power requested usually occur at night. This occurs because of the high instantaneous power required by container cranes that often work at night, the absence of PV production that satisfies part of the daily loads, and the required power for the lighting system.

4.3 The ASDC Status

From the 1st of January 2022 the port will become a so-called "Altro sistema di distribuzione chiuso" (ASDC)-his new status of the port will require a different management of the port electrical infrastructure by part of Port Utilities S.p.A.. As a matter of fact, an ASDC is a Closed Distribution System (CDS) existing into a geographically limited site, connected to the national grid through one or more points at different voltage levels that connects one or more consumption units and or one or more production units. Into an ASDC producers and clients are different subjects and it distributes electrical energy to industrial commercial or shared services. Managers of CDS are obliged to unbundle, meaning that the management of the infrastructure needs to be separated from every other activity. For this reason, Port Utilities S.p.A. will have to perform accounting separation f it is willing to also manage the PV plants and sell the energy produced as it will act as distributor and producer. In a CDS the access to the free market must be guaranteed to all the users of the grid. Is not possible for the managing company to directly sell energy produced from local power plants to its users. Furthermore, energy production is viewed as if it was on the free market and so there are no exemptions from system charges usually allowed for auto-producers.

4.4 Distributed Generation

4.4.1 PV Systems

Concerning distributed generation, the harbour currently possesses 5 different PV systems whose capacity and surface are listed in the table below (See Table 5). Of these, only 2 are operating, indicated in the table as PV1 and PV2. They are used for self-consumption and satisfy a portion of the daily energy needs of the port facilities. Figure 16 shows the total PV energy production by month. (Taking as reference PV2 whom data of production were available the other PVs production has been estimated based on their rated capacity and year of installation). The yearly total production is estimated to be 2 741 MWh covering the 20% of the port energy consumption. Figure 17 shows the PVs monthly energy production. The seasonality of the port's energy consumption, higher in summer months and lower in winter months leave space for improvement for PV system that can be used to cover part or most of the port's consumption. Anyway, as is possible to see in figure 15 the peaks of power request occur over night hence is so necessary to shift the new PV systems power production during night. As this study shows, this can be done with the implementation of Energy Storage Systems (ESS).

Table 5 PV Systems Characteristics

PV system	Surface (m2)	Total Power (kW)
PV1 (DR)	850	115.20
PV2 (CFFT)	4 051	583.84
PV3	35 000	1 100
PV4	100	15
PV5	1000	75
Total	**41 001**	**1 889.04**

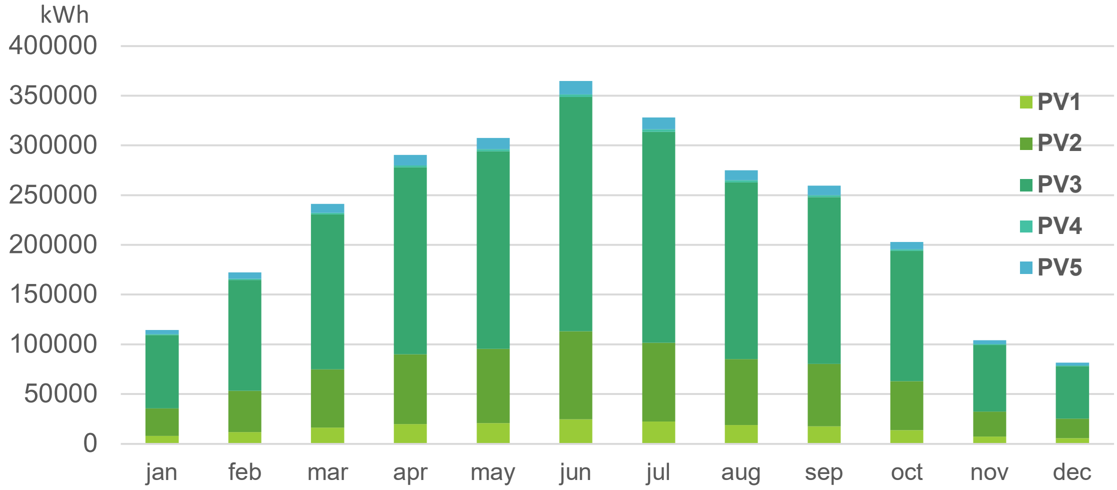

Figure 17 PV Monthly Energy production

The first PV system, visible in Figure 18, was installed in 2010 on top of the multifunctional building of the Darsena Romana. It extends for 850 m^2 and has a total installed power of 115 kWp. It is composed of 576 PV modules polycrystalline at high efficiency model Suntech STP 200W. The Conversion system is made of two inverters type "Sunway Tg 61 660V", located inside the MV/BT station. In addition, the PV system is equipped with a system through which it is possible to remotely control its productivity.

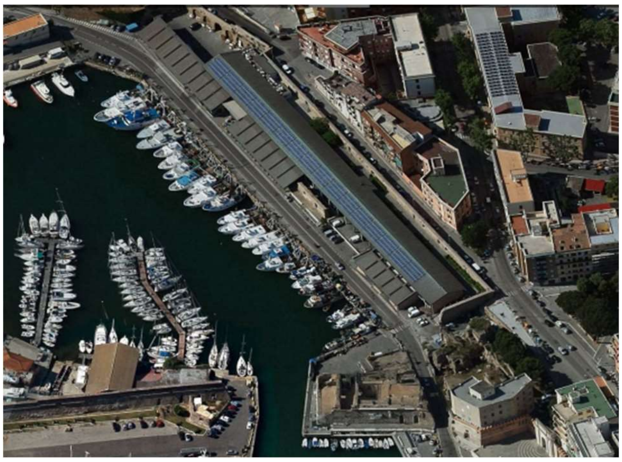

Figure 18 PV 1 PV system on the Darsena Romana

The second PV system started to produce in 2012 and is installed on top of the cover of the storage of the CFFT (Civitavecchia Fruit & Forest Terminal - S.p.a). The PV system develops over 4051 m^2 with a total power of 583 kWp. It is composed of 2.383 PV modules of 245 Wp nominal power each. The inverters are located inside a substation located close to the building.

The third PV system also started operating in 2012 and it is realised over the cover of the Privilege Yard S.p.A. buildings. The PV system develops over 35 000 m^2 divided in 4 sections, for a total power of 1 100 kWp. The PV system is composed of modules of amorphous silicon (Unisolar Ovionic) completely integrated in the cover of the building. The inverters (Power One) are located into a small structure close to the same edifice. PV systems 2 and 3 are shown in Figure 19.

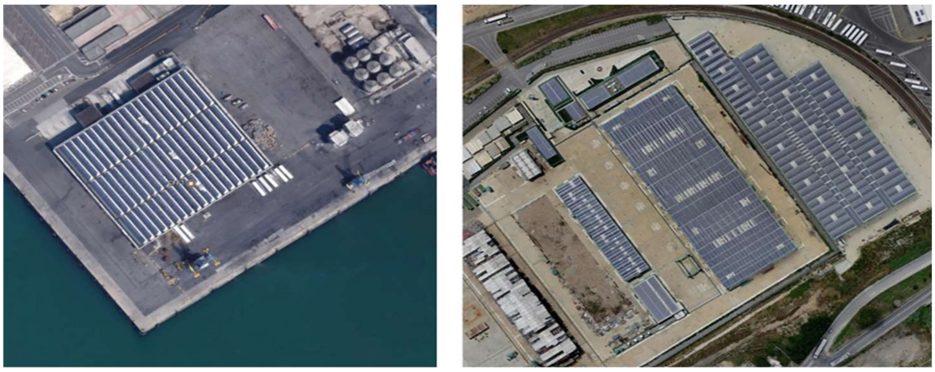

Figure 19 PV system 2 left, 3 right [38]

The fourth PV System started operating in 2017 and is realised on top of the rooftop of the infirmary of the Meeting Village. The PV system is composed of 60 PV modules of the nominal power of 250 kWp each. It develops on a surface of over 100 m^2 for a total installed power of 15 kWp.

Finally, the fifth PV system started working in 2017, it is realised on the cover of the new cruise passenger's Terminal of the Roma Cruise Terminal Spa (RCT) at the pier number 12 Bis North of the Port. The PV system extends over an area of 1 00 m^2 for a total power of 75 kWp. It is composed of 300 PV modules of the nominal power of 250 Wp each. The inverter is located in a small cabin next to the terminal. These last two PV systems are visible in Figure 20.

Figure 20 PV system 4 left, 5 right [38]

4.4.2 Additional PV

The port also has the possibility to install other PV systems in other areas. One is the Polyfunctional Centre “Saraceno " close to pier number 23 (see Figure 21). The building has a homogeneous rooftop which allows the installation of 600 PV modules of 300 kWp of rated power for a total rated power of 180 kWp. The building does not directly face south so the productivity can be smaller here, the estimated yearly energy production is 220 000 kWh/year. The other area consists of the rooftop of the “Autostrade del Mare" terminal (see Figure 21). It is made of three big arches, thus, to avoid ruining the aesthetic of the building it is expected to install flexible PV modules capable of adapting to the surface. Being the exposition not too optimal, only half of the rooftop is usable allowing to install 420 PV modules for a total rated power of 102.48 kWp the expected model to be installed is the F-MWT325M60S from the Fly Solartech. The estimated energy production is of 120 000 kWh/year.

Figure 21 Saraceno Building’s rooftop left, Terminal Autostrade del Mare right [38]

Other areas available are the rooftops of the factory “Grande Meccanica”, with 2 000 m^2 of area where it can host up to 200 kWp of PV system (see Figure 22) and the warehouse called “ex Campostano” of 3 000 m^2 that allows the installation of around 300 kWp of PV system.

Figure 22 rooftop of the factory Grande Meccanica.

The port is in possession of fields nearby the portual area where more extended PV systems can be installed in order to reduce the dependency from fossil fuels. The fields are divided into two major areas: Area Zephiro, of 29 000 m^2 and Villa Romana, of 25 000 m^2. If we consider that over 15 000 m^2 is possible to install 1 MWp of PV system, the two areas will allow the installation of 1.93 MWp and 1.66 MWp respectively for a total of 3.6 MWp. The rated power of the above listed PV systems is shown in Table 6 and the total expected monthly power production is plotted in Figure 23.

Table 6 Possible PV Systems to Be Installed

New PV system	Total Power (kW)
PV6 (Sa)	180
PV7 (AdM)	102
PV8 (GM)	200
PV9 (eC)	300
PV10 (AZ)	1 933
PV11 (VR)	1 666
Total	**4 381**

The energy production with the installation of these above-mentioned PV systems would increase from 2 741 MWh per year to 8 169 MWh per year covering 63% of the port's yearly energy consumption.

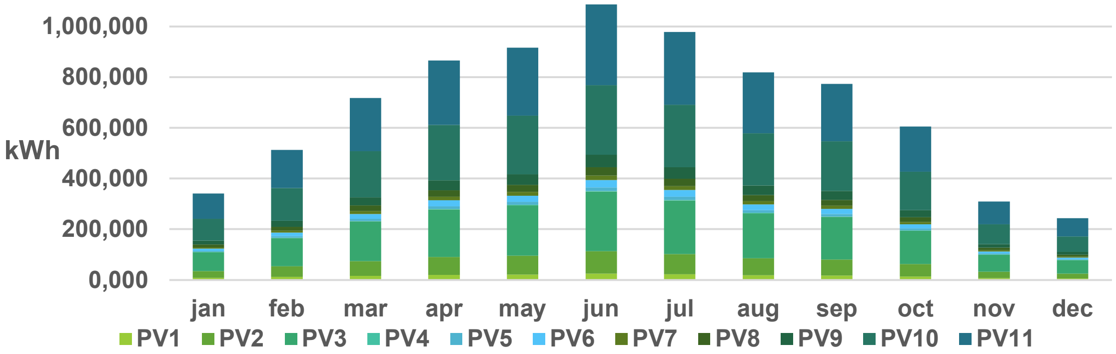

Figure 23 PVs energy Production with additional PV systems

4.4.3 PV yearly Power Curve

The power curve with hourly time step is available only on the first two PV systems: Darsena Romana and CFFT. To obtain a power curve of those that are not available the following methodology has been used: First, the CFFT (Container Fruit & Forest Terminal) PV system has been considered as reference. An adjustment factor has been used in relation to the year of production (to estimate the efficiency losses through time and technology advancement of the panels). Furthermore, the value of 1 was given for the PV system of the same year of the CFFT (2012) and the value of 1.2 for those built in 2017 1.3 for those to be built in the future. A scaling factor is obtained by the relation between the CFFT maximum produced power and the rated power of the PV system. With these two factors a correction factor is obtained. Finally, to compute the missing PV system power production it has been divided the reference value of the CFFT by the correction factor, obtaining the hourly estimated power profile shown in Figure 24.

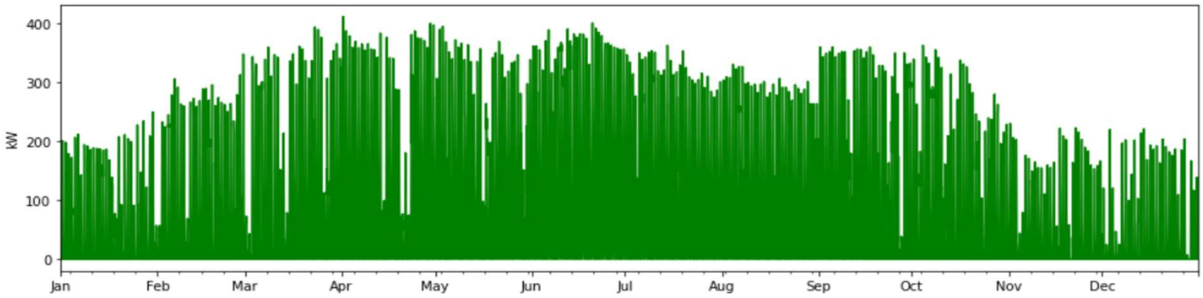

Figure 24 Yearly CFFT PV Power Curve

4.4.4 Wave Energy Converter

Wave energy is an indirect form of solar energy indeed, waves are generated from wind blowing on the sea surface. It is one of the most recent forms of renewable energies. To date there are many different devices used to make use of it however, no predominant technology has yet conquered the market. Nonetheless, one of the most reliable ones is that of the Oscillating Water Columns (OWCs). These devices convert the wave kinetic energy into electricity. The device consists of a semi submerged air chamber that has on top a orifice where a bidirectional turbine is installed. The motion of the seawater surface due to wave oscillations compresses and decompresses the air that flows into the turbine that with a generator produces electrical energy. The most developed typology of these devices consists into a fixed structure installed on the shoreside typically incorporated into breakwaters.

The port of Civitavecchia has been recently provided with a set of breakwaters with this characteristic capable of absorbing energy from the wave motion and converting it into electricity using a specific turbine. The breakwater provided by OWCs is composed of 17 caissons each provided by 8 semi submerged chambers where air is compressed and decompressed thanks to the water surface motion. This particular OWC is composed of a U-shaped cross section with the opening facing upwards, which increases the duct length where water will be flowing. The OWC type of Civitavecchia was first proposed by Paolo Bocotti and can be considered as a two-dimensional wave terminator thanks to its small opening into the wave direction. Its technical name is REWEC3 that stands for Resonance Wave Energy Converter and it can be appreciated in Figure 25 and 26.

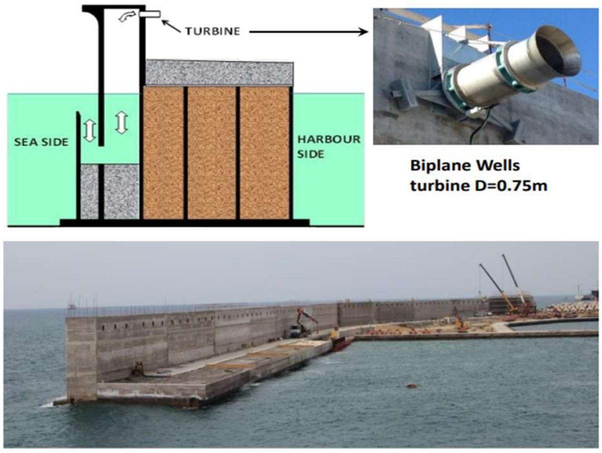

Figure 25 Civitavecchia Breakwater. Top left section of U-shaped OWC in a REWEC3 caisson. Top right: Wells turbine at one of the OWCs, installed in November 2015. Bottom: nearly completed breakwater [39]

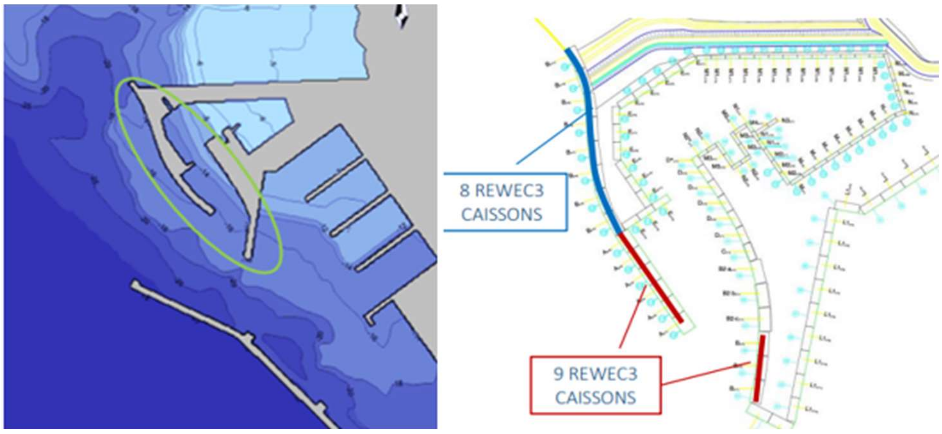

Figure 26 REWEC3 Caissons Location [39]

Each chamber can be equipped with 20 kW rated Wells Turbines. Up to date, only one turbine has been installed in 2015 for experimental purposes. The total rated power of the WEC can be obtained from:

$$N_{Caissons} \cdot N_{Chambers} \cdot P_{Turbine} = P_{REWEC3} \tag{2}$$

Where $N_{Caissons}$ is the number of caissons installed in the port, 17, $N_{Chambers}$, the number of chambers per each caisson, 8, $P_{Turbine}$ the rated power of a turbine, 20 kW and P_{REWEC} the rated power of the whole WEC.

$$P_{REWEC} \ = 2\ 720\ kW \tag{3}$$

Resulting into 2.72 MW of Rated Power. Obviously, it must be pointed out that the efficiency of the energy conversion will have to be taken into account. Also, the power exploited by the system is dependent on the sea swell ratings, hence, the value here computed is only indicative.

The Mediterranean Sea is characterised mostly by short period and low height wind swells which characteristics can be seen below (see Figure 27).

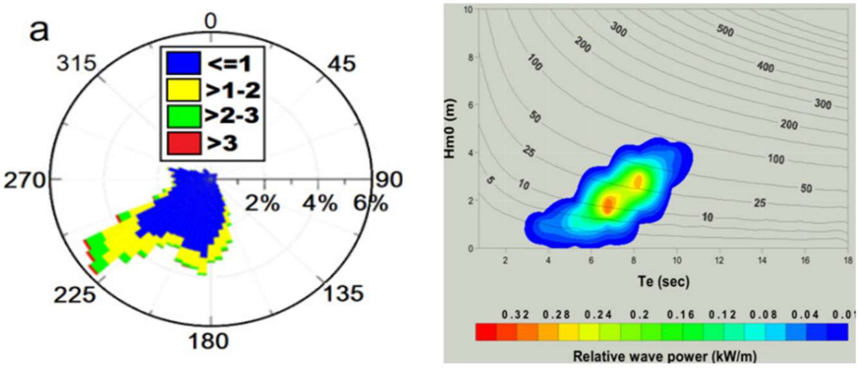

Figure 27 Left: Directional distribution of waves (colours indicate significant wave height expressed in metres). Right: Typical Mediterranean wave climate [40]

4.4.5 REWEC3 Power Curve estimation

To estimate the power production of the REWEC3 the main steps undertaken are the followings:

1) Determination of the generator power output by different sea conditions.
2) Creation of a Time series of the sea conditions over a year (2019).
3) Creation of the estimated hourly power curve of the turbine Generator.

Assumption:

Each REWEC 3 chamber is equipped with a Wells Turbine with the same characteristics shown in the paper [36].

1) **Determination of the generator power output by different sea conditions**.

a. Sea state Wave Power determination

Paper [36] considers 12 sea states that are characteristics of the REWEC 3 location (Civitavecchia). The sea states are in table VI and are described by H_s the significant wave height (in metres) and T_p the mean spectral period (in seconds). From these values with the formula:

$$P_{\,wave} = \frac{\rho \cdot g^2}{64 \cdot \pi} \cdot H_s \cdot T_p \qquad (4)$$

where $P_{\,wave}$ stands for power per unit length in W/m; g is the constant of gravity equal to 9.81 m/s2; ρ is the sea water density considered equal to 1025 g/m^3. The wave power per unit length obtained is reported in Table 7 of this document in kW/m.

Table 7 Different Sea State Significant Wave Height and Spectral Period and Wave Power

Sea state	**Hs [m]**	**Tp [s]**		**Pwave (kW/m)**
1	0.5	3	-->	0.368
2	1	4.3	-->	2.110
3	1.5	5.2	-->	5.740
4	2	6	-->	11.775
5	2.5	6.7	-->	20.544
6	3	7.4	-->	32.674
7	3.5	8	-->	48.079
8	4	8.5	-->	66.722
9	4.5	9	-->	89.413
10	5	9.5	-->	116.519
11	5.5	10.5	-->	155.828
12	6	10.4	-->	183.683

b. Generator power determination by sea state

Table **III** of the paper [36] is considered, it gives the mechanical and the generator converted power per each sea state. Values are given as a mean and as a maximum power output in kW, for the following computations only the mean power output of the generator is considered (column 4 of table **III** of the paper).

For each sea state the obtained mean Wave power per unit length P_{wave} (kW/m) is so associated to the respective mean power generated by the turbine P_{g_mean} (kW) as shown in table 8.

Table 8 Wave power per unit length and mean generator power by Different Sea State

Sea State	P_{wave} **(kW/m)**	P_{g_mean} **(kW)**
1	0.368	0
2	2.110	0.5
3	5.740	2
4	11.775	4.1
5	20.544	6.2
6	32.674	9.4
7	48.079	11.7
8	66.722	14.4
9	89.413	15.4
10	116.519	16.2
11	155.828	17
12	183.683	17.5

Their relation will be used to determine the generator power output given a time series of the sea conditions of a typical year in section 3). The relation between the generator power output and the mean wave power is plotted in Figure 28.

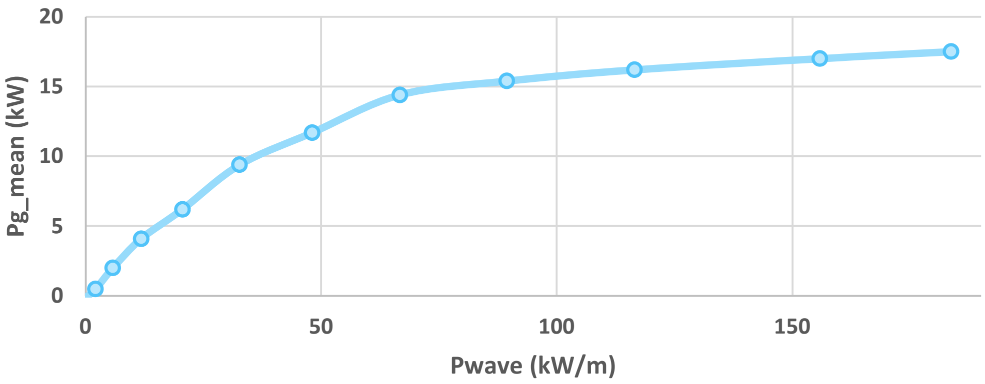

Figure 28 generator power variation by mean wave power

2) Creation of a Time series of the sea conditions over a year (2019).

To define a time series of sea conditions of a typical year, historical forecast data are retrieved from the recordings of the Buoy present in front of the Civitavecchia Coastline. After generating the hourly time series of sea conditions H_s and T_p with the formula (5):

$$P_{\ wave} = \frac{\rho \cdot g^2}{64 \cdot \pi} \cdot H_s \cdot T_p \tag{5}$$

the mean wave power $P_{\ wave}$ per each hour is computed. By doing so an hourly timeseries of the mean wave power per hour is obtained.

3) Creation of the estimated hourly power curve of the turbine Generator.

In the first section (see Section 1) a relation between the mean wave power and the generator Power output is defined and shown in Table 7. Departing from the obtained hourly mean wave power data series in section 2) the hourly power output of the generator is computed through a linear interpolation of the values of table 7. When the mean wave power exceeds the value obtained for sea state 12 the power of the generator is 20 kW as it is the max power output of the generator. The power output curve of one generator is finally obtained and shown for the period of 1st January 2019 to 28 February 2019 (see Figure 29).

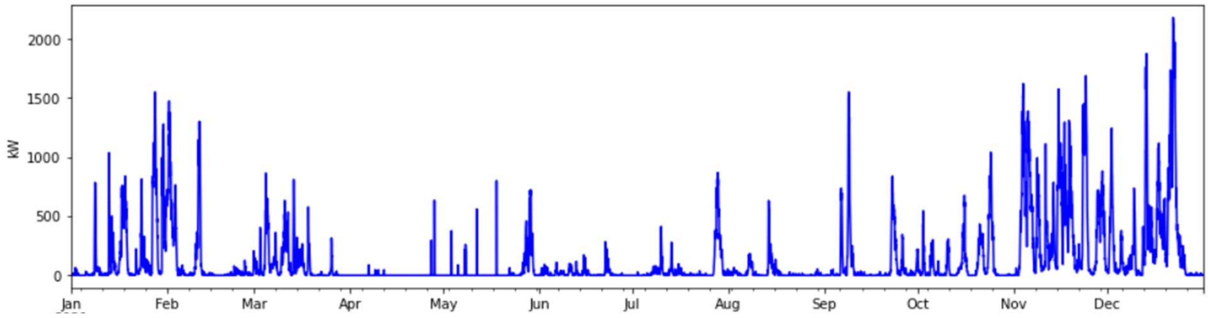

Figure 29 Estimated hourly Power curve of the REWEC3 turbine’s generator

The REWEC 3 of Civitavecchia has the possibility of installing up to 136 Wells turbines so the total power output of the WEC may be the output of 1 generator multiplied by 136. Ideally, Maintenance is expected to be done when sea conditions do not allow power production, to avoid interruption of the WEC operations. Nonetheless this is a hypothetical scenario and adjustments still can be performed. The efficiency of power conversion and transmission may be assumed or computed and multiplied to obtain the effective power output of REWEC3. There is also to consider that the estimation is achieved from data recording the operation of a turbine that was not tuned hence, a higher efficiency of the system is to be expected. Therefore, the efficiency of the power conversion can be expected to be one as losses may already be included in the power estimation. From the obtained power curve by hour the energy production can easily be created by summing the product of the mean hourly power multiplied by one hour (the time step). From this data is possible to estimate the monthly production (see Figure 30).

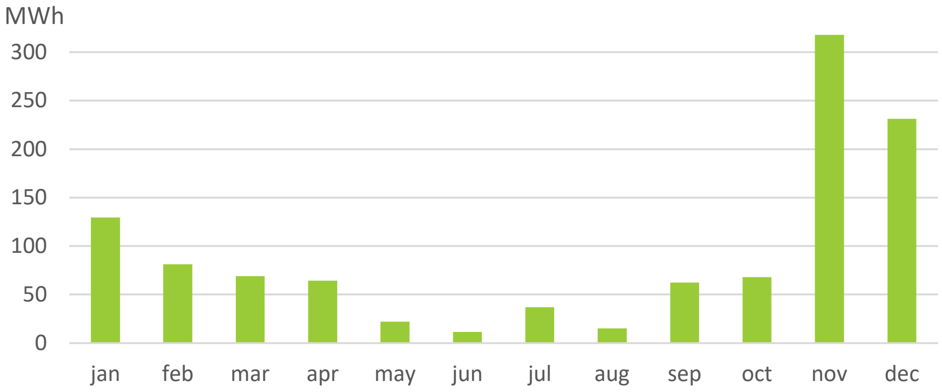

Figure 30 Monthly estimated REWEC3 Energy Production

It is above shown how this type of renewable in this location is strongly affected by seasonal trends being winter the most productive season and November the most producing month reaching up to 317 MWh (see Figure 30). Also, that wave climate can roughly change every year and some big discrepancies can be expected year by year. The total estimated productive energy for the year 2019 is around 1.1 GWh.

4.4.6 WaveSax

The WaveSax is a OWC device operating with a bidirectional Wells turbine. It has been developed by the Gestore del Servizio Elettrico (G.S.E. S.p.A) and Ricerca sul Sistema Elettrico S.p.A. (R.S.E. S.p.A.). The main difference between the previously described OWC is that the turbine is located under the mean sea level. Hence, the latter operates not with air as a fluid yet with sea water [40], its components and installation site are in Figure 31. It is a relatively small device that can be easily installed on the port’s main breakwater without major civil construction. The advantages of these devices are the flexibility and replicability; indeed, they can be installed easily in different configurations reducing maintenance and costs of installation. They can also be placed in modules according to the power request and morphological condition of the installation site.

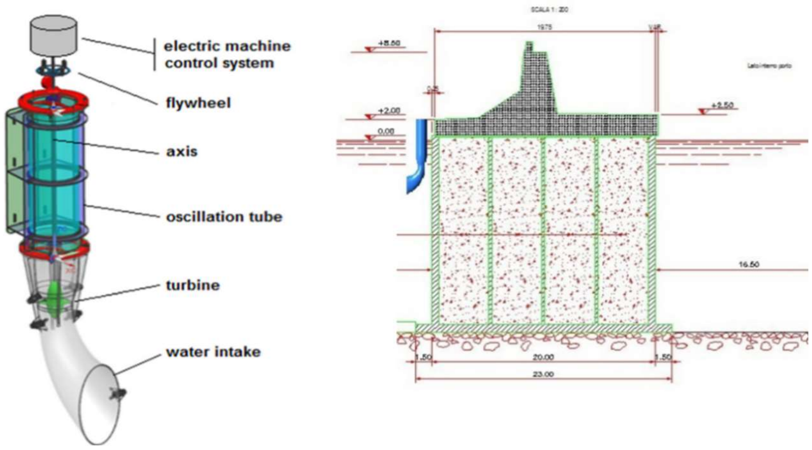

Figure 31 Left: WaveSax Device. Right: WaveSax on the Breakwater Sideview [40]

In the future, 500 devices are expected to be installed on the port's main breakwater [38]. Each device is expected to have a turbine power between 12 and 15 kW for a total of 6-7.5 MW of installed power. The estimated energy produced by year ranges between 3 and 4 GWh. Anyway, these are relative numbers that do not match with the following estimations considered to be more consistent for the purpose of this work.

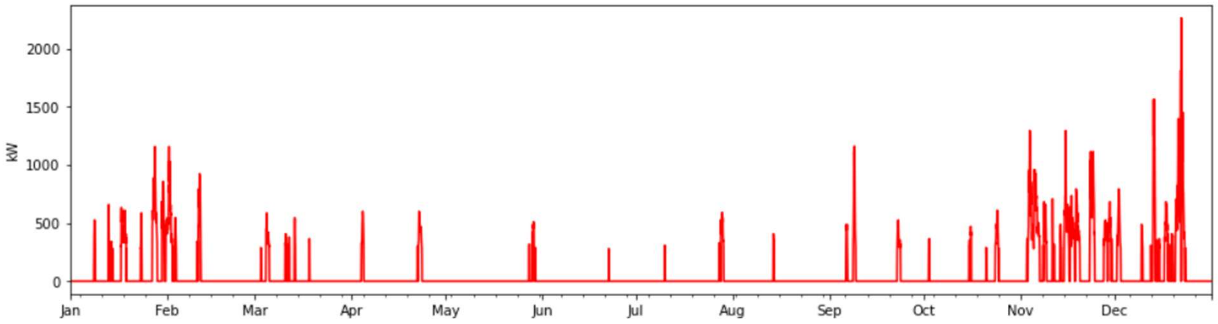

Figure 32 Yearly power curve of a WaveSax device

To obtain the yearly power generation curve of the WaveSax devices (see Figure 32) the power curve in Figure 33 has been utilized.

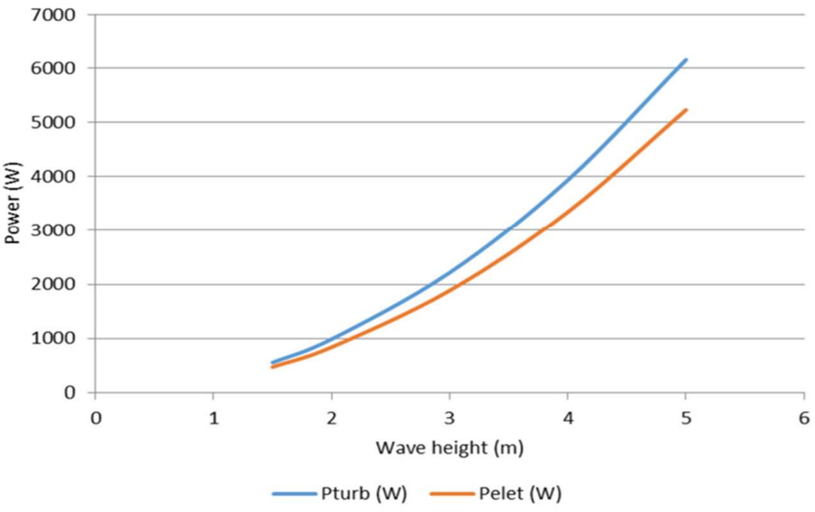

Figure 33 Mean turbine and electric generation [40]

From the graph the function $\boldsymbol{P_{WaveSax} = 235.66 \cdot H_s^2 - 191.3 \cdot H_s + 303.63}$ has been obtained where $\boldsymbol{P_{WaveSax}}$ is the electrical power output of the WaveSax and $\boldsymbol{H_s}$ is the significant wave height. With historical data of wave forecast the power of the Wave Sax device has been obtained. According to this estimation, yearly production of the 500 WaveSax is expected to be 541 MWh only 4% of the Port's Yearly Energy Consumption.

4.6 Cruise Ships

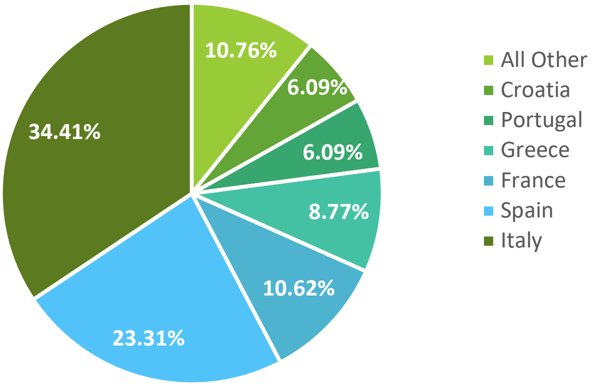

Figure 34 Cruise calls in the Mediterranean Sea (total 13 692) [37]

Italy is one of the most visited countries by cruise ships of the Mediterranean Sea by cruise ships as visible from the chart in Figure 34. Only in 2019 reached 4 156 cruise calls. Between those the port of Civitavecchia races with the port of Barcelona for the first spot in number of calls. The cruise ships calls within the port of Civitavecchia increased through the time recording a total of 828 cruise ship calls. A big drop in the number of calls has been registered in 2021 as the covid pandemic blocked the traffic.

4.6.1 Cruise ships Power and Energy Needs

To determine the impact of a cold ironing infrastructure for cruise ships in the port of Civitavecchia the cruise ships traffic of 2019 has been analysed. From the ships visiting the port only those that could receive OPS or be retrofitted have been selected, reducing the number of ships to 778. The average obtained characteristics of the cruise that visited the harbour are shown below (see table 8).

Table 9 Averages of Cruises visiting the harbour

Time of Arrival	6:40
Time of Departure	18:54
Berthing Time	12:13
Mean Hoteling Power (MW)	6.2
Max Hoteling Power (MW)	14.5
Energy consumed (MWh)	75.8

The Estimation of the berthing power of Cruise Ships is not an easy task as to date few data is available and the confidentiality of this information. To estimate the average power that cruise ships need for hotelling services it has been used as a reference, the Port of Los Angeles Inventory of Air Emission – 2019 where the average hotelling power requested by cruise ships depending on the passenger's capacity is given, here resumed in table 10. This Source has been chosen as the Port is the most developed in providing OPS to cruise ships and data are obtained also from Port and terminal shore power activity data.

Table 10 Cruise Ship Hoteling Power Demand Per Passengers Capacity

Passengers	Berth Hotelling (kW)
1250	3069
1750	5613
2250	6900
2750	6089
3250	8292
3750	10455

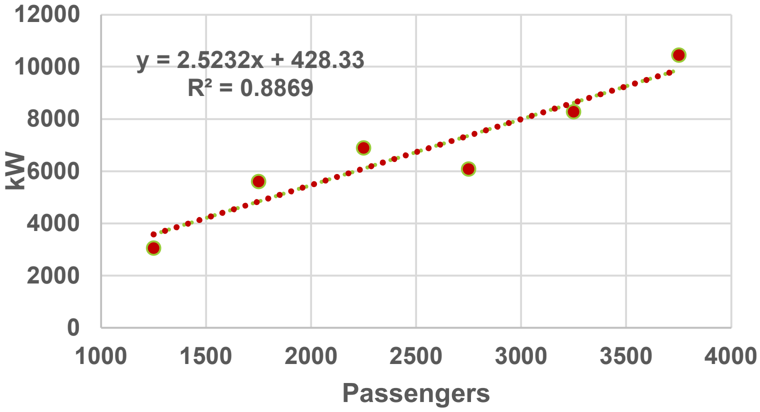

Figure 35 Passenger Range vs Auxiliary Engines Load (kW)

From these values above, by applying a linear regression to determine the power required by every ship in function of their passenger's capacity equation has been computed (plotted in Figure 35).

$$P_{hot} = 2.5232 \cdot p + 428.33 \tag{5}$$

Where P_{hot} is the power required at hotelling by the cruise ship and p is the number of passengers. Obviously, the level of accuracy decreased for cruises with less than 1250 passengers or more than 3750. The biggest and so the most power demanding ships that visited the harbour in 2019 are listed in table 11 with the respective hotelling power estimation (remaining data can be seen in **ANNEX II**).

Table 11 Biggest Ships Visiting the Harbor Characteristics

Ship	**Passengers Capacity**	**Favourite Quay**	**Hotelling Power**	**N° of calls**
Oasis O.T.S.	5592	12 BN	14 MW	20
Costa Smeralda	5282	12 BN	13 MW	8
Aida Nova	5200	12 BN	13 MW	28
Msc Grandiosa	4888	12 BN	12 MW	6
Msc Meraviglia	4488	12 BN	11MW	15
Norwegian Epic	4288	25S	11MW	27

The number of ships calling at the harbour by season and by quay are shown in Figure 36.

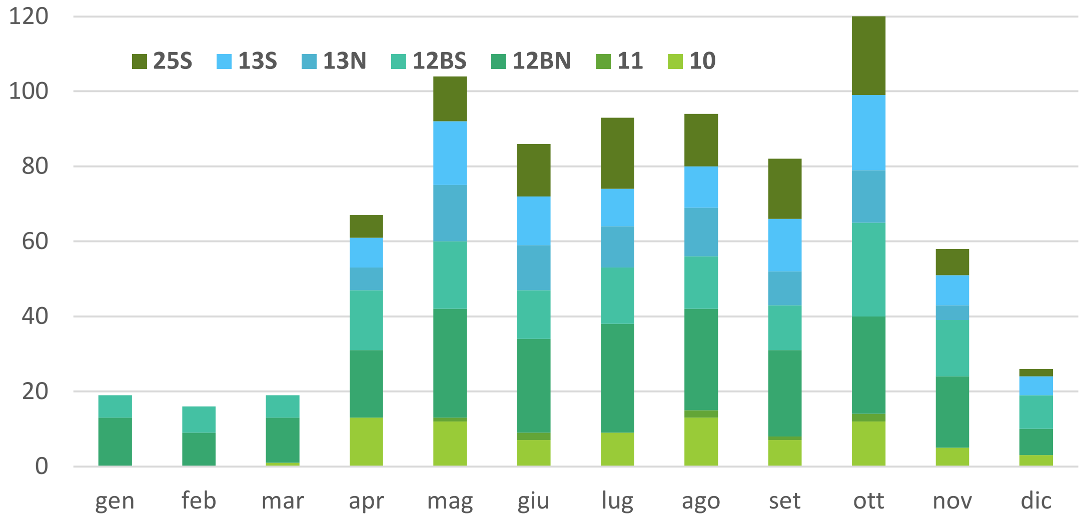

Figure 36 Cruise calls per month by Quay

The busiest day was the 15 of May with a total of 8 cruise ships visiting the port at the same time. The total power that might have been required if all the ships were connected to an OPS infrastructure would have been 54 MW. To give an idea of the impacts that providing electrical energy from shore in the port of Civitavecchia the power available at the MV PODs, their average and peak of power request are compared with the power needed by berthed cruise ships. The same is done with the monthly energy required by the port and the monthly energy requested from cruise ships.

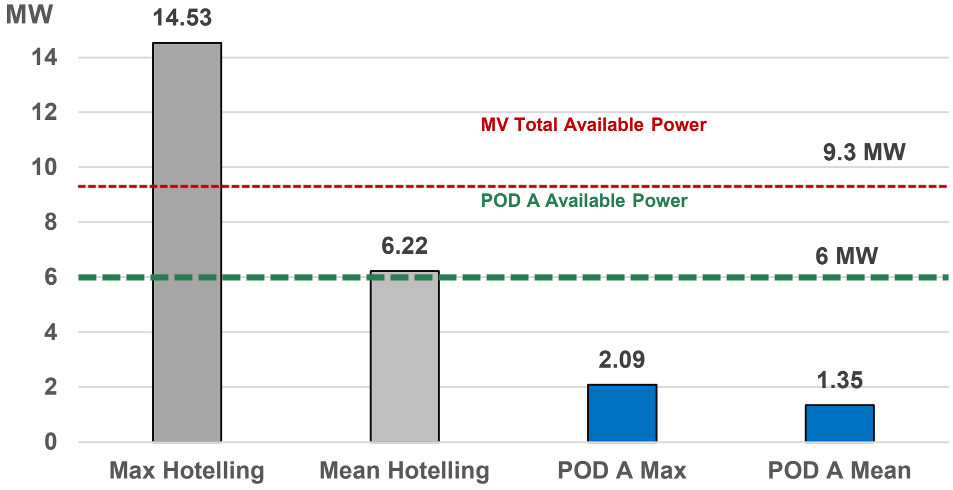

Figure 37 Power availability at MV levels and Power requested by Cruise ships

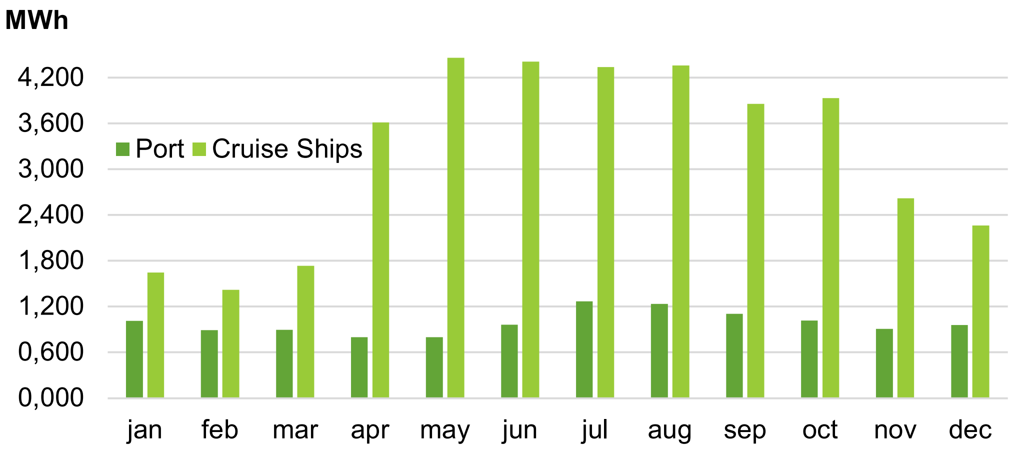

Figure 38 Energy Requested by Cruise Ships at berth and by the Port

Figure 37 shows the magnitudes regarding the power available in the port's grid compared to that requested by cruise ships, while Figure 38 compares the total monthly consumption of the port with the hoteling requested power from cruise ships. It is possible to see from the previous graphs that cruise ships' power and energy needs are highly demanding for the port electrical infrastructure. It is crucial to increase the production capacity of the port's grid and its energy productivity if a CI infrastructure is going to be installed. The total energy requested in 2019 from cruise ships at berth resulted in 38.648 GWh around three times the power consumed by port in the same year (13 GWh).

4.7 Ports most visited Quays

Between the port quays dedicated to cruise ships docking the two most visited are the number 12 bis north and 12 bis south with respectively 237 and 156 calls in the year 2019. These two piers are preferred from the cruise traffic as they have the biggest cruise ships passengers' terminals the Amerigo Vespucci and the Bramante. Table 12 counts the yearly calls by pier per month.

Table 12 Cruise Ships Calls Per Quay

Pier	**10**	**11**	**12BN**	**12BS**	**13N**	**13S**	**25S**
jan			13	6			
feb			9	7			
mar	1		12	6			
apr	13		18	16	6	8	6
may	12	1	29	18	15	17	12
jun	7	2	25	13	12	13	14
jul	9		29	15	11	10	19
aug	13	2	27	14	13	11	14
sep	7	1	23	12	9	14	16
oct	12	2	26	25	14	20	21
nov	5		19	15	4	8	7
dec	3		7	9		5	2
Total	**82**	**8**	**237**	**156**	**84**	**106**	**111**

For this reason, Pier 12BN and 12BS are selected to be the most preferable location to install a CI infrastructure. The high traffic and the proximity of the two piers allows to install a movable infrastructure that allows one ship to connect at a time depending on which is the occupied pier. If both piers are occupied a preference criterion must be created in order to choose which is the ship to be connected. Anyhow this study first analyses only the traffic of pier 12 BN due to the high energy and power demanded by the cruise ships. In the 237 cruise ships calling at the pier those capable of being connected to a CI infrastructure nowadays to shore have been catalogued. Of these only 44 are fitted to be supplied electrically from shore, their at berth power request in a year is plotted in Figure 39.

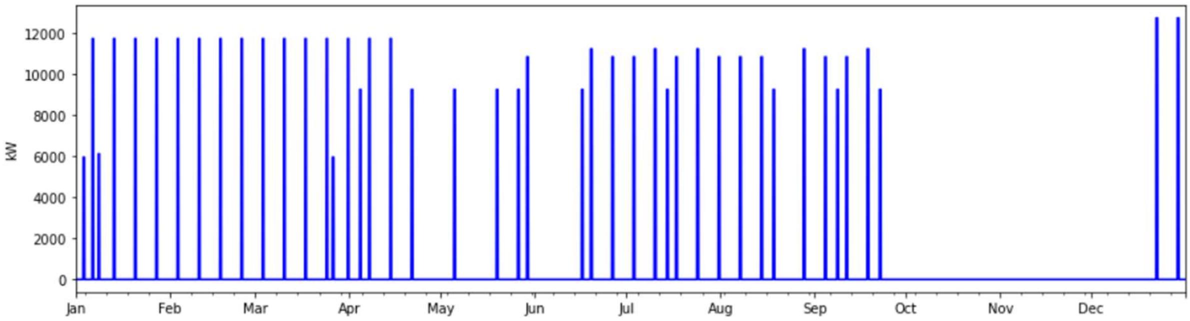

Figure 39 Fitted cruise ships yearly power load at quay 12BN

5 ENERGY STORAGE SYSTEM

5.1 Definition

An Energy Storage System is a device capable of storing energy into a particular form for a limited time in order to release it when needed. The storing and releasing process is characterized by time required by the processes and relative efficiencies. An ESS is characterized by many features such as: capacity (Wh), efficiency, charge/discharge behaviour, lifetime, cost and environmental/location issues [42]. There are plenty of typologies of ESS depending on the storing technology, process of conversion and form of energy stored.

5.2 Typologies

ESS can be classified between High-Energy and High-Power types or more specifically into the typology of energy they store. According to the second classification we can highlight 4 major groups: [43]

- **Electrical Energy Storage (EES)**

Electrostatic energy storage: Supercapacitors, Capacitors;
Magnetic/current energy storage: Superconducting magnetic energy storage (SMES).

- **Mechanical Energy Storage**

Kinetic Energy Storage: Flywheel
Potential Energy Storage: Pumped Hydro Energy Storage (PHES), Compressed Air Energy Storage (CAES)

- **Chemical Energy Storage**

Electrochemical Energy Storage: Batteries;
Chemical Energy Storage: Fuel Cells; molten-carbonate fuel cells – MCFCs and Metal-Air batteries
Thermochemical Energy Storage: Solar Hydrogen, solar metal, solar ammonia dissociation–recombination and solar methane dissociation–recombination

- **Thermal Energy Storage**

Low Temperature Energy Storage: Auriferous cold energy storage, cryogenic energy storage.
High Temperature Energy Storage: steam or hot water accumulators, graphite, hot rocks and concrete, phase change materials

Each typology will be better suitable depending on its characteristics and purpose of use (mobile or stationary). The principal characteristics of an ESS are the power deliverable and the energy storing capacity. Other important features are the lifetime or number of cycles that it can perform, the energy density or power density, working temperature and costs. Some of them are illustrated below (see Figures 40 & 41).

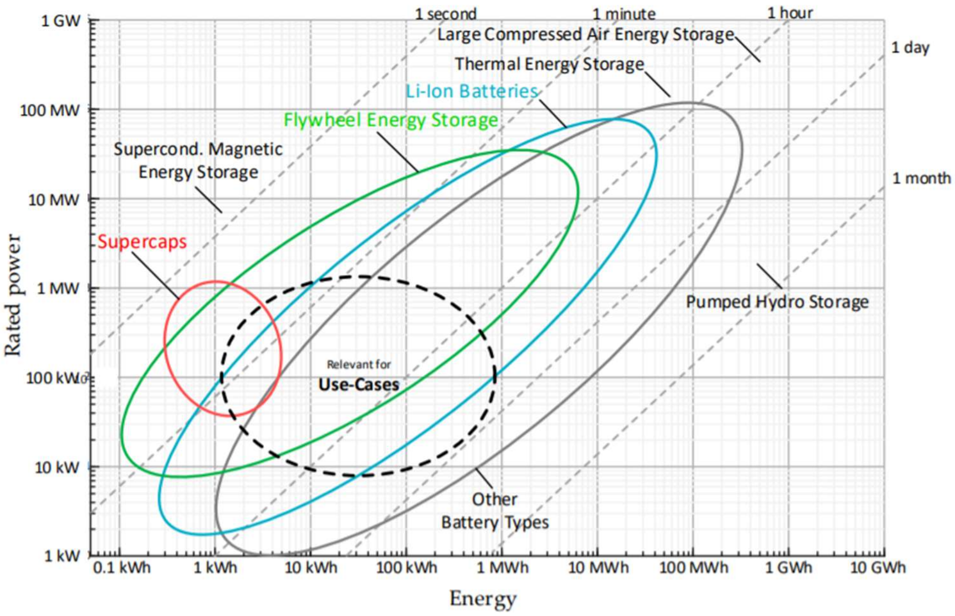

Figure 40 Power rating and Energy capacity of ESS [43]

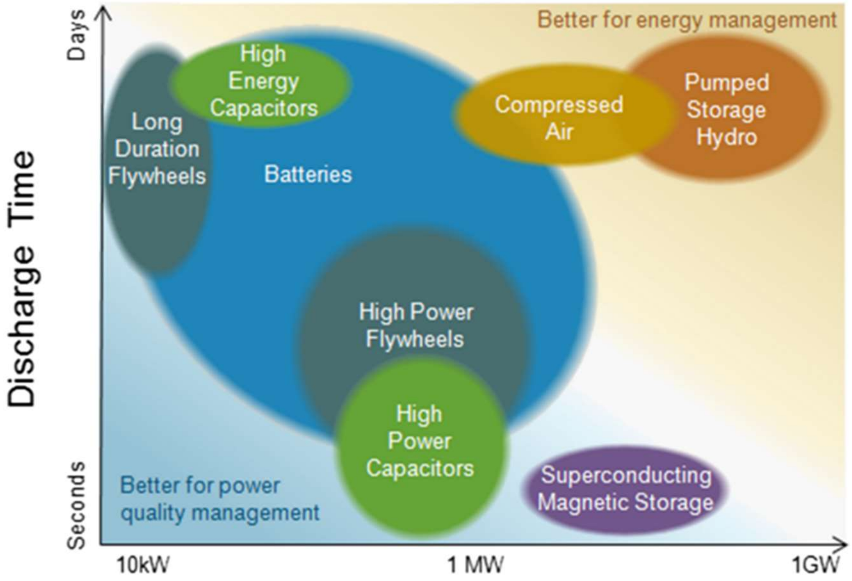

Figure 41 Power Rating vs Discharge time of ESS [43]

5.2.1 Pumped Hydroelectric Energy Storage (PHES)

This type of ESS consists of an electric power plant with two reservoirs, an upper one and a lower one, Figure 42 shows a scheme of a PHES. Electricity is stored under the form of potential energy by pumping water in the upper reservoir at low demand hours. The energy can be produced through a turbine when required. The energy capacity is proportional to the volume of water stored in the upper reservoir and the height of it from the turbine level. PHES is a mature technology and consists of 3% of the total world capacity. In 2018, the installed capacity in the world of this technology was 183 GW [44]. Its power can range from 100 to 3000 MW. The energy strictly depends on the upper basin volume as mentioned above. Difficulties of its implementation is the scarcity of sites where to install it, a large lead time and high costs.

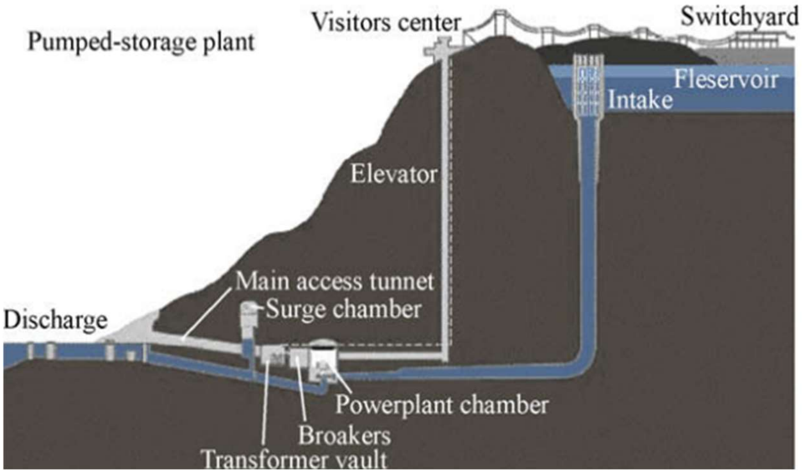

Figure 42 PHES scheme [43]

5.2.2 Compressed Air Energy Storage (CAES)

CAES is the second technology capable of delivering very high power (above 100 MW) after PHES. Its working principle is that of the gas turbine with the introduction of high compressed air in the cycle. It stores the energy into the form of elastic potential energy of compressed air into a cavity or container.

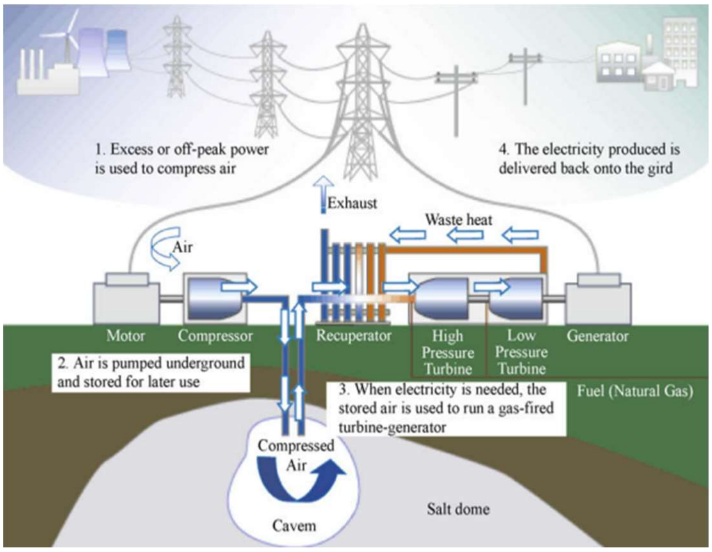

Figure 43 CAES scheme [43]

Major components of the CAES are: a motor or generator, an air compressor with more stages intercoolers and aftercoolers, a turbine train with low and high pressure stages, a cavity or container where compressed air is stored typically an underground rock cavern or ex mine, and equipment for the control and auxiliaries (see Figure 43). It works as follows: during low demand air is compressed into a tight space to 4-8 MPa, when demand is high air is drawn from the storage vessel heated up and expanded in the turbine. The turbine connected to a generator produces electricity while waste heat can be recovered though a recuperator. This type of ESS can support daily basis cycles, partial loads, fast changes between compression and decompression, perform load following also with high load vibrations and can support up to years of energy stored. It has relatively low capital cost between 4 to 8 hundred euro per kilowatt, a high efficiency and rating ranging from 50 to 300 MW. Difficulties in its implementation are the strict need of a storage site (a cavern, an aquifer, an ex-mine underground), the associability only with gas turbines and that requires combustion so pollution of the nearby area.

5.2.3 Batteries

Batteries are devices capable of storing energy under electrochemical form. They can be of many different typologies according to the materials, they are basically constituted by one or more cells. Cells are composed by a liquid, paste or solid electrolyte, a positive electrode (anode) and a negative electrode (cathode). A battery can be constituted by more interconnected cells. Charge and discharge processes consist of chemical reactions at the two electrodes that generate a flow of electrons through an external circuit. Reactions are reversible and allow the battery to recharge by applying external voltage to the electrode. A battery is schematized in Figure 44.

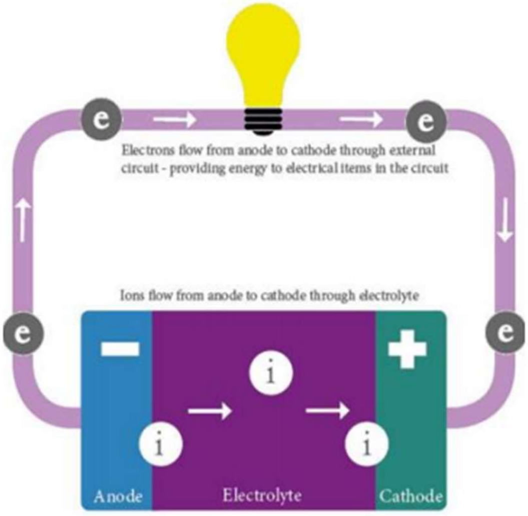

Figure 44 Battery working Principle [45]

Advantages of the batteries are their fuel flexibility as they do not consume any, numerous benefits to the electric utilities, fast response to load changes and the possibility to be introduced into third or cogenerated power systems to enhance their stability. They have low standby losses, high efficiencies from 60 to 95%, very low lead time and technology modularity. Threats to their implementation are the fact that they are composed by toxic materials and require to be disposed properly. They can be constituted of different materials and so their properties, the most known in the market are the Lead-Acid batteries, Nickel Cadmium Battery, Sodium sulphur (NaS), Lithium Ion (Li-ion). The different characteristics of each battery type are appreciable in Figure 45.

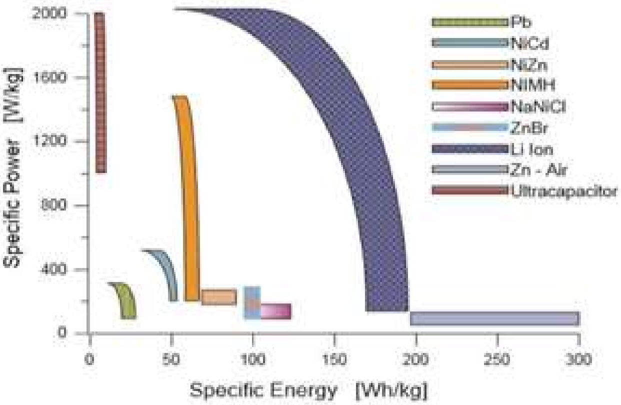

Figure 45 Different Batteries Characteristics [46]

5.2.3.1 Lead Acid Batteries anode is made of lead dioxide (PbO_2) cathode of Lead submerged into a sulphuric acid electrolyte. They are the most mature technology in Battery Energy Storage Systems (BESS) used mostly as starter service for cars or uninterruptible power supply units (UPS). They can be used also for small PV system backup. This technology is one of the most diffused in the market and is the most recyclable ones with99.3% of Lead acid batteries being recycled. [45]

5.2.3.2 Nichel Cadmium (NiCd) Batteries have centuries of maturity. The cathode is composed of Cadmium hydroxide and the anode of Nickel Hydroxide, the separator is an alkaline electrolyte. The electrodes are rolled in a spiral inside a metal case leading into a robust device. They are characterized by a high energy density 50-75 Wh/kg but low life cycle 2 000 – 2 500 and high cost. A further issue is caused by the toxicity of Cadmium that requires particular disposal and the memory effect that reduces the battery capacity during usage.

5.2.3.4 Sodium Sulphur Batteries (NaS) has the anode made of molten sulphur (S) and the cathode of molten Sodium (Na). they are separated by a solid ceramic that works as electrolyte, as the chemical reactions occur at high temperature (around 600K) a heating system is required this make this technology expensive. They are constituted by a good energy density, high efficiency (75-85%) high life cycles and fast response. [45]

5.2.3.5 Lithium-Ion Batteries (Li-ion) are constituted by a lithium metal oxide anode and mixed or carbon-based material cathode. The two electrodes are separated by a porous polymeric material that allows the motion of ions between them. The electrolyte is made from Lithium salts dissolved into organic liquids. Sony was the first producer of this battery in the 90s currently, this type of battery dominates the electronic market due to its high efficiency, high-power and energy density long life cycles. It is used also for Electric Vehicles (EVs) and stationary applications. Advantages of this battery type are the scalability and flexibility that allows their use for different operations such as time shifting self-consumption of local PV, voltage support, ancillary services (frequency regulation), smoothing and shaping services and frequency support to integrate RES. This type of Battery is expensive even if the price is expected to come down in the future. They can be composed of different chemistries. The most common typologies are lithium-ion titanate (LTO) the lithium iron phosphate ($LiFePO_4$) and lithium nickel manganese Cobalt (NCM). The LTO can reach up to 20 000 cycles, it has a high-power density, and is the fastest in terms of recharging process. LTO batteries anyway have low energy densities and higher costs. The NCM is the most used in grid scale applications as it has reasonable characteristics in terms of power energy and costs. The $LiFePO_4$ are the safest of the Li-ion technology, they have a reasonable price, high power density and can also reach the 100% of depth of discharge but on the other hand they have a low energy density that limits its application. [45]

5.2.4 Flow Battery

Flow Batteries are batteries whose electrolyte contains one or more dissolved electroactive species that flows through a power cell or reactor in which chemical energy is converted into electricity. Additional electrolyte is stored into tanks and pumped into the cell reactor; the scheme of a see battery is shown in Figure 46. The reaction is reversible and allows the battery to be charged (reverse the reaction), discharged and recharged (replacement of the electrolyte). Differently from batteries the energy is stored into the electrolyte solution. Electrolytes are separated by a membrane that allows ions to flow. Energy and power are decoupled as power depends on the number of modules combined and energy on the size of the storing tanks. They have high life cycles over 10 000 and offer flexibility in terms of medium and large amounts of energy they can operate into long term storage. On the contrary the flow battery is expensive, requires large areas for the tanks and due to the pump usage has some parasitic losses. [45]

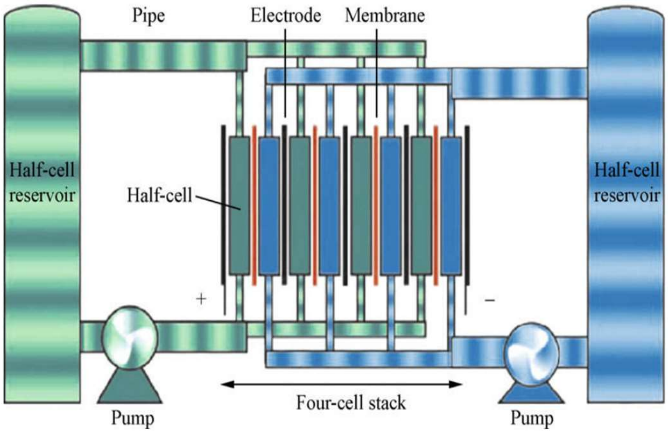

Figure 46 Flow Battery scheme [43]

5.2.5 Capacitors

Capacitors consist of two metal plates separated by a dielectric material. One of the plates is charged electrically with a dc source and the other is going to have an induced charge of the opposite side. They can charge and discharge relatively fast; they can support thousands of cycles. The energy is stored into electrostatic form without any conversion reason why they are characterized by high efficiencies. Their problem however is the low energy density and their requirement of a big dielectric area. If high capacity is needed their high self-discharge and losses make them not suitable for large ESS.

5.2.6 Supercapacitors

Supercapacitors, as the capacitors, store energy between the two electrodes directly into electrostatic form. Their efficiency is high due to the absence of energy conversion. Electrodes are made of porous carbon with very high surface area up to 2 000 m^2 per gram. The capacitance and energy density are thousand times higher than usual capacitors. The structure is double layered, and the electrodes are divided by an electrolyte as visible in Figure 47. The latter can be aqueous or organic being the last one higher in energy density. Characteristics of supercapacitors are: fast and efficient charging and discharging process, low energy density, high power density and good behaviour in hybrid ESS for example coupled with a high energy ESS.

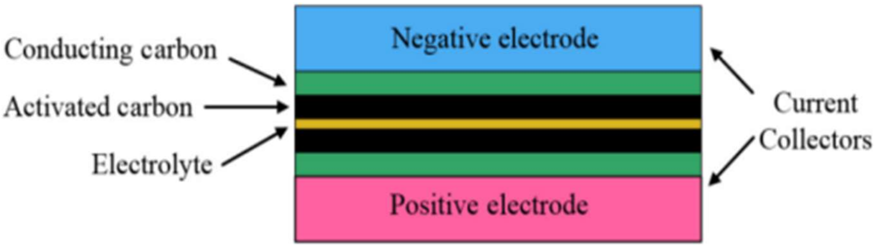

Figure 47 Supercapacitor structure [47]

5.2.5 Superconducting Magnetic Energy Storage (SMES)

SMES stores energy in magnetic form into a superconducting coil. The basic formula of energy stored consists in $E = \frac{1}{2} \cdot L \cdot i^2$ (7) where E is the energy stored, L is the inductance and i is the current. The inductance of the device depends on the coil size, geometry and cross-sectional area. They operate at very low temperature (1.8-4.2 K) hence, refrigeration is required usually in a helium vessel. Typically, they are made of Nobium and Titanim (NbTi). SMES fastly reacts in terms of milliseconds and releases Megawatts of power which have a long-life cycle. Their characteristics allow them to be utilized into industrial power applications and power grids. Figure 48 shows a scheme of their structure. [47]

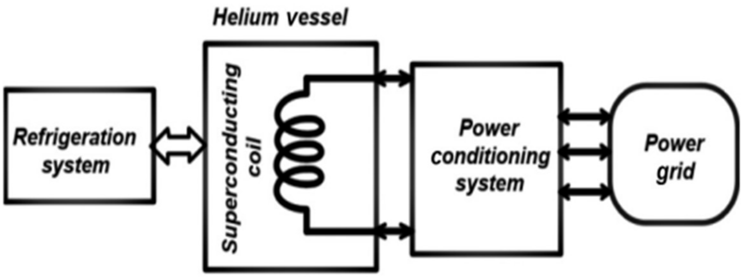

Figure 48 SMES structure [47]

5.2.6 Flywheels

Flywheels consist of a spinning disc connected to a central shaft rotating on two magnetic bearings placed in a vacuum to reduce losses. The device stores the energy into kinetic form, the disc is speeded up when energy is absorbed and slows down when it is released. Its energy formula is $E = \frac{1}{2} \cdot I \cdot \omega^2$ (8) where E is the Energy stored I is the moment of inertia and ω the rotational speed. If the flywheel is circular $I = m \cdot r^2$ where m is the mass and r is the radius of the circumference obtaining so equation $E = \frac{1}{2} \cdot m \cdot r^2 \cdot \omega^2 = \frac{1}{2} \cdot m \cdot v^2$ (9) where v is the disc spinning velocity. From the formula it is possible to notice that the fastest the flywheel spins the more energy it can store. As with the supercapacitors, they can also be coupled with high energy storage systems as they have only high-power density. They are for instance utilised by airplanes and powertrains that require high power for a very short time. [48]

5.2.7 Fuel Cells

A fuel cell is an electrochemical energy conversion device, it produces electricity from external supply. In fact, the anode side receives the fuel and at the cathode side the oxidant these two react in presence of an electrolyte. Differently from batteries, here reactants flow in the product flows out and electrolyte remains in the cell. It can operate continuously if the flow of reactants is maintained. Reversible fuel cells exist, and they are designed to consume chemical A to produce electricity and chemical B, and reversed to consume electricity and chemical B to produce chemical A. Their difference with batteries is that they are an open system and reactants are consumed, batteries electrodes instead react and change while in a fuel cell they are catalytic and stable. Many different combinations of fuel and oxidant are possible. One type of Fuel cell is the Hydrogen fuel cell that works with Hydrogen and Oxygen and produces water and electricity, successively water can be separated with electrolysis and reused to power the fuel cell (scheme in Figure 49). It has a high energy density around 0.6-1.2 kWh/kg and can reach different scales from kW to MW due to its modularity. Also, it is environmentally friendly due to its green fuel and oxidant. On the other hand, it has a low round trip efficiency around 20-50% and is expensive from 6 to 20 dollars per kWh.

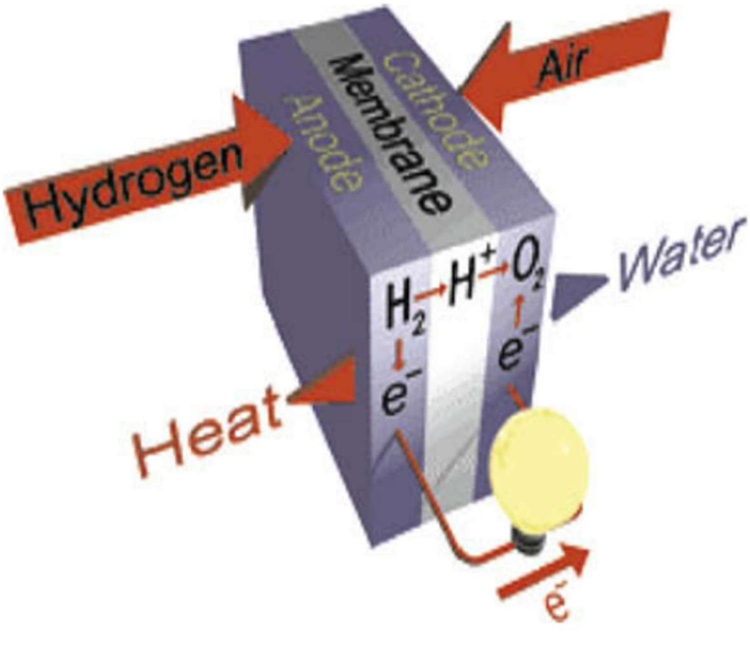

Figure 49 Hydrogen Fuel Cell [43]

Table 13 lists the main features of the above-mentioned ESS and Figure 50 shows the respective ESS efficiency.

Table 13 ESS Characteristics [42] [44]

	Power Rating	**Discharge time**	**Self-Discharge per day**	**Suitable Storage Duration**	**Cycle Life (cycles)**	**Lifetime (years)**	**Capital cost $/kW**	**Capital cost $/kWh**
PHES	100-5000 MW	1-24h	very small	Hours-months	-	40-60	600-2000	5-100
CAES	5-300 MW	1-24h	small	Hours-months	-	20-40	400-800	2-50
Lead-Acid Batteries	0-20 MW	seconds-hours	0.1-0.3%	minutes-days	500-3000	5-15	300-600	200-400
NiCd Batteries	0-40 MW	seconds-hours	0.2-0.6%	minutes-days	2000 - 2 500	10-20	800-1500	800-1500
NaS Batteries	50 kW - 8 MW	seconds-hours	20%	seconds-hours	2 000 - 5000	10-15	1 000-3000	300-500
Li-ion Batteries	0- 50 MW	seconds-hours	0.1-0.3%	minutes-days	2000 - 10000	5-15	1200-4000	600-2500
Flow Battery	100 kW - 10 MW	hours	-	minutes-days	12 000	5-10	600-1500	150-1000
Capacitor	0-50 kW	milliseconds - 1 hour	40%	seconds-hours	50 000+	5	200-400	500-1000
Supercapacitor	0-300 kW	milliseconds - 1 hour	20-40%		50 000+	5	100-300	300-2000
SMES	100 kW - 10 MW	milliseconds - 8 seconds	10-15%	minutes-hours	100 000+	20+	200-300	1 000-10 000
Flywheel	0 - 250 kW	milliseconds - 15 mins	100%	seconds-minutes	20 000+	15	250-350	1 000-5000
Fuel Cell	0-50 MW	seconds - 24h	0%	Hours-months	10 000+	5-15	10 000+	5-15

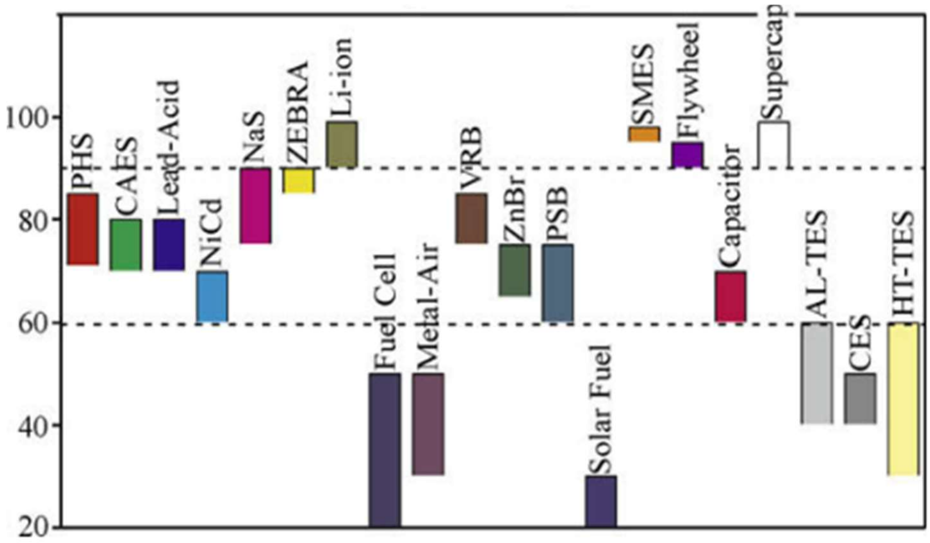

Figure 50 Cycle Efficiency of ESS [43]

5.3 ESS functions

The utilization of ESS grew in the last years with the increase of usage of RES. They allow flexibility to the power system and provide non-stop power supply to the network bridging the gap of RES volatility.

Typically, power systems operate into a top to bottom regime where at the top we can collocate the generation system in the middle the distribution and at the bottom the different energy users.

Nowadays, distributed renewable energy sources have been introduced at the distribution level. This change into the power system needs to be compensated with ESS as the fluctuations of the RES may not provide the continuity required from the power system service. ESSs can be used for different purposes at the different power system levels: [43]

- **Generation level**
  Commodity Storage, the ESS can be used to substitute the generation units storing energy at night and using it during peak hours. This allows arbitrage of the production price and a smoother production transmission and distribution system usage. The ESS can be used for *Contingency Service* adding the power capacity necessary to provide power to additional customers whose demand would fall offline to the power facility. *Area Control* consists in avoiding the transfer of power between utilities. *Frequency regulation* consist in the maintenance of the required ranges of frequency in the power system, imbalances may occur from unpredicted and large changes in loads or production, and this can damage generators or customers equipment. *Black Start* consists in using the ESS to restart facilities that have been turned down and synchronises them with the grid.

- **Transmission and Distribution level**
  System stability maintenance of all system components in synchronous operation with each other to avoid the system collapse. *Voltage regulation* maintenance of the same voltage level between the two ends of lines. *Asset deferral* delays the installation of new transmission lines by installing an ESS that will avoid the underusage and capital expenses of new lines.

- **Energy Service level**
  Energy Management consents to shift energy demand through peak shaving and so reducing the time of usage charges. *Power Quality* the provision of high-quality power to users consisting of no oscillation or disruption of the waveform. *Power Reliability* or uninterrupted power supply capacity to deliver power with no interruption caused by RES volatility or generation turning off.

- **RES generation**

  Intermittent generation of RES requires demand flexibility, backup power sources and ESS. *Transmission curtailment* consists of the reduction of power delivery restrictions due to low transmission capacity. *Time-Shifting* fixing and reshaping the energy produced by RES. *Forecast Hedge,* reduction of errors in RES bids before delivery into the market, reducing the variability of the spot market price and the risk of consumers. *Grid frequency supports* maintenance of frequency levels into the grid due to RES high oscillations. *Fluctuation suppression, absorption* and discharge of energy to avoid frequency fluctuation is short periods.

5.4 ESS for the Port of Civitavecchia

The typology of ESS strictly depends on the purpose of use for instance, in the case of the Port of Civitavecchia the ESS will be stationary and will need to meet the following requirements:

- High-power due to the big power gap (around 10 MW) that it needs to fill to power cruise ships.
- High-energy capacity due to the high energy required from cruise vessels
- Fast charge
- Daily discharge rate
- High number of life cycles
- High lifetime

Most preferably the lower the costs the better.

On a first approach the energy it will have to be capable of storing will range around 100 MWh and the power rating will be ranging around 10 MW. These values are obtained by analysing the power and energy requested from Cruise Ships at berth (Table 8).

The ESS must also be able of delivering the energy daily to the ships and the port's grid and recharge over night-time. This last consideration may be a problem as there is no PV production during night, most of the energy used to recharge it will come from the National grid and this will mean expenses for the Port.

Due to the high power requested and high energy the best ESS candidates for our purpose are PHES, CAES, Batteries, Flow Batteries or Fuel Cell. The first two require high space but especially in the case of the PHES a basin needs to be found. The port possesses a basin of 240.000 m^3 at 60.75 m on the sea level, there is no equal capacity in the port for a lower basin. However, as it has already happened in some cases [48] the sea can be used for this purpose. Anyway, the use of seawater is not optimal as it causes corrosion and may need to be filtered before passing into the pump or the turbine. Also, it would be necessary to find a space where to install the pump and the turbine along with the ducts of the hydroelectric system. We can consider PHES a highly time demanding hence a non-optimal solution. The CAES can be excluded due to the need of a storage for the compressed air that is not available in the port area. The Flow Battery represents a good option due to its high power and energy ratings but is not a very diffused technology. Fuel Cells technically represent a very good candidate, but its high cost of investment and operation make its use not economical worth. Therefore, two remaining possible options are Batteries and Flow Batteries. Among the two, options batteries represent the most intriguing solution due to their large possibility of configuration use and management. On the market ready to go solutions are offered packed into containers that can be transported and located easily in the harbour. This solution offers modularity and flexibility, in addition being already diffused as ESS gives an extra warranty.

6 SIMULATIONS

6.1 The Energy Management Simulation Software (EMSS)

To study the performance of the port's grid with the different assets and the introduction of the BESS, an EMSS ("Microgrid Simulator") developed by Falck Renewables – Next Solutions has been used. The latter is an in-house developed software for the simulation of Microgrids. It allows the design of microgrid systems by introducing distributed energy productions, electrical consumptions, energy economics aspects, and, particularly, ESS to perform yearly or multiyear simulations. Within these simulations, different managements and commitments, based on scenarios and markets (wholesale and ancillary), can be optimised and compared.

The Falck Renewables Group operates in Italy, UK, Europe and worldwide as a developer of renewable assets and storage systems. Falck Renewables – Next Solutions works in all areas of the energy sector, from generation to distribution, and from management to consumption. In a market with constantly shifting boundaries, Next Solutions is a pioneer focused on claiming large spaces in new markets, offering cutting-edge to benefit from the possibilities of the ecological transition, making optimal and increasingly efficient and greener use of energy. The trading company Falck Next Energy operates in Italy, London (UK) and Madrid (Spain) proposing itself as a partner for renewable generators.

6.2 Preparation of Data

Before performing any simulation, different data have been collected to determine the characteristics of the system in which the ESS would have operated.

6.2.1 The Grid

The portion of the grid at which the Cold Ironing infrastructure will be connected is the one powered by the POD of Flavio Gioia. Its main characteristics are the power capacity of 6MW a yearly consumption of 10 GWh and the following power consumption profile (see Figure 51).

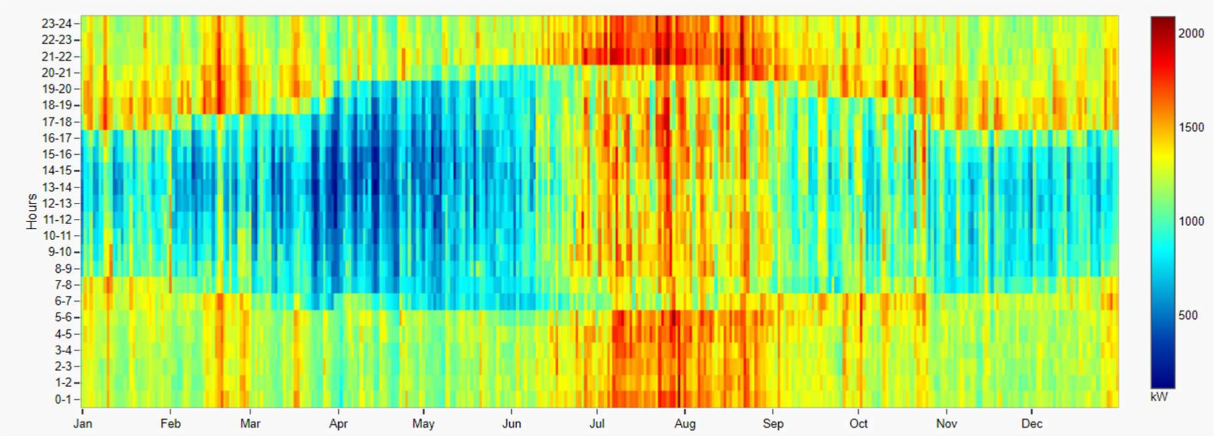

Figure 51 Flavio Gioia's Consumption Heatmap

It is clear from the heatmap that consumption grows in the summer months when the port increases its duty. The heatmap has been obtained from the sum of the Flavio Gioia's POD and the PVs power curves. From figure 50, it is still also noticeable the decrease of energy withdrawal during the day due to the PVs energy production. This is because, not possessing the PVs power curves of 2019, PVs power curves of 2020 have been used. This sum does not compensate for the reduction of power request during the day, showing still a higher consumption during no light hours. However, it is a characteristic of the port's load to have high consumption at night due to the usage of port's cranes and the extended areas to be lighted up.

6.2.2 Energy Contract

The year taken as reference is 2019 therefore it will use the prices of energy and the contract agreed at that year. The purchase of energy is so made according to band rates, their characteristics are reported below (see Table 14 & Table 15).

Table 14 Band Rates Prices

F1	F2	F3
82.733 €/MWh	79.268 €/MWh	63.756 €/MWh

Table 15 Band Rates Distribution

hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Mon	3	3	3	3	3	3	3	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	3
Tue	3	3	3	3	3	3	3	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	3
Wed	3	3	3	3	3	3	3	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	3
Thu	3	3	3	3	3	3	3	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	3
Fri	3	3	3	3	3	3	3	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	3
Sat	3	3	3	3	3	3	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3
Sun	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

The price at which the energy will be sold is going to be the zone price that in this case is the Centre-South of Italy's energy market. Its value along the year is presented below (see Figure 52).

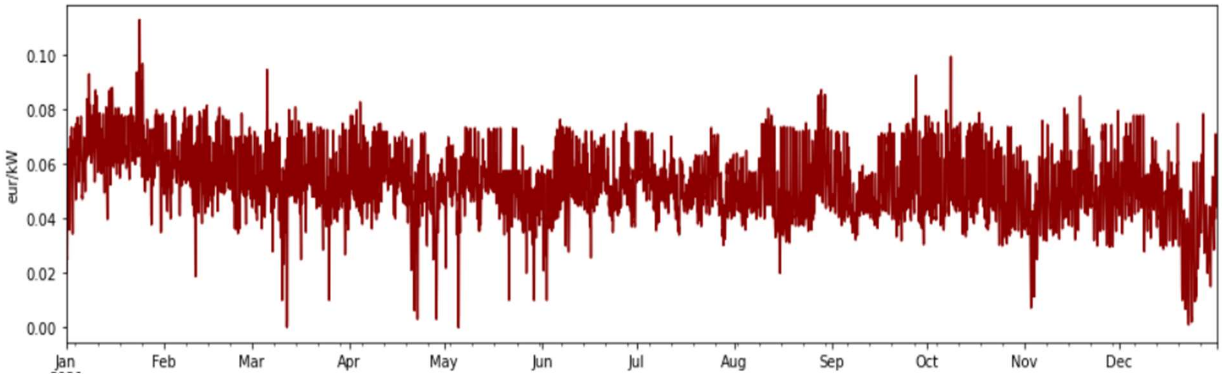

Figure 52 Electricity sale price of 2019 for the Centre-South of Italy [49]

6.2.3 Loads

To set up the problem the loads must be determined. Hence, the loads considered will be the power requested from the port at the Flavio Gioia MV POD and the Cruise Ships that are expected to be connected to the port grid. The yearly profile of the users connected to Flavio Gioia is shown below (see Figure 53).

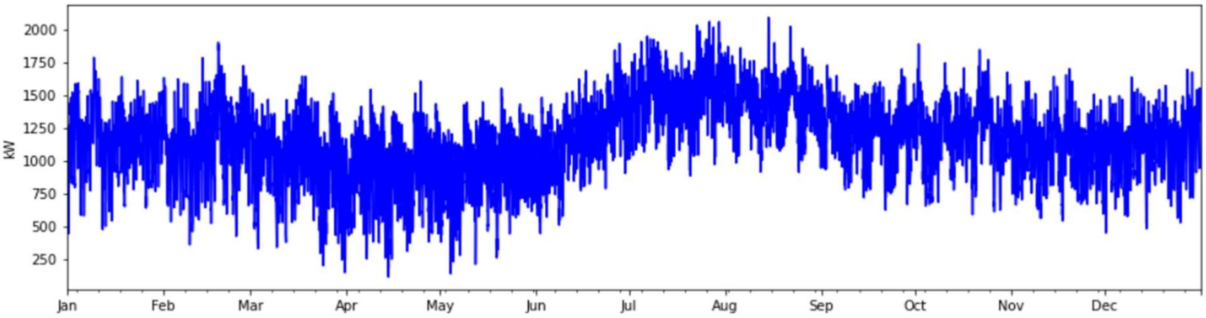

Figure 53 Flavio Gioia (6MW) POD yearly power curve

Regarding the Cruise Ships loads, it must be taken into account that not all the ships calling at Pier 12BN are fitted to receive electricity from shore. For this reason, this study has selected only the ones which would be capable of adopting this system. Overall, 44 where the calls of complementary ships in the whole year. The total estimated energy requested by those ships during a year is 5 288 MWh reaching a peak power of 12.76 MW. The yearly estimated power curve of the Cruise Ships load is plotted in Figure 39. By adding the two loads the energy consumed by year is 15.4 GWh and the peak power is 14.23 MW reached on December 29 at 7 AM due to the arrival of one of the biggest fitted ships (total yearly power curve in Figure 54).

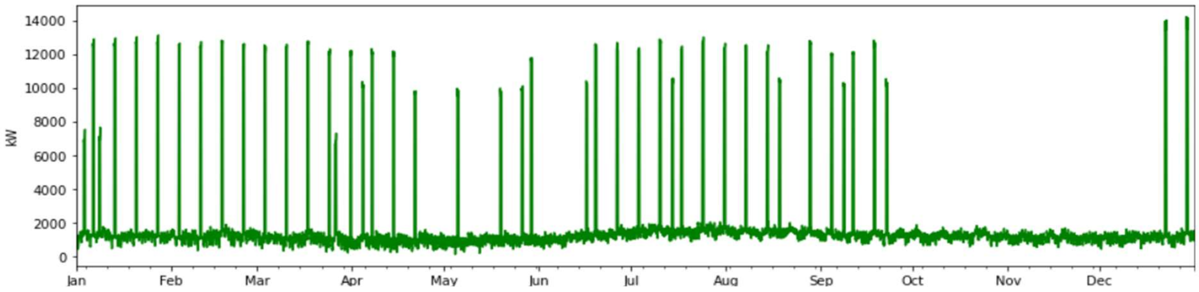

Figure 54 Total Yearly Load

6.3 Sizing of the ESS

The purpose of the ESS is to supply enough power to the port system so that the latter is capable of satisfying the previously estimated load. It is also necessary to settle the two main characteristics of the BESS: power rating and total capacity. The BESS is going to be of Li-ion technology, it will have a maximum and minimum State of Charge (SoC) of 90% and 5% respectively of its nominal capacity. The Depth of Discharge (DoD) will be assumed equal to 85% of its nominal capacity. The capital investment cost based on the capacity of the BESS is supposed to be 297.5 €/kWh. The BESS assumed characteristics for the sizing are resumed in Table 16.

Table 16 BESS features

BESS Technology	Lithium Ion	**Depth of Discharge**	85%
Max/Min SOC	90%/5%	**Capex**	297.5 €/kWh

The ESS has been sized in the worst-case scenario occurring when there is no RES available in the port's grid and only the ESS and the Grid can provide power to the loads.

The first objective of the simulations was determining the minimum power of the ESS to satisfy the given loads. It has been chosen as starting point the value of P1 corresponding to:

$$P_1 = P_{peak\_Load} - P_{Grid} \tag{9}$$

$$P_1 = (14.23 - 6)\ \text{MW} = 8.23\ \text{MW} \tag{10}$$

From the above-mentioned value simulations, the ESS power has increased by 100 kW keeping its energy capacity constant. The power selected from the simulations is the minimum obtained that allows the load's satisfaction without requiring any extra power. The real capacity of the BESS for these simulations was set to 110 MWh. This value was chosen as it does not interfere with the power determination. The longest continuous power request occurred on December 29th from 7 AM to 7 PM and required a total energy of 165 MWh. During the whole period, the port's grid - with a constant power output of 6 MW - could provide 72 MWh; the remaining energy to be supplied at the same time would have been 93 MWh, a value way lower than the one considered. This confirms that the energy capacity, given to the ESS in these simulations, will not interfere with the power determination. Figure 55 allows to visualize the power requested in December 29th and the missing power to be satisfied from the BESS.

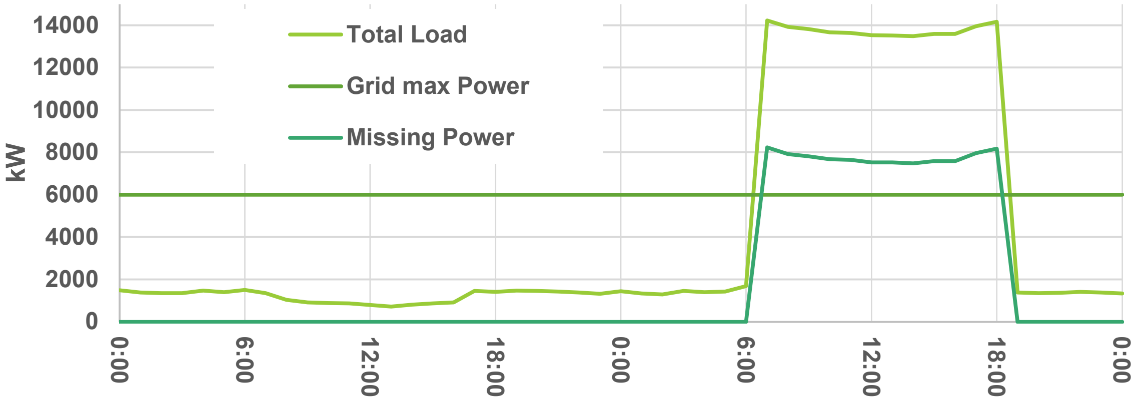

Figure 55 Load and Power of the port's grid from 28th of December

To determine the BESS capacity, a similar process has been initiated, the power of the BESS has been kept equal to the previously determined value while the real capacity of the BESS has been decreased by 1 MWh in each performed simulation. This has been done to find the last feasible value to satisfy the load without requiring extra energy. Therefore, starting from 110 MWh, the minimum value of the real capacity of the BESS with 8.73 MW power that was found to satisfy the load was 103 MWh corresponding in the given BESS characteristics to a rated capacity of 121.25 MWh. The BESS is characterized by a real C-Rate of 0.072 and nominal of 0.08. According to the price by kWh given a CAPEX of 30.6 million €. The outcomes of the sizing are resumed in Table 17.

Table 17 BESS characteristics

Rated Power	8.73 MW
Real Capacity	103 MWh
Nominal Capacity	121.25 MWh
Real C-rate	0.076
Nominal C-rate	0.08
Total Cost	30.6 million €

6.4 Yearly Simulations

6.4.1 Overall Yearly results

The BESS integration is studied under 5 different conditions of the port's grid, whose difference depends on the assets available in the port's distributed energy production mix. The different simulations performed consist in 5 different Scenarios whose characteristics are described below (see Table 18).

Table 18 Characteristics of the simulation's scenarios

Simulation	NoRes	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Port Load	**x**	**x**	**x**	**x**	**x**
Cold Ironing Load	**x**	**x**	**x**	**x**	**x**
BESS	**x**	**x**	**x**	**x**	**x**
PV 1-2-3-4		**x**	**x**	**x**	**x**
PV 5-6-7-8-9		**x**	**x**	**x**	**x**
PV 10-11				**x**	**x**
REWEC3			**x**	**x**	
WaveSax			**x**	**x**	

All the scenarios include the port's load, the CI load and the designed ESS of 8.73 MW of rated power and 121.25 MWh of rated capacity. The first scenario, *NoRes*, is the worst-case scenario in which there are no RES installed in port and the port's load and CI infrastructure can only be satisfied by the national grid and the ESS. Scenario 1 (*S1*) introduces to the previous configuration the PV systems from 1 to 9 for a total PV rated capacity of 2.67 MW. Scenario 2 or *S2*, adds to scenario 1 the two Wave Energy Converters (WECs) the Rewec 3 and the WaveSax. Scenario 3 (*S3*) considers all the RES installable in the port from PV1 to PV11 and both the WECs. Scenario 4 (*S4*) consists of only PV systems as distributed energy sources with a total rated capacity of 6.27 MW.

Each simulations consider the following costs:

- Excise Duty for large customers:
  Monthly consumption higher than 1 200 MWh with band rates consisting of 0.0125 €/kWh when the monthly consumption is lower than 200 000 kWh and 4 820 €/month if this value is exceeded.

- Purchase of energy from the grid at the Zone Price.

- Technologies Capex (only in Multiyear Simulations) and Opex.

Table 19 Technologies Capex and Opex

Technology	Existing PV	New PV	REWEC3	WaveSax
CAPEX [€/kW]	-	1000	6 756	7 000
OPEX [€/kW year]	21	21	85	51

- Yearly fixed cost of 981.75 € for the connection to the National Grid
- Power costs: monthly peak power cost of 3.4 €/kW.

Revenues are made from the energy sold to the national grid at the Zone Price of C-SUD of year 2019 Figure 51.

The different Scenarios are going to be analysed first into a one-year period and successively into a 20-year horizon.

6.5 Yearly Simulations Result Analysis

The Results of the Simulations are outlined below (see Table 20 & Table 21) for what concerns the Energy consumption and production and the economic values respectively.

Table 20 Yearly simulations results

Scenario	**Yearly total Load [MWh]**	**Purchased Energy [MWh]**	**Sold Energy [MWh]**	**Res Share**	**BESS Gen [MWh]**	**BESS Load [MWh]**	**BESS NCycle**
NoRES	26 405	17 752	462	0%	8 653	10 535	79.15
S1	24 754	13 934	691	15%	7 109	8 656	64.97
S2	24 322	12 316	751	22%	6 705	8 164	61.25
S3	25 175	8 626	1 501	38.8%	6 789	8 267	62.03
S4	25 297	10 065	1 291	32.3%	7 061	8 598	64.53

Table 21 Economic results of yearly simulations

	Cost of operation [€]	**Purchase [€]**	**Sale [€]**	**Avg Price of sale [€]**	**Grid Tot Cost [€]**	**Opex [€]**
NoRES	2 014 760	462 474	38 875	0.08395	1 379 511	635 249
S1	1 795 306	691 078	56 897	0.07601	1 106 060	689 246
S2	2 219 688	812 190	61 378	0.07499	994 892	1 224 796
S3	1 954 506	567 620	112 788	0.07023	678 773	1 275 982
S4	1 551 863	661 975	97 611	0.07049	808 444	743 419

The yearly total load is the sum of the energy requested in a year by the loads in the port's grid they include the energy absorbed by the users connected to the Flavio Gioia POD, the Cold Ironing's load and the ESS Load when in charging mode. It can be seen how it is not the same in all the simulations as it varies slightly depending on the RES available. Purchased and sold energy in MWh are the input and output of energy through the POD, they are strictly connected with the Purchase and Sale in €, that respectively represent the income and outcome from the participation to the electricity market as a buyer or a seller. The RES share is given in percentage and returns the portion of total load satisfied by RES production. The ESS Gen and ESS Load indicate the MWh released and absorbed by the storage system. The ESS NCycle gives the yearly number of cycles performed by the BESS, considering one cycle the equivalent of one full charge and full discharge. The Average price of sale indicates the mean value at which energy is sold in each scenario. The Opex considers all the operational and maintenance costs: the excise duty and each technology Opex during the year. The Grid total cost is determined by the sum of the energy charge (the sum of energy bought and sold total) and the power charge that depends on the monthly peak reached by the port's POD.

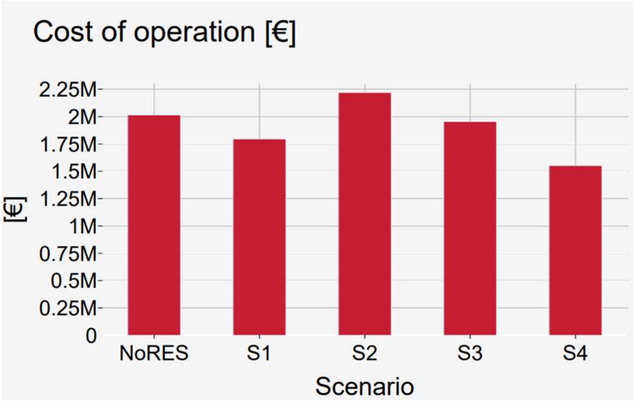

Figure 56 Yearly simulations cost of operation by scenario

It can be clearly inferred how, over a year the less expensive configuration concerning the port's grid operation is Scenario 4 with a total of 1.552 million €/Year. The production of the PV systems during the day allows to satisfy a big portion of the CI infrastructure power request, cutting the need to purchase energy from the grid reducing the expenses related to it especially during peak hours (see Figure 59).

Overall, the cost of operation (plotted in Figure 56 for the different scenarios) of the other scenarios ranges between 1.5 and 2.2 million €/Year being *S2* the most expensive and *S4* the cheapest. When compared to the *NoRes* scenario only *S2* leads to an increase of the yearly cost of operation, requiring 205 thousand € more per year. In the other cases operation cost is lower for *S3* of 60 thousand € and for *S1* and *S4* of 219 and 463 thousand € respectively. This highlights how the presence of the WECs (in *S2* and *S3*) does not bring an economic profit in the yearly performance of the system due to their high Opex costs. The impact of introducing the WECs into the port's grid is appreciable by comparing the overall costs between *S1* and *S2* or *S4* and *S3* (whose difference is the addition of the WECs). In both cases the cost of operation rises around 400 thousand €. Differently, introducing a PV system clearly brings its economic benefits. From *NoRes* to *S1* where the PV rated capacity goes from 0 to 2.67 MW the operation cost decreases of 220 thousand € and of around 250 thousand € when the large PVs are introduced in the other scenarios, consisting of the same capacity increase. The introduction of the large PVs in *S3* allows to compensate for the high expenses related to the WEC operation and maintenance. It shows that, even if the WECs are an expensive technology, if combined with the sufficient PV capacity their high operation costs can be balanced.

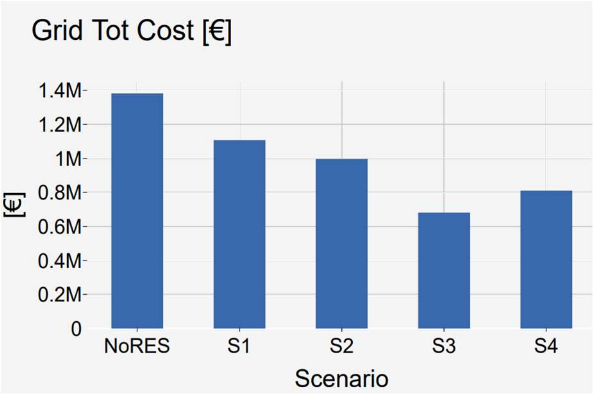

Figure 57 Yearly simulations Grid total cost by scenario

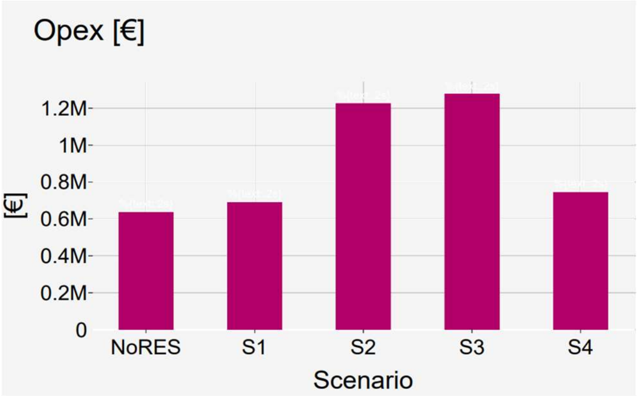

Figure 58 Yearly simulations Opex by scenario

Instead, when not considering Opex and only looking at the total grid costs (see Figure 57) the trend is completely rearranged. The higher is the RES share the more is the energy sold and less the purchased. For this reason, the grid costs are the lowest in *S3* and the highest in *NoRes* being the first equal to 679 thousand €, approximately the half of the second (1 380 thousand €). When Opex costs are not considered the introduction of all the mentioned RES is economically convenient. However, when Opex (shown in Figure 58 for each scenario) are considered, the situation is completely reversed. As a matter of fact, the cost of operation of the WECs in total amounts to 533 thousand €/year and it is not compensated by the savings which its energy production may create. Consequently, the most convenient technology between the two are the PVs systems. Indeed, the latter decrease the necessity to acquire energy from the grid while also working at a cheaper operational cost. This is enforced if comparing the respective opex costs 21 €/kW year for PVs and 51 or 85 €/kW for WECs. Dividing the energy produced in a year by their yearly opex cost, it emerges that the cost of production of a MWh for PV is 13.55 €/MWh 25 times more convenient of WECs whose cost is 337.86 €/MWh (Capex not considered).

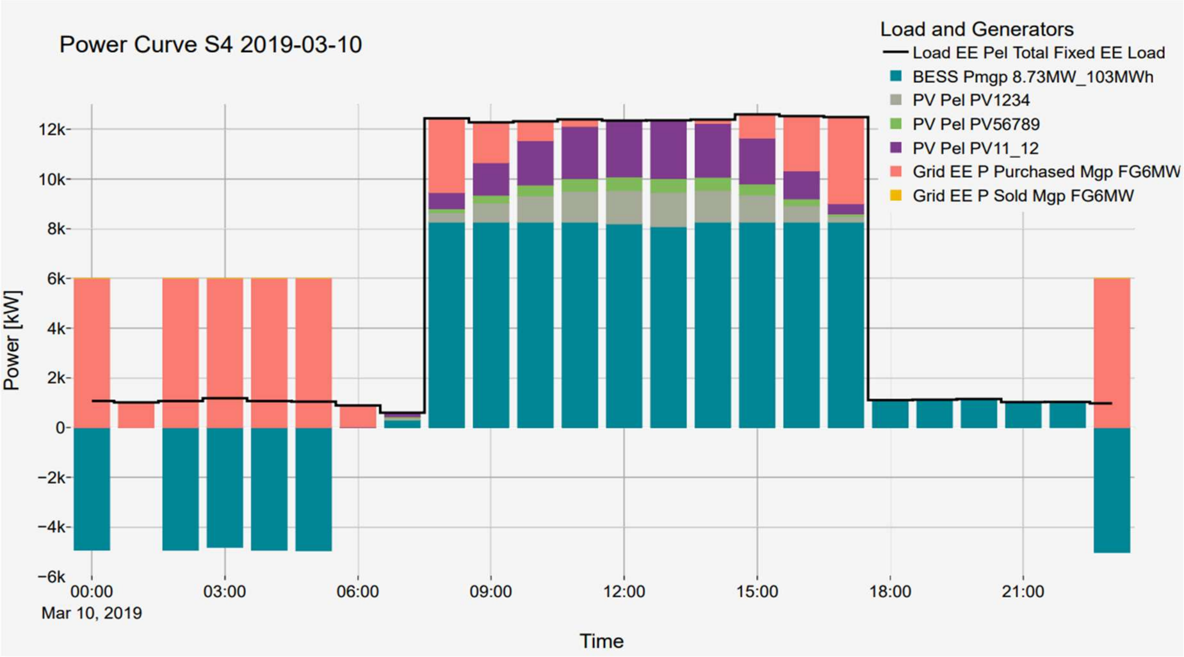

Figure 59 10th of March power Curve, showing the high infiltration of the PV systems

Another difference worth mentioning between the two technologies is that the PV system are a daily producing RES hence their production happens to be in the same moments in which cruise ships are requiring power (during their diurnal stops at the port). The fact that the energy produced by the PV systems when requested from the CI infrastructure is directly consumed and not stored, as it may happen for the WECs energy produced at night, reduces the losses caused by the storage process and increase of energy conversion steps. This makes the PV systems even more an attractive and efficient solution. In Figure 59, it is possible to see how a great portion of the energy requested by the CI infrastructure can be satisfied by the PV systems.

The seasonality of PV systems production whose period of maximum production (summer) corresponds with the most trafficked by cruise period of the year, makes them a highly suitable form of local energy production to satisfy CI power request. Contrary, the WECs production occurs mostly in winter when the CI infrastructure requires less energy. Hence, clearly, a more profitable investment would be to increase PV systems capacity rather than WECs. In *S3* the increase of the PV capacity of 2.6 MW allows to reduce the total cost of operation by 265 m€ compensating the high costs related to the introduction of the WECs.

Still this study acknowledges that the Opex prices of the WECs are just an assumption other simulation may be performed to assess the impact that they have in the overall results. For example, it may be considered that the Capex and Opex costs of these technologies may be subsidised by an external entity as result of an incentive in reducing the port's impact in an innovative way.

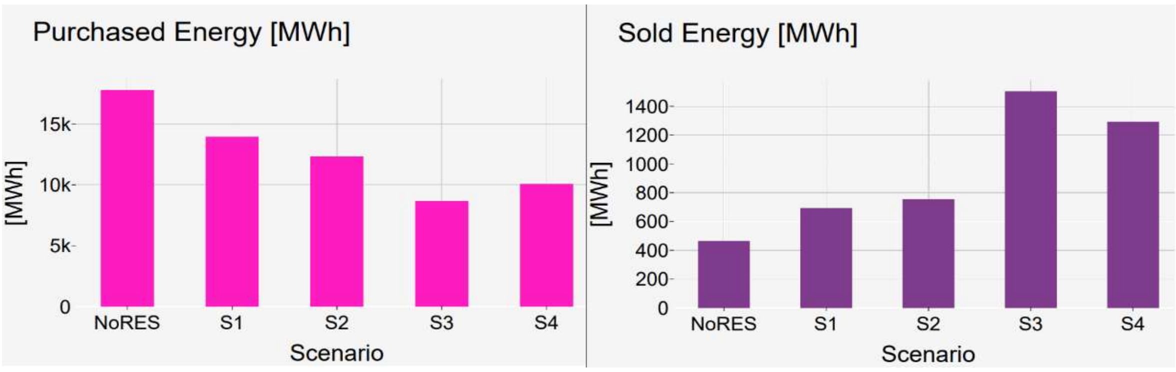

Figure 60 Yearly simulations purchased and sold energy by scenario

By comparing the yearly simulations scenarios, it emerges that the greater is the RES share, the more is the energy sold to the national grid and the less is the energy bought from it (as visible in Figure 60). The purchased values can go from the maximum in the *NoRes* scenario with 17 752 MWh bought in one year to the value of 8 626 MWh for *S3*. This shows how the introduction of RES can play a pivotal role in determining a higher saving regarding the total cost of operation. Noticeably, these savings depend strictly on the type of technology used to produce local energy as seen before. For instance, the total grid cost, thanks to the reduced amount of energy purchased and the higher quantity of energy sold, is the lowest in *S3* with 679 thousand € spent in a year. This is nearly half of the value of the *NoRes* scenario with 1 380 thousand €, on the contrary, when analysing the Opex costs is *S3* the most expensive with 1 275 thousand €/year with respect to the 635 thousand €/year of NoRes. This makes the total cost of operation equal to 2 220 thousand € and 2 015 thousand € respectively for the *NoRes* and *S3* scenarios, making in a yearly period, only when not considering Capex and Opex, the introduction of all the considered RES the most economically viable.

The value of the BESS yearly total load decreases by increasing the RES capacity from *NoRes* to *S2* as the BESS production is substituted by the RES and so its load behaviour is reduced. Then it increases in *S3* and *S4* as RES excess of production increases requiring the BESS to behave as a load while storing this energy. At the same time the energy the BESS will release will follow the same trend and so its number of cycles, going down from *NoRes* to *S2* and back up from *S3* to *S4*.

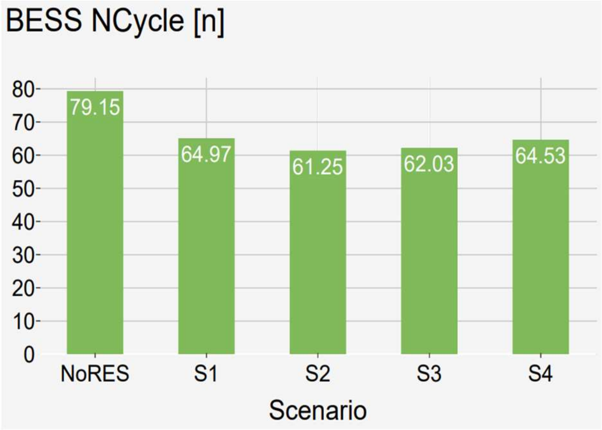

Figure 61 Yearly simulation BESS number of cycles by scenario

The BESS number of cycle (plotted in Figure 61 per scenario) parameter provides a clear outlook on the usage of the BESS. The scenario in which the storage system is less used is *S2* with 61 cycles in a year. The number of cycles decreases noticeably only when comparing the *NoRes* scenario, 79 cycles with the others, where the minimum difference is of 14 cycles with *S1*. In the other cases the difference is less appreciable, varying maximum of 3 cycles a year.

The cycles number are very low when compared to those required until the BESS reaches its end of life equal to 6000 for an average Li-ion battery [43]. The low number of cycles is determined by the fact that the BESS completes at most a cycle when a Cruise Ship is connected to the CI facility, so 44 times in a year and the remaining cycles are related to the usage to satisfy other energy requests of the port and allow demand response or load shift. For example, in S1 the POD rated capacity is exceeded 44 times and the total number of cycles is 64.96 meaning that the exceeding cycles computed as the difference of these two values are related to the charge and discharge of the BESS to operate in the electricity market or satisfy the different users of the port's grid. The number of cycles after reaching its minimum in *S2* rises as the RES share increases showing that after a certain value of the distributed energy production the BESS is more active.

The capacity of only 6MW of power transfer through the POD limits the performance of the BESS, not allowing it to be charged or to sell energy to the national grid at its maximum power capacity of 8.73 MW. For this reason, the number of cycles performed from the BESS will always be lower than the maximum theoretical it can perform in a year.

6.5.1 Monthly average comparisons

From the monthly average values of loads and generation (see Figure 62 and **ANNEX III**) it is possible to infer that the introduction of RES in the port's grid directly impacts the POD energy transactions. As the RES infiltration increases the purchase of energy reduces while the amount of energy sold rises. On the contrary, between all the scenarios containing RES the ESS performance varies less significantly with a yearly consumption around 7 GWh. This underlines the fundamental contribution that the ESS gives for the performance of the port grid.

In absence of RES, the most expensive month results to be July due to the high port consumption and the dock of 6 cruise ships that require to use the CI infrastructure (see Figure 63). Following the PVs introduction, the most expensive month becomes January as the number of cruise ships requiring CI are the same as July, but the PV production is approximately three times less than in July. The less expensive month is November in Scenario 4. This is due to the absence of CI usage from cruise ships that significantly lessen the monthly load and leaves the PV production fully available for the other port's loads. Moreover, the PVs systems and BESS for this reduced load are oversized allowing to buy less energy and sell more energy with respect to the other scenarios and satisfy the port's load through the PV production. The above-mentioned month exemplifies what would occur if there would not be any berth to the CI dock.

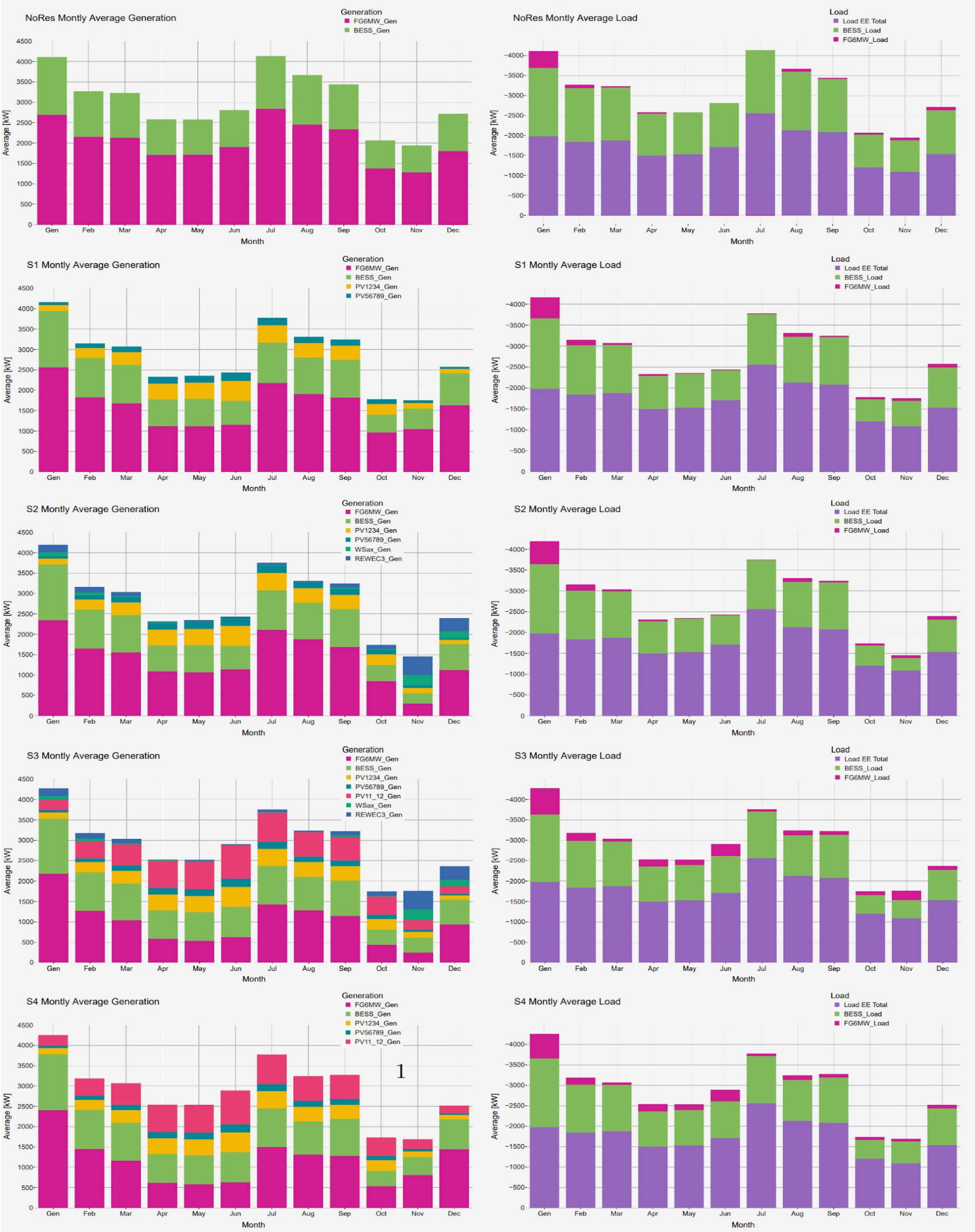

Figure 62 Energy monthly averages of power generation and load by scenario

Concerning the energy sold to the national grid, the month with the higher price of sale is January and for this reason is also the month with the higher energy sale. When the PV installed capacity is only 2.67 MW there is no sale of energy for the months of May, June and July caused by the lower sale prices and the need to satisfy the higher seasonal port’s load. In all the simulations, the monthly power peak requested from the national grid is always of 6MW corresponding to the max power available at the POD, this corresponds to a monthly power charge of 20 340 €. The only exception happens in S4 during the months of October and November when no Cruise Ships capable of being connected to the CI infrastructure visit the port. The high presence of local energy production allows it to not reach the max power available at the POD hitting the values of peak power of 3.6 and 2.4 MW and the power charge of 12.3 and 8.2 thousand € for October and November respectively.

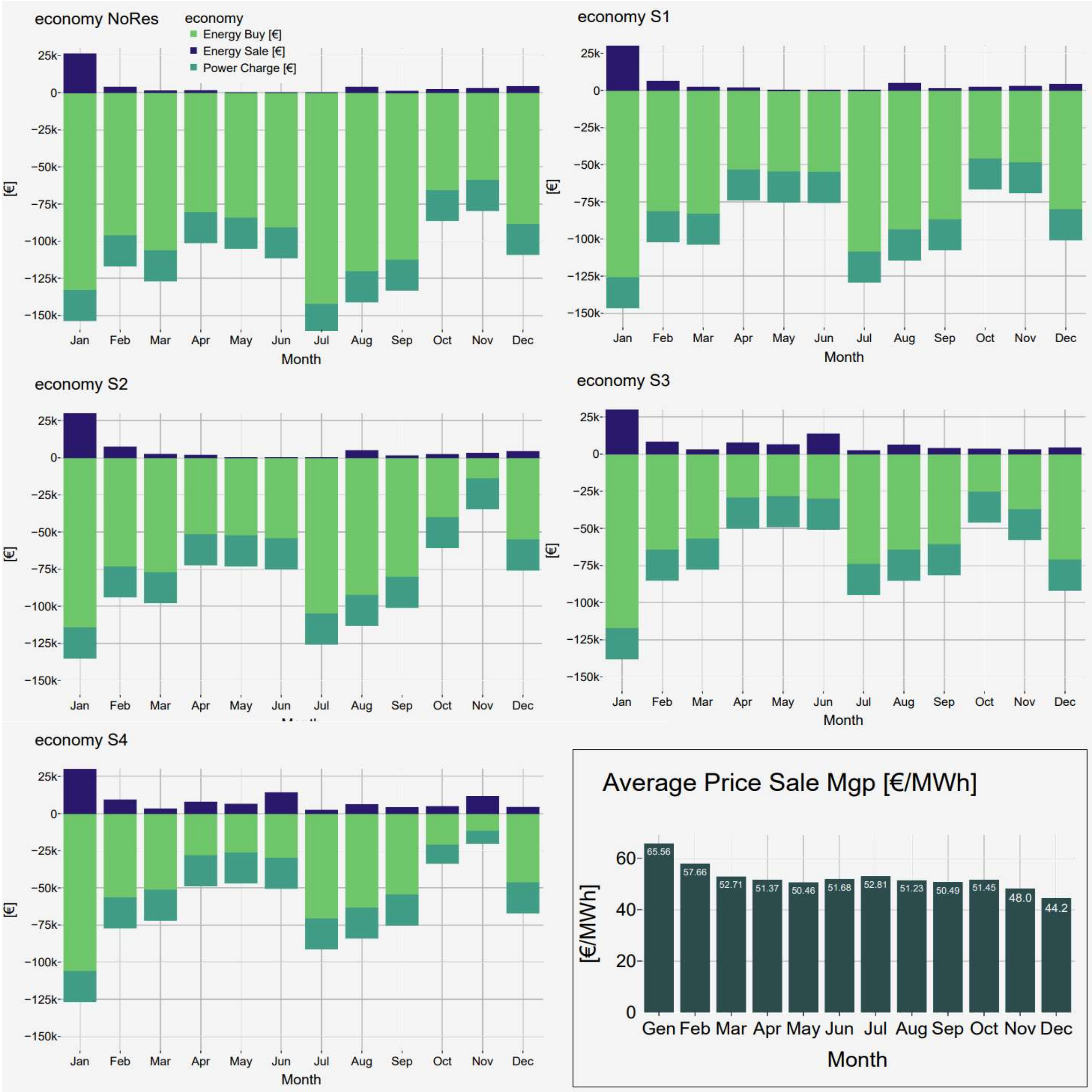

Figure 63 Yearly simulations economy by scenario; bottom right: electricity average monthly sale price

6.5.2 Participation to the Electricity Market

The simulations results allowed to visualize the optimal performance of the whole designed system, to evaluate the performance of it in the day ahead market five days (from November 11th to 15th) are compared for scenario NoRes, S3 and S4. Figure 64 shows the sale and purchase prices through the time period and Figure 65 the hourly power curve of the designed system.

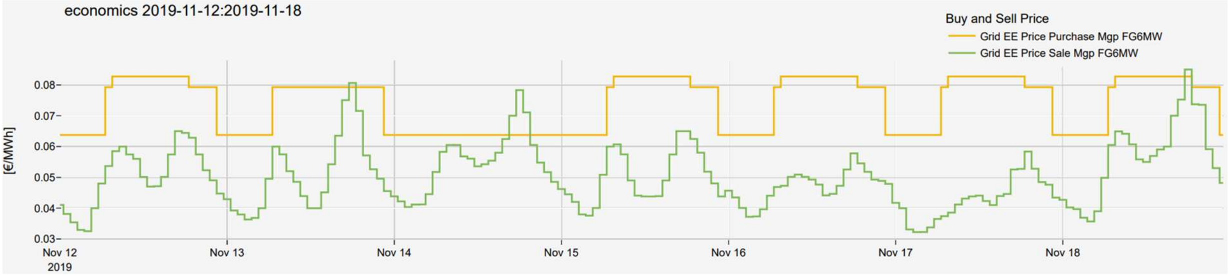

Figure 64 Electricity purchase and sale price from November 11th to 18th

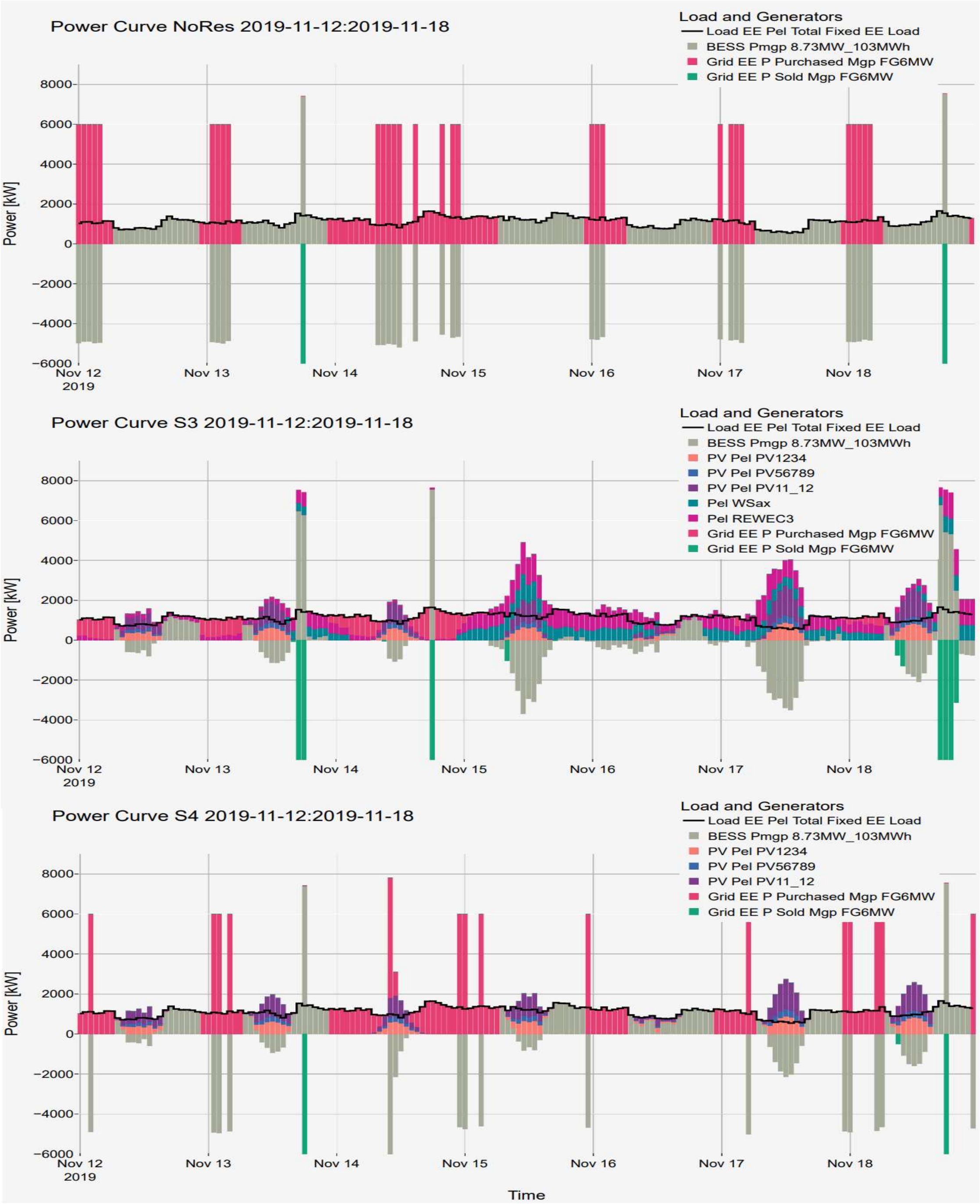

Figure 65 NoRes, S3 and S4 power curve from November 11th to 18th

By analysing these two figures (see Figure 64 & 65), it clearly emerges how the presence of local energy production in *S3* and *S4* allows to reduce the usage of the BESS while increasing the participation in the energy market as a seller (green bars). In *NoRes* (first graph) the BESS can only be charged through the national grid while in *S3* and *S4* it can be done from the excess of RES production offering great economic benefits. From Figure 65, it is possible to see how the energy is sold only when an economic profit is guaranteed. Hence, when its sale price is higher than the price of purchase. The higher is the RES share the lower is the average price of sale since it will be sold more frequently. Moreover, because the energy generated by the RES, ideally at 0 marginal cost, hence bringing profit every time it is sold at any positive price. Whereas in a *NoRes* scenario energy is sold at a price higher than the highest purchase band price while when RES are available energy is sold also when lower than the F2 or F3 prices.

6.5.3 ESS SOC distribution analysis

The BESS is used the most in the *NoRes* as it must compensate for the absence of local generation that can help satisfy the port's load. Therefore, the frequency of high SOC is higher in this case and lower in the other ones (Figure 66).

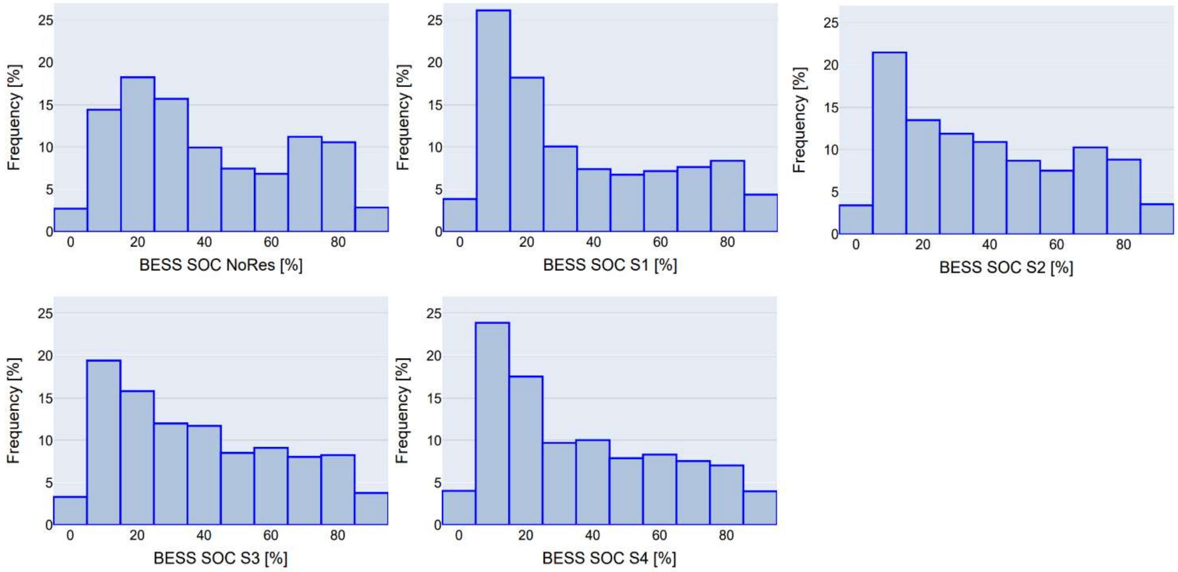

Figure 66 Yearly simulations BESS SOC frequency of cooccurrence by scenario

The presence of local energy production decreases the usage of the BESS. Noticeably, from Figure 66, it emerges it that as RES are available the frequency of lower SOC increases being the highest for the cases in which only PV systems are producing. This happens because the energy produced by the PVs, or part of it, is directly consumed from the daily load hence decreasing the possibility of storing it. When WECs are part of the local energy production, a higher frequency of high BESS SOC emerges. This occurs as the energy production of WECs does not always correspond to the load's request and hence requires to be stored. The full charge of the BESS always corresponds to the moment before the stop of a cruise ship that requires electricity from shore (Figure 67), followed by the discharge of it.

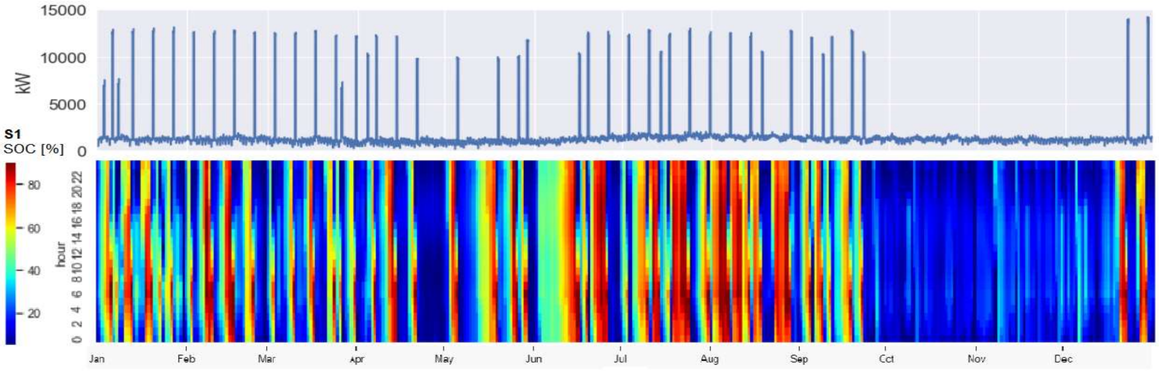

Figure 67 Top yearly port's load (peaks are cruise ships CI usage); bottom *S1* BESS yearly SOC.

6.6 Port's grid performance

The difference between the performance of the analysed scenarios will be highlighted in the paragraphs which follow.

6.6.1 Winter days analysis

The graphs below (in Figure 68) show the difference between the performance of the analysed scenarios from December 21st to 23rd.

Figure 68 December 21st to 23rd power curves by scenario

The 21st 22nd and 23rd of December are considered as a case study. It can be seen how during these days the total load reaches a peak of 14 MW at 18 PM on the 22nd and exceeds the POD capacity on the same day from 7 AM to 18 PM. During this period, the presence of a swell that allows the local production of energy through the WECs is the reason why in *S2* and *S3* the purchase of energy from the grid is significantly reduced. The seasonality of the WECs production may be complementary to the PV systems' and compensate for their reduction of power output occurring in winter. The purchase of large amounts of energy to recharge the BESS occurs during the period of the cheapest price band, F3 (from 23.00 to 8.00) to minimise the whole system costs.

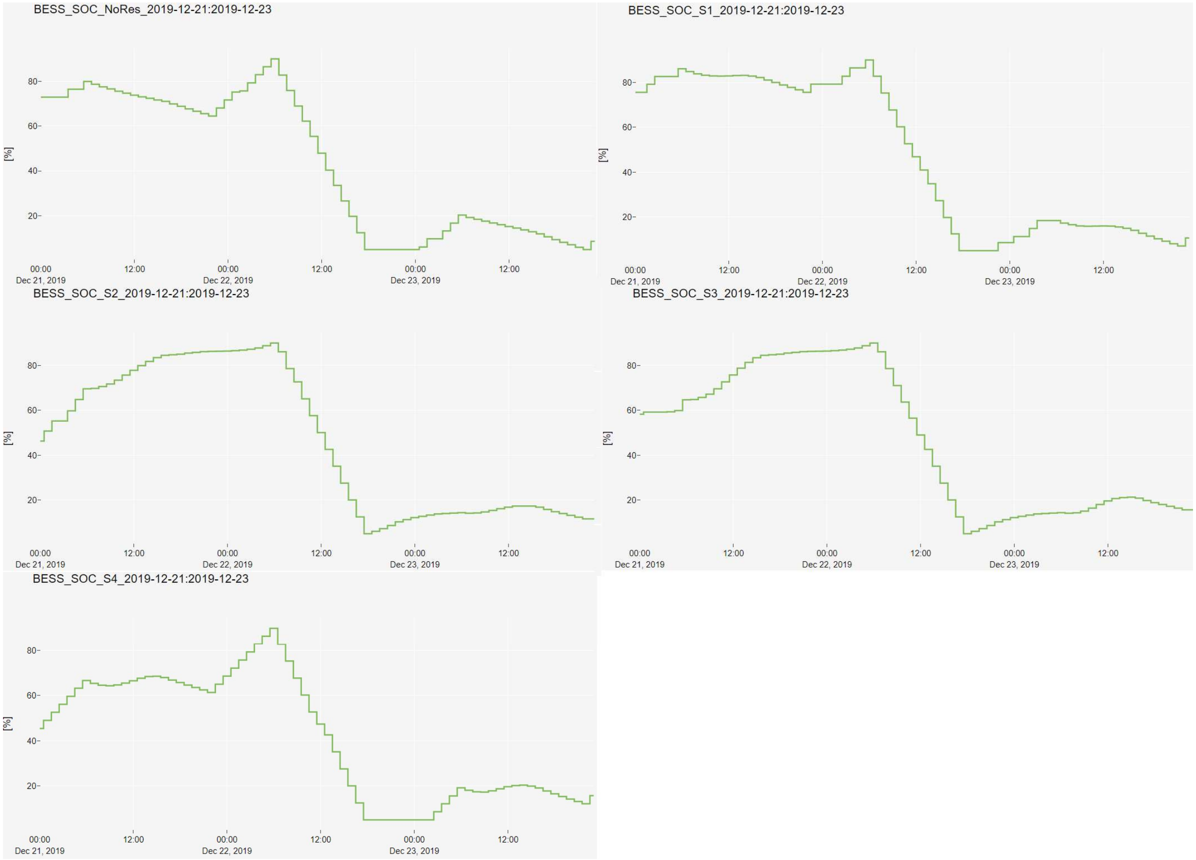

Figure 69 December 21st to 23rd BESS SOC by scenario

From Figure 69 it can be seen how the BESS reaches its maximum SOC just before a cruise ship is connected to the CI infrastructure and decreases as the ship is connected being used at its maximum potential in all the scenarios. When the total load is lower than the energy produced from the RES, the excess is stored increasing the ESS SOC.

6.6.2 Summer days analysis

In summer PV production reaches its maximum output and contributes actively to the satisfaction of the port's load. This is clearly exemplified in Figure 70 where the power curves of the 15th 16th and 17th of July are shown.

Figure 70 15th to 17th of July power curves by scenario

The arrival of a cruise ship in the port on the 16th of July brings the port load from 7.00 slightly above 10 MW for 12 hours. During the period taken into account, the port's load is satisfied by the combination of the PV systems and the BESS stored energy. When the PV share is the highest, the energy purchase to recharge the BESS in anticipation of the high load is lower than in the other scenarios. At the same time, the ESS is partly charged by the PV day ahead excess of production. For this reason, just before daylight of July 15th the SOC is lower as the PV capacity is higher. The SOC over the period analysed can be seen in Figure 71.

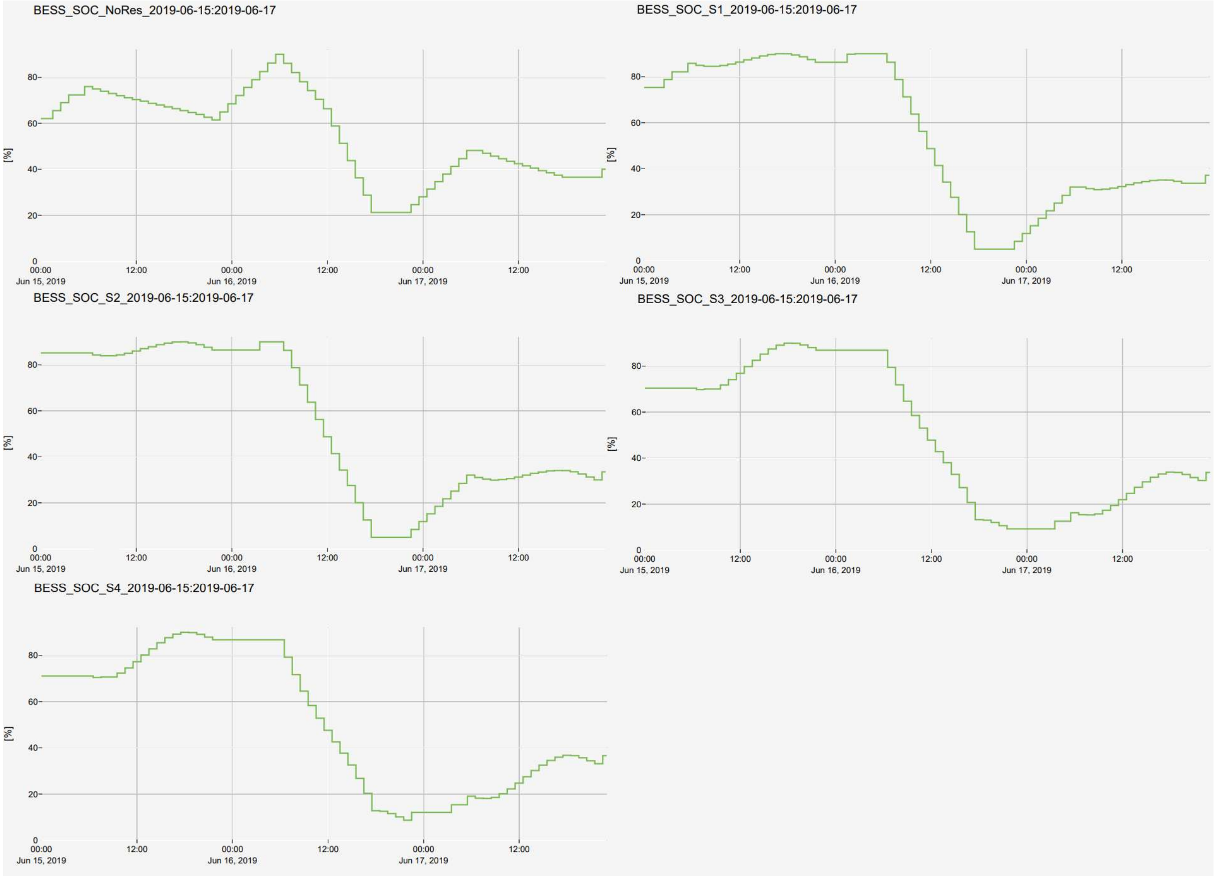

Figure 71 15th to 17th of July BESS SOC by scenario

In all the scenarios, even those with the highest RES share, when the total load exceeds 6 MW of request (when cruise ships are using the CI infrastructure) it emerges that the BESS is always providing power to the grid. Additionally, under the same condition for the total load, the BESS power output constantly overcomes the power delivered from the POD. This means that to optimize the economic impact of the port's grid performance the consumption of the energy stored in the BESS is preferable to the instant purchase of it.

6.7 Multiyear Results Analysis

This section serves to compares the results of a 20-year period performance of the port's grid under the different scenario's conditions. The multiyear simulations are done considering a hurdle rate of 7% to calculate the Net Present Value (NPV) and the Internal Rate of Return (IRR). In addition, the Capex of each RES listed in Table 19 are used. Table 22 lists the main results of the multiyear simulations.

Table 22 Results of multiyear simulations by scenario

	Total	**LCOE**	**IRR**	**NPV**
NoRES	75 096 995 €	11 970.98 €	-183.23 %	-58 198 957 €
S1	71 152 950 €	10 033.1 €	-182.56 %	-56 294 566 €
S2	121 503 525 €	19 820.64 €	-180.36 %	-102 676 141 €
S3	117 961 921 €	4 059.87 €	-179.47 %	-101 795 215 €
S4	67 945 665 €	2 500.44 €	-181.39 %	-55 611 189 €

6.7.1 Total Cost

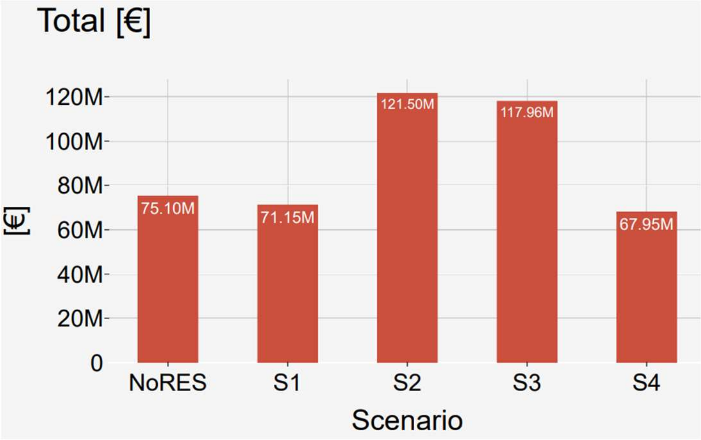

Figure 72 Multiyear total operation cost by scenario

Over 20 years, the less expensive scenario in terms of total cost emerges to be *S4* with approximately 68 milion € followed by *S1* (71 million €) and *NoRes* (75 million €). The scenarios respective multiyear operation total cost is plotted in Figure 72. Due to the high costs related to the WECs *S2* and *S3* nearly double the cost of the other scenarios reaching 121 and 117 million € respectively. In the yearly simulations the increase of PV capacity allows to compensate a portion of the WECs high costs because only Opex were considered. It is not the same in the multiyear simulations as Capex are considered, being the estimated initial investment cost of the WECs very high, of nearly 41.1 million €.

6.7.2 Levelized cost of energy (LCOE)

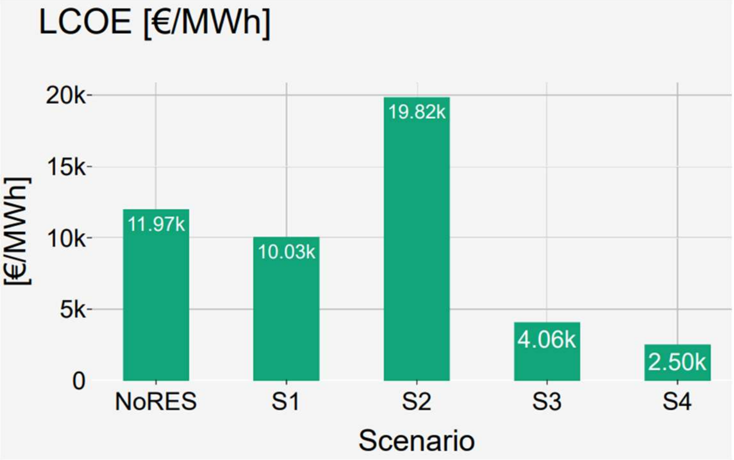

Figure 73 Multiyear LCOE by scenario

The LCOE related to the different scenarios (shown in Figure 73) is highly influenced by the presence of PV systems, it is the lowest in *S4* (2.5 thousand €/MWh), followed by *S3* (4.06 thousand €/MWh). *S1* and *NoRes* have an LCOE of 12 thousand €/MWh and 10 thousand €/MWh respectively while *S2* is the highest with approximately 20 thousand €/MWh. The LCOE highly decreases as the PV 10 and 11 are introduced as they allow to reduce drastically the purchase of energy from the grid, this is the case for *S3* and *S4*. Contrary, the introduction of WECs at this high capex and opex costs brings the LCOE up as it can be seen comparing *S1* with *S2*. When the PV capacity is only 2.67 MW (*S1*) the LCOE is reduced but their capacity is still not enough to allow a major energy purchase reduction as in *S3* and *S4*.

6.7.3 Net Present Value (NPV)

Furthermore, the NPV is calculated to determine which is the scenario that will be more favourable as an investment. When the NPV of a future investment is positive it follows that the discounted present value of expenses and revenues is positive. Hence, the investment is economically worthy, when negative it will be the opposite. Even if all the resulting values are negative it is a great tool to compare the different scenarios attractiveness, being the lower in absolute value the best.

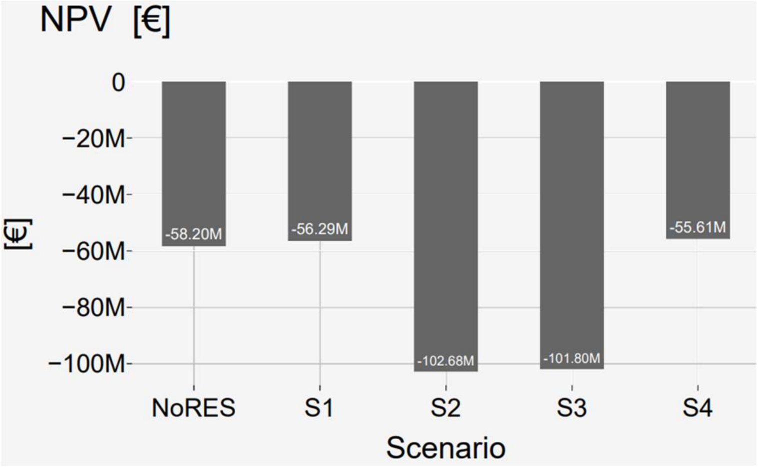

Figure 74 Multiyear NPV by scenario

Additionally, results (NPV values per scenario in Figure 74) show that the scenario that will lead to lower expenses is *S4* with -56.6 million € a few points less than *S1* (-56.3 million €) and *NoRes* (-58.2 million €). *S2* and *S3* almost double these amounts reaching -102.7 million € and -101.8 million € respectively. This difference shows how the PV introduction always brings savings in the port's grid operation. These results also confirm that the introduction of WECs at these high Opex and Capex is not convenient unless other values are possible to be considered or part of their expenses are sustained from incentives or external investments.

The high capital costs majorly influence the NPVs (especially for *S2* and *S3*) for example if capital cost is not considered in *S3* the NPV would pass from -101.8 million € to -21.2 million € being the total initial capex equal to 80.6 million €.

6.7.4 Internal Rate of Return (IRR)

The IRR corresponds to the hurdle rate that makes the NPV equal to zero, it is an indicator to define whether an investment will be profitable or not. The greater the NPV, the more profitable the investment.

In this case all the IRR are negative and so in all the scenario a negative hence return will be experienced. For all the scenarios the IRR ranges around the -180 % being extremely unprofitable, showing that expenses will greatly overcome the revenues of each investment. Anyway, the scenario that has a higher IRR is *S3* equal to -179% while the higher is *NoRes*. This entails that *S3* has a higher yearly income when compared to the others and this is due to its higher sale of energy and lower purchase.

From the NPV and IRR analysis it is possible to deduce that all the scenarios under the given conditions are not profitable and attractive from an economic point of view. Additionally, it must be taken into account that the energy provided to the cruise ships will be sold to the shipowner at a special tariff and also its price is expected to be discounted from excise taxes and power system duty [21]. Doing so, this will increase the value of the yearly income rising the NPV and the IRR. In this case the NPV and IRR are calculated only for the purpose of comparing one scenario to the other.

6.7.5 BESS analysis

The BESS performance outcomes can be appreciated in Table 23.

Table 23 BESS multiyear simulations result by scenario

Parameter	Energy In [MWh]	Energy Out [MWh]	Losses [MWh]	N Cycle [n]	N Cycle per Year [n]	SOC Decay [%]
NoRes	188 288.26	171 699.84	16 588.41	1 636	82	9.97
S1	146 506.2	136 330.36	10 175.83	1 256	63	7.83
S2	138631.11	129 727.53	8 903.59	1 186	59	7.43
S3	154 082.09	143 634.29	10 447.79	1 334	67	8.28
S4	153 878.51	143 925.84	9 952.66	1 333	67	8.28

Overall, in 20 years, the BESS cycles are expected, to reach more than 1180 in all the scenarios. As seen for the yearly simulations, *S2* witnesses the lowest (1 186) value and *NoRes* is the greatest (1 636). The total energy that flows through the BESS in 20 years for these two scenarios is 154 GWh and 188 GWh respectively. The BESS capacity in the worst-case scenario over 20 years decreases by 9.97% in the best case only of 7.43%. In both cases this capacity decrease does not influence the grid performance which also on the 20th year can operate without any power generation increase to satisfy the total load. Theoretically the BESS after 20 years would be still usable for its purpose, but a more accurate study may be required to confirm it.

6.8 Results Discussion

The EMSS simulations allowed to evaluate the embedding of the ESS, the CI load and the RES in the port's grid over a year and a 20-year time period. Firstly, it emerges that, to satisfy the designed total port's load, the ESS, with the characteristics of Table 16, must have a minimum rated power of 8.73 MW and a rated capacity of 121.5 MWh.

When RES are combined with the sized ESS energy, withdrawals from the national grid are reduced hence the purchase of energy decreases. Consequently, an economical and environmental benefit can be obtained from this configuration. From the simulations, arises that the most economically convenient scenario is *S4*, where the PVs rated capacity is equal to 6.27 MW. This occurs because the combination of ESS and PV systems allows to directly satisfy the large cruise ships power demand noticeably decreasing the purchase electricity during their docking at the port. Additionally, the energy produced by the PVs allows to reach a RES share of the 32% satisfying a great portion of the total load. Moreover, *S4* is the scenario that achieves the highest NPV between the others and the cheapest LCOE, being so the one with the lowest expenses and the most convenient in term of electricity cost. Even though, S3 results to be the highest in terms of RES production and so GHG emissions reductions, it follows that is the most expensive due to the WECs high Capex and Opex.

From the simulations it emerges that, even when the port includes the all the available RES their power generation, is not sufficient to satisfy the whole cruise ships load. This highlights the pivotal role of the BESS when the target is to power the CI load without modifying the capacity of the port's PODs.

7 CONCLUSIONS

This thesis can be divided in two main parts: the description of cruise ships CI technique and the case study of the port of Civitavecchia simulated and analysed thank to a EMSS software. More in particular, CI for cruise ships is reported highlighting the benefits it provides and the main difficulties its implementation may encounter. The greatest advantage of CI is the reduction of local GHG emissions hence the compliance with the current maritime transportation emission reduction policies, especially when electricity is produced by RES. While the most complex barrier, to break for powering cruise ships from shore, is to design the port's electrical system in order to provide the adequate electrical power to these vessels that can reach up to 14 MW. Another complication resides in avoiding the waste of energy produced in excess from RES that in consequence must be instantly consumed or stored. The proposed solution to overcome this barrier in this study is to implement a large-scale ESS to increase the port power capacity and RES infiltration potential. This option is researched taking the Port of Civitavecchia, one of the most visited from cruise ships in the world, as case study. Therefore, simulations of the port's grid performance with the integration of a large BESS and RES are performed with an EMSS developed by Falck Next Solutions s.r.l.. The simulations enable size the BESS and to visualize the optimal performance of the port's energy and cash flows. After defining the ports load, the distributed generation the CI power request and the electricity prices and relative charges, the EMSS is run simulating yearly and 20-year time periods of port operation.

The first part of this study consists of a bibliographic research and merges multiple information found in literature resulting into a comprehensive guide on cruise ships CI. The second part of the thesis contributes to the literature, by analysing through the case study of the Port of Civitavecchia, the performance of port's grid when CI is introduced, furthermore with the addition of a large-scale BESS. The latter is implemented to overcome the poor power capacity of one of the most important cruise ships calls being the first study with this scope. Another relevant aspect that makes this study unique is that combines the implementation of Wave Energy in port's areas to power CI infrastructures and analyses its performance. The investigation made on the Port of Civitavecchia case study reveals its energy consumption patterns, cruise traffic data and determines from its yearly cruise docking schedule which are the ships that will receive CI. Additionally, the diffusion of the mentioned information lay the foundations for future works on CI implementation.

The first part of the research exposes how CI is still a rare practice and it is implemented only in 19 ports of the world for cruise ships being only 68 cruise ships fitted to receive shore power. The realization of the infrastructure has been incentivized by the introduction of regulations, international standards and incentives and these must be promoted to further develop this technology.

In Chapter 5 the qualitative analysis comparing the different ESS typologies proved that a Battery based technology is the most suitable to support cruise ships CI, thanks to its flexibility, modularity, technologic advancement and space requiring characteristics.

From the simulations, it results that to provide shore power to the cruise ships visiting the Port of Civitavecchia, under the designed conditions of the port's grid a BESS of 8.73 MW and 121.5 MWh is required. The introduction of RES as distributed energy sources connected to the port's grid allow to reduce the purchase of energy and consequently reduce the port's environmental impact. Moreover, the sale of energy increases resulting into higher incomes. Between the proposed scenarios reliant on the RES that can be installed in the port, it emerges that the most economically convenient is *S4* consisting of a rated PV capacity of 6.27 MW. This result highlights the virtuous effect that PV systems adoption in port areas may have in satisfying cruise ships CI load that typically occurs during day light hours. It is so preferable to invest on PV systems technologies to enhance the port's grid power and reduce the overall GHG emissions. As visible in Table 21 & 22, economically, *S2* and *S3* are not convenient due to the high expenses related to WEC technologies. Anyway, if their investment is supported from external entities or the costs are neglected, their implementation can noticeably contribute to the port's RES Share. The ESS has a power capacity higher than the port's POD capacity. This feature strictly limits the potential power and time at which energy can flow through the ESS restricting the number of cycles it can perform in a year that in a *NoRes* scenario reach (the maximum possible) of 79 per year. Therefore, over 20 years the ESS performs a maximum of 1600 cycles without affecting the batteries State of Health or noticeably decreasing the ESS capacity. However, when RES are included in the port's grid the BESS usage decreases. By analysing the yearly BESS SOC curve (Figure 67) it comes out that the full charge of the BESS only occurs before an high energy-demanding cruise ships connects to the CI infrastructure.

The outcomes of the multiyear analysis show how NPV of all the scenarios is negative and does not provide any economical profit. Anyhow, the NPV, when used to compare the different scenarios highlights *S4* as the most convenient. The LCOE in the 5 different analysed scenarios varies noticeably going from 19.82 thousand €/MWh in *S2* to 2.5 thousand €/MWh in *S4.* This outcome shows again how the impact of increasing the PVs capacity in the system is economically convenient.

In future works, sensitivity analysis of the different parameters used for the simulation can be performed. For example, by varying the Capex or Opex cost of the Wave Energy technologies or simulating the introduction of external funds into the initial investment. Moreover, it may be researched the rated capacity of PV systems or other technologies (i.e., Wind Turbine) to be introduced in the port to set to zero the cruise ships at berth consumption. Furthermore, the variability of electricity prices can be introduced or different energy contracts for the port utility company can be considered; also considering the current European energy markets framework. It also can be investigated the profit that the port utility company can obtain by selling electricity to cruise ships and by using different sale prices determine which would be the most adequate to reduce at the minimum the investment's payback period. As it is becoming always a more frequent practice for ESS to participate to the Ancillary Services Market (ASM), further simulations can be performed to evaluate the profits that joining the ASM may introduce. In addition, future research can focus on obtaining the best combination from the economic and technical perspective between the port's delivery infrastructure power capacity and the ESS dimensions (power and capacity).

REFERENCES

[1] https://unfccc.int/process/the-kyoto-protocol/mechanisms/emissions-trading [Accessed: 07/2021]

[2] https://ourworldindata.org/emissions-by-sector [Accessed: 07/2021]

[3] Sergi Espinosa Sanes; Design of A Shore Power System For Barcelona’s Cruise Piers; Facultat de Nàutica de Barcelona; 2015.

[4] IMO; Third IMO Greenhouse Gas Study 2014; retrieved from: https://wwwcdn.imo.org/ [Accessed: 07/2021]

[5] P. Ericsson; I. Fazlagic’; Shore-Side Power Supply; Chalmers University of Technology; Göteborg; 2008.

[6] Thalis P.V. Zis; Prospects of cold ironing as an emissions reduction option; Transportation Research Part A Policy and Practice; 2019.

[7] L. Browning; K. Bailey; Current Methodologies and Best Practices for Preparing Port Emission Inventories; U.S. Environmental Protection Agency; 1990.

[8] A. Rolan; P. Manteca; R. Oktar; P. Siano: Integration of Cold Ironing and Renewable Sources in the Barcelona Smart Port; IEEE Transactions on Industry Applications; 2019.

[9] D. Colarossi; P. Principi; Technical analysis and economic evaluation of a complex shore-to-ship power supply system; Applied Thermal Engineering; 2020.

[10] J. Prousalidis; G. Antonopoulos; C. Patsios; A. Greig; R. Bucknall: Green Shipping in ECAs: Combining Smart Grids and Cold Ironing; 2014 International Conference on Electrical Machines; 2014.

[11] F. Ballini; R. Bozzo; Air Pollution from ships in ports: The socio-economic benefit of cold ironing technology; Research in Transportation Business & Management; 2015.

[12] R. Winkel; U. Weddige; D. Johnsen; V. Hoen; S. Papaefthimiou: Shore Side Electricity in Europe: Potential and environmental benefits; Energy Policy; 2015.

[13] G. Parise; L. Parise; L. Martirano; P. Ben Chavdarian; Chun-Lien Su; A. Ferrante: Wise Port and Business Energy Management: Port Facilities, Electrical Power Distribution; IEEE Transactions on Industry Applications; 2015.

[14] G. Caprara; V. Armas; D. de Mesquita e Sousa; M. Kermani; G. Martirano; An Energy Storage System to support Cruise Ships Cold Ironing in the Port of Civitavecchia; EEEIC / I&CPS Europe; 2021.

[15] Ports of Genova; L’elettrificazione delle banchine dei porti del Mar Ligure Occidentale; retrieved from: https://www.adspmarligureorientale.it/ [Accessed: 07/2021]

[16] IMO Train the Trainer (TTT) Course on Energy Efficient Ship Operation Module 5 – Ship Port Interface for Energy Efficiency; retrieved from: https://www.imo.org/en/OurWork/Environment/Pages/IMO-Train-the-Trainer-Course.aspx [Accessed: 07/2022]

[17] COUNCIL DIRECTIVE 2003/96/EC; restructuring the Community framework for the taxation of energy products and electricity; 27 October 2003.

[18] IMO; Resolution Mepc.323(74); Invitation To Member States To Encourage Voluntary Cooperation Between The Port And Shipping Sectors To Contribute To Reducing GHG Emissions From Ships; MEPC 74/18/Add.1 Annex 19; 2019.

[19] CARB, At Berth Frequently Asked Questions 2020; retrieved from: https://ww2.arb.ca.gov/our-work/programs/ocean-going-vessels-berth-regulation [Accessed: 06/2022]

[20] DIRECTIVE 2014/94/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL; on the deployment of alternative fuels infrastructure; 22 October 2014.

[21] IEC/ISO/IEEE 80005-1; 2012.

[22] CLIA; ENVIRONMENTAL COMMITMENT, INNOVATION, AND RESULTS OF THE CRUISE INDUSTRY; retrieved from: https://cruising.org/en-gb [Accessed: 07/2021]

[23] British Ports Association; reducing emissions from shipping in ports examining the barriers to shore power; 2020; retrieved from: https://www.britishports.org.uk/ [Accessed: 07/2021].

[24] EPA; Shore Power Technology Assessment at U.S. Ports; 2017 retrieved from: www.epa.gov [Accessed: 07/2021]

[25] AAPA; Cold Ironing emission reduction alternative for cruise ships while in port; 2004; retrieved from: https://www.aapa-ports.org/ [Accessed: 07/2021]

[26] L. Čampara; N. Hasanspahić; S. Vujicic; Overview of MARPOL ANNEX VI regulations for prevention of air pollution from marine diesel engines; SHS Web of Conferences 58; 2018.

[27] DIRECTIVE 2005/33/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL; 6 July 2005.

[28] COMMISSION RECOMMENDATION on the promotion of shore-side electricity for use by ships at berth in Community ports (2006/339/EC); of 8 May 2006.

[29] Julie Lechanteux; Question for written answer E-002668/2019 to the Commission; 5 September 2019 retrieved from: https://www.europarl.europa.eu/doceo/document/E-9-2019-002668_EN.html [Accessed: 07/2021]

[30] Ms Bulc; EN E-002668/2019 Answer given by Ms Bulc on behalf of the European Commission; 23.10.2019; retrieved from: https://www.europarl.europa.eu/doceo/document/E-9-2019-002668-ASW_EN.html [Accessed: 07/2021]

[31] COUNCIL DECISION authorising Germany to apply a reduced rate of electricity tax to electricity directly provided to vessels at berth in a port ("shore-side electricity") in accordance with Article 19 of Directive 2003/96/EC; 2011.

[32] Fetting, C.; “The European Green Deal”, ESDN Report, 2020; retrieved from: https://www.esdn.eu/ [Accessed: 07/2021]

[33] COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS; Sustainable and Smart Mobility Strategy – putting European transport on track for the future; 2020.

[34] V. Naso, L. Cedola, M. Villarini, L. Del Zotto, Analisi tecnico-economica della elettrificazione del porto di Civitavecchia, Osservatorio ambientale di Civitavecchia sezione ambiente; 2006.

[35] PNRR; retrieved from: https://italiadomani.gov.it/it/home.html; [Accessed: 07/2021]

[36] Arena, F.; Fiamma, V.; Laface, V.; Malara, G.; Romolo, A.; Strati, F.M.; Monitoring of the U-OWC under construction in Civitavecchia; EWTEC; 2015.

[37] MedCruise; Statistics Cruise Activities in MedCruise Port; 2019 retreived from: https://www.medcruise.com/2020-statistics-cruise-activities-in-medcruise-ports [Accessed: 07/2021]

[38] Autorità di Sistema Portuale del Mare Tirreno Centro - Settentrionale; DOCUMENTO DI PIANIFICAZIONE ENERGETICA ED AMBIENTALE dei Porti di Civitavecchia – Fiumicino – Gaeta; 2021.

[39] António F. O. Falcão; Modelling of Wave Energy Conversion Lecture Notes; Instituto Superior Tècnico; Lisboa; 2020.

[40] M. Peviani; WaveSAX, wave energy converter; Energie Rinnovabili Marine: Progresso tecnologico, prospettive e trend nel mercato delle tecnologie pulite; ENEA; 2018.

[41] Starcrest Consulting Group, LLC; Port of Los Angeles Inventory of Air Emission -2019; retreived from: https://www.portoflosangeles.org/environment/air-quality/air-emissions-inventory [Accessed: 07/2021]

[42] P. Medina; A. W. Bizuayehu; J. P. S. Catalão; E. M. G. Rodrigues; J. Contreras; Electrical Energy Storage Systems: Technologies’ State-of-the-Art, Techno-Economic Benefits and Applications Analysis; 2014 47th Hawaii International Conference on System Science; 2014.

[43] Haisheng Chen; Thang Ngoc Cong; Wei Yang; Chunqing Tan; Yongliang Li; Yulong Ding; Progress in electrical energy storage system: A critical review; Progress in Natural Science 19 (2009); 2009.

[44] Héricles Eduardo Oliveira Farias; Luciane Neves Canha; Battery Energy Storage Systems (BESS) Overview of Key Market Technologies; 2018 IEEE PES Transmission & Distribution Conference and Exhibition - Latin America (T&D-LA); 2018.

[45] BATSTORM project; Battery storage to drive the power system transition; retrieved from: https://energy.ec.europa.eu/topics/research-and-technology/energy-storage_en [Accessed: 07/2021]

[46] G. Caprara; L. Martirano; C. Balletta; Preliminary Analysis of the Conversion of a Leisure Boat into a Battery Electric Vehicle (BEV); 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe); 2020.

[47] Mustafa Farhadi; Osama Mohammed; Energy Storage Technologies for High-Power Applications; IEEE Transactions on Industry Applications; 2016.

[48] Akitaka Hiratsuka; Takashi Arai; Tsukasa Yoshimura; Seawater pumped-storage power plant in Okinawa Island, Japan; Engineering Geology; 2019.

[49] https://www.mercatoelettrico.org/it/ [Accessed: 07/2021]

[50] IMO; Historic Background; retreived from: https://www.imo.org/en/OurWork/Environment/Pages/Historic-Background-.aspx- [Accessed: 07/2021]

[51] EGCSA; What is an exhaust gas cleaning system?; retrieved from: https://www.egcsa.com/technical-reference/what-is-an-exhaust-gas-cleaning-system/ [Accessed: 07/2021]

[52] Porti verdi: la rotta per uno sviluppo sostenibile, Enel X, Legambiente, retrieved from: https://www.legambiente.it/wpcontent/uploads/2021/02/Porti-Verdi-Enelx_Legambiente.pdf [Accessed: 05/2021]

8 ANNEXES

8.1 ANNEX I Ships Air Pollution regulations and reduction methodologies

The International Maritime Organization (IMO) is the United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships. It supports the UN sustainable development targets. To regulate ships Marine Pollution Prevention, it adopts the MARPOL convention. Air pollution from ships was the last contamination typology to be included in IMO's regulations. With the Marpol Annex VI, from 2005 shipowners are required to comply with air pollutants emissions limits. The restrictions, limiting pollutants contents in fuels or in emissions led to the application of different measures. Cruise Ships companies adopted different solutions: scrubbers, alternative fuels (LNG), or Cold Ironing.

8.1.1he MARPOL Convention [27]

To control the security and safety of shipping and regulate the atmospheric pollution caused by maritime transport the United Nations formed in 1948 the International Maritime Organization (IMO). The organization joined by 175 parties, generated 50 conventions. The convention focused on Maritime Pollution Prevention MARPOL aims to regulate and minimize pollution from ships. It was firstly adopted in 1973 but took officially effect in 1983 during the years was amended multiple times. In 1997 a new Protocol amended the convention to introduce and additional annex to the five already in force. The sixth technical annex that is focused on the prevention of air pollution from ships, and it only entered in force in 2005.

The MARPOL convention is divided in six annexes, each of them focused on different types of regulations and pollution type prevention.

Annex I considers the safeguard from oil pollution in operational measures and fortuitous leakages. For example, after 1992 amendment the Annex made mandatory the use of double hulls for oil tankers.

Annex II sets the rules for pollution from cargo harmful liquid substances, it defines the criteria and conditions for liquid pollutants discharge. It also sets the limit of 12 nautical miles from land for the discharge of noxious residues.

This first two annexes entered in force in 1983.

Annex III, entered in force later in 1992, has the scope stop pollution caused by noxious matter carried by ships in packaged forms. It sets the standards and limits on packaging procedures, documentation and reporting.

Annex IV controls the pollution by sewage in maritime transport, it entered in force in 2003 and prohibits sewage discharge in the sea except if sewage treatment is applied on board or the discharged sewage has been disinfected by standardised procedures at more than 3 nautical miles from land. It permits the discharge of not disinfected sewage at more than 12 miles from land.

Annex V enforced in 1988 details the procedures of garbage pollution produced by ships. It regulates the distances at which garbage can be disposed and specifically totally avoid the disposal of every form of plastic.

Annex VI is the latest entered into force on the 19th of May of 2005. It regulates the air pollution produced by maritime transport imposing limits on the emissions from ship exhausts of particulate matter (PM) sulphur oxide and nitrogen oxide (respectively SO_x, NO_x) and ban voluntary emissions of any ozone consuming substance. It also defines emission control areas (ECAs) where more stringent limits on emissions are set.

In 2011 a chapter related to compulsory technical and energy efficiency standards was introduced with the purpose of decreasing GHG emissions from ships defining the EEDI Energy Efficiency Design Index. The EEDI is used to promote the use of more energy efficient equipment and engines. It needs a minimum energy efficiency level for different ship type and size. Form 2013, ship design needs to meet the reference level for their ship type. The tier is tightened stricter every five years, and so stimulates continuous innovation and development, reducing energy consumption and pollution. The EEDI provides is expressed in grams of carbon dioxide (CO2) per ship's capacity-mile (the smaller the EEDI the more energy efficient ship design).

8.1.2 MARPOL ANNEX VI

8.1.2.1 Historic Background [50]

The problem of Air pollution was already discussed in the first meetings of the convention but not included in the regulations at that time. It followed that as international interest on air pollution started to rise in those years and multiple studies led to the validation that air pollutants could travel long distances with negative effects on the environment and on human health. Causing problems such as acid rains, generated by airborne sinks of SO_x and NO_x emitted from oil and coal fired power plants or vehicles are a relevant cause of the damage of forests and agricultures.

In 1987 the Montreal Protocol regulating restrictions on Ozone Depleting substances was signed by the United Nations. 2000 was the year in which halons and ozone consuming substances as CFCs had to be prohibited. The CFCs were commonly used as cooling substances for ship container and bulk carriers and in emergency fire extinguisher. In the 80s the Marine Environment Protection Committee (MEPC) analysed the quality of fuel oil to check the requirements of Annex I and so the air pollution problem was discussed. Norway made notice the magnitude of the problem of air pollution from ships exhausts and with the Second international conference on the protection of the North Sea while discussing standards on heavy fuel oils it was agreed to involve in the consideration of the air pollution problem the IMO. After MPEC discussion on fuel oil requirements it was decided to control the GHG emissions from ships. Norway, still leader in tackling the air pollution problem, submitted a study to the MEPC highlighting that Sulphur emissions from ships accounted for 4% of worlds emissions, affecting in particular areas with high maritime traffic as the English Channel, South China and the strait of Malacca. The study put in evidence also that Nitrogen oxide emissions from ships accounted 7% of the whole global emissions and caused local problems as acid rain and health problems in harbours. Concerning Ozone depleting substances Norway also reported that the emissions of CFCs from the world shipping fleet where approximately 1-3% of yearly global emissions and Halon emissions from maritime shipping sector accounted for 10% of the world's gross. MEPC adopted so an IMO assembly to prepare a new Annex to regulate air pollution from maritime transport. In 1997 the new Annex VI of MARPOL was included in the Protocol, but it only took effect on the 19th May 2005.

8.1.2.2 Annex VI highlights [26]

Annex VI is divided in 5 chapters with a total of 26 regulations. Introduces definitions, necessary surveys certifications, control methods emissions limits, energy efficiency, audits verifications. The Annex has 10 appendices and 30 guidelines in constant update to facilitate implementations from IMO member states.

Regulation 13 sets the limits on Nitrogen Oxide emissions from ships exhausts. This compound is generated in the combustion of fuel oil combustion leading to the formation of smog in the atmosphere, contributing to the global warming and acid rains. Additionally, it plays a part in the generation of ground-level ozone when interacting with Volatile Organic Compounds and solar radiation.

The Regulation sets limits for from Marine Diesel Engines with a power higher than 130 kW built after 1st January 2000 or that after the same date were subject to modifications that could increase their emissions level. This restriction is not applied to boilers or gas turbines.

In 2008 Annex VI was reviewed and lowered the limits on NOx emissions introducing two additional levels also known as Tiers based on the ship's construction date. The limit of NOx is given in g/kWh and depends on the engine rated speed. Tier III only applies for ships operating in the Emission Control Areas. Table 24 highlights the tiers of ECAs.

Table 24 NO_x Emissions Limits [26]

Tier	Ship's Construction date	Total weighted NOx emission limit value (g/kWh) n = engine's rated speed (rpm)		
		n < 130	130 < n < 1999	n >= 2000
I	1 Jan 2000	17	$45 * n^{-0.2}$	9.8
II	1 Jan 2011	14.4	$44 * n^{-0.23}$	7.7
III	1 Jan 2021	3.4	$9 * n^{-0.2}$	2

Regulation 14 sets the limits for Sulphur Oxides (SOx) emissions and Particulate Matter (PM) from all Marine Fuel Oils (MFOs) used on ships so, differently from Regulation 13 that applied only on Marine Diesel Engines, it applies also to boilers gas turbines and other on-board devices.

Sulphur Oxides are SO_2 Sulphur dioxide and SO_3 Sulphur trioxides, defined acidic gasses as their transformation generates acidic particles that cause land acidification when left in the environment from acid rains. These compounds transported in short distances (10-100 km) are deleterious for the environment and can damage human's health, plants, and buildings.

The Particulate Matter (PM), very small particles of ash and dust, are generated in complex reactions of chemicals products of fuel ignition. The higher is the content of SO_x and NO_x the most PM is formed. Due to their very small dimensions, PM can be inhaled causing significant health issues, the smaller the particle the highest the damage as. Particles smaller than 10 micrometres can penetrate deep in lungs and reach bloodstream. The inbreath of this substance can cause stroke, asthma, lung cancer, cardiovascular and pulmonary diseases. Progressively with time the percentage in mass of Sulphur allowed in MFOs has been reduced as the table x shows, setting an overall limit of 0.5% m/m and 0.1% m/m in ECAs (see Table 25 & Figure 75).

Table 25 Sulphur Limits [26]

Global sulphur limits	**ECAs Sulphur limits**
4.50% m/m before 1 Jan 2012	1.50 % m/m before 1 Jul 2010
3.50% m/m after 1 Jan 2012	1.00 % m/m after 1 Jul 2010
0.50% m/m after 1 Jan 2020	0.10 % m/m after 1 Jan 2015

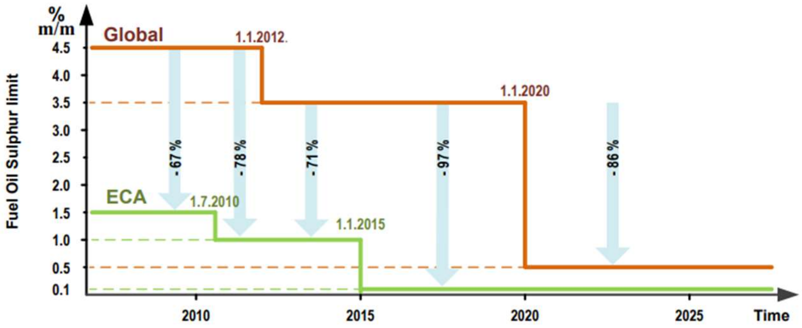

Figure 75 SO_x limits in fuels [26]

The regulation accepts any methodologies agreed by the flag Administration to comply with the emissions limits. This allows the installation of Exhaust gas cleaning systems (scrubbers) according to the guidelines of the MEPC. These methods of reduction of Sox emissions are called secondary methods as the pollutants are removed before they can enter in contact with the atmosphere. This technology allows the use of high suphur content MFOs if the emission limits are complied. The limit entered in force in 2020 according to IMO will cause a 77% drop in global SOx emissions and reduce PM generation.

The **Energy Efficiency Design Index** is presented in Chapter 4 inserted in Annex VI in 2011 and enetered in force in 2013. It includes the control methods and compulsory measures to be applied in order to reduce GHG from ships. The EEDI is a performance-based instrument that defines the least admittible energy efficiency of a ship, depending on its characteristics and a specific formula defined by IMO. The EEDI is defined in grams of carbon dioxide (CO2) per ship's capacity-mile being the smallest the value the most efficient the ship. The CO2 emissions level are lowered every five years as shown in Figure 76.

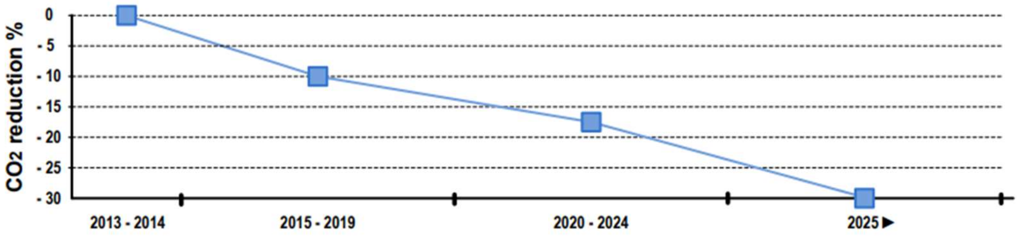

Figure 76 Example of EEDI CO_2 emissions reduction through years

This developing method is adopted in order to stimulate innovation and technical advancement in the ships energy efficiency improvement. Additionally, for ships over 400 GT, the **Ship Specific Energy Efficiency Plan (SEEMP)** is required in order to define methods to improve the fuel efficiency and the ships energy efficiency performance. In relation with the SEEMP some guidelines on how to increase the efficiency of the ship such as using operational techniques are given. These include improved trip planning, speed and power optimization, energy management and control instruments as the Energy Efficiency Operational Indicator (EEOI). The EEOI consent to visualize fuel efficiency while the engine is running evaluate the effect of any change in any modification during ships operation. It considers improved voyage planning, propeller cleaning or substitution or heat waste recovery. The SEEMP is specific for every different ship and must be defined before the emission of the first International Energy Efficiency Certificate (IEEC) required in the ANNEX II of the MARPOL Convention. In 2018 for ships over 5.000 GT was added a new regulation for the Collection and Reporting of Ship Fuel Oil Consumption Data to improve decisional making in ships efficiency increase.

8.1.3 Methods to reduce Cruise ships air pollutants emissions

Concerning the Ships SO_x emissions reduction, the IMO guides to some alternative solutions when fuel oil with a sulphur content lower than 0.50% m/m is not available. For example, it promotes the use of an Exhaust Gas Cleaning System also known as “scrubber” or the use of alternative fuels as Liquified Natural Gas (LNG) or if available the use of On-shore power supply, commonly known as Cold Ironing, preferably powered by RES [19]. The restrictions are applied to every vessel type, sometimes depending on its size, in this study the focus will be made on the Cruise ship sector of which some highlights are listed in the following paragraph.

The Cruise Lines International Association (CLIA) committed to a 40% CO2 emissions reduction by 2030 according to IMO’s targets and to be carbon free by the end of the century. The members of the Association showed their intent in complying with these targets with the implementation of many energy efficiency solutions. A major part of CLIA members adopted the use of ecological, non-toxic, slick hull paint coatings capable of improve fuel efficiency by 5%. Design of bulbous bow that can reduce fuel usage up to 15% if compared with the classical V shape. Use of innovative materials to reduce the ships weight and provide fuel savings. Implementation of heat recycling for HVAC systems, use of LED lights and installation of solar panels to have zero impact energy on board.

In this context of increasing restrictions on emissions and concern about environmental impact the maritime transport sector and the cruise industry is adopting different solutions. Starting from data analysis, optimization, and automation to improve route, trim or other vessel-level decisions as combustible type and engine utilization to the hull design or use of special paintings that reduce drag forces and use of special materials on board to reduce ships weight.

The main solutions adopted to reduce Ships emissions are the followings:

8.1.3.1 Exhaust Gas Cleaning Systems

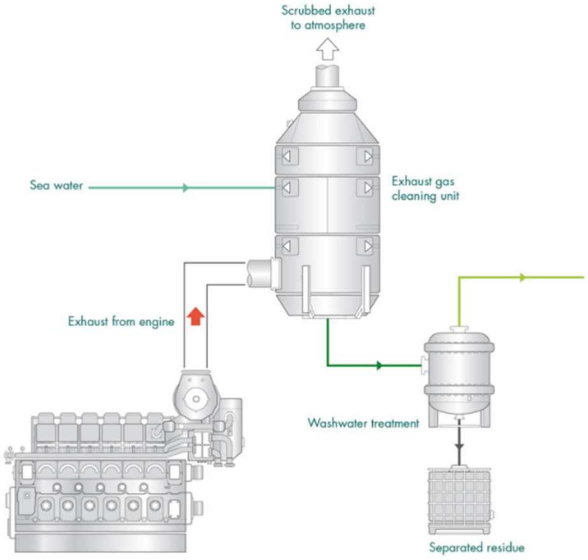

Figure 77 Exhaust gas cleaning system basic components [52]

To comply with IMO’s regulations many of the already existing cruise ships had to install Exhaust Gas Cleaning Systems also known as Scrubbers (device scheme in Figure 77). This technology allows the emissions reduction up to a 98% of Sulphur Oxide and more than 50% of PM permitting the use of High-Sulphur Fuel Oil (HSFO) but at the same time comply with air pollutants emissions limits. Cruise ships and their engines endurance moderates the rhythm of transition to alternative fuels or propulsion, so this is one of the most adopted emissions reduction solutions from around 69% of total passenger’s ship. According to CLIA’s report EGCS application increased over 25% from 2018 in the CLIA’s member’s fleet. In the meanwhile, new greener cruise ships are being built so, only 5% of the new ships to be added at CLIA’s fleet will have this technology on board. In addition to EGCS to further tackle ships emissions also Water Fuel Emulsion (WFE) treatments are applied to heavy fuels and diesel oil. This practice consisting in combining water with the combustible using different methods can reduce NOx emissions to 50% and particulate matter by 90% permitting also a 5% of fuel saving.

8.1.3.2 Alternative Fuels

To reduce the ships environmental impact use of alternative fuels instead of the Marine Fuel Oil is one of the most applied solutions.

8.1.3.2.1 Liquified Natural Gas (LNG)

The first application of Liquified Natural Gas LNG powered cruise ships appeared in 2015 with the deployment of the cruise ship AIDAsol. The ship with dual-fuel engines only while at berth can be fed by LNG trucks onshore reducing the quantity of air pollutants emissions in the harbour. AIDA, after deploying 2 other similar cruise ships, AIDAperla (2016), AIDAnova (2017), added to its fleet AIDAnova in 2018 the first cruise ships powered by LNG also when at sea. The next year Costa launched its first LNG powered cruise ship following AIDA's trend. Actually, according to the CLIA Environmental Report of September 2020 [23], in which is conducted an inventory of the Environmental Technologies and Practices (ETP) 258 oceangoing ships (98.5% of the of existing passenger capacity) and the 76 currently under order, there are 25 LNG powered cruise ships on order or under construction expected to be deployed, showing that the trust of LNG powered cruise ship is going to play a major role in the sector transition. LNG is a tested and efficient technology and its use compared to the traditional maritime fuel oils brings a noticeable emissions reduction. Appropriate engines and before combustion gas treatments allows achieving nearly total SO_x and up to 85% of NO_x emissions reduction. Particulate Matter release in air is decreased and between 95 to 100% of Particulate matter emissions. The CO_2 emissions are only decreased by a small percentage, but the overall GHG emissions are noticeably reduced permitting the new boats to comply with the IMO emissions limits and have a lower impact if compared to traditional technologies. The main technical difference between LNG powered and traditional powered MFO ships is that for the first case a gas turbine is required instead of the traditional Internal combustion Engine. The difficulties encountered by this type of ship powering is the requirement of investment, structure development and global availability. Nowadays only few harbours have the possibility to refuel LNG powered cruises for example in the Mediterranean this service for cruise ships is available only in the harbour of Barcelona.

8.1.3.2.2 Ammonia

Ammonia is another candidate for alternative marine fuel oil being the most promising low emissions fuel. Main advantages are that it can be used in Internal Combustion Engines differently from LNG and it can be stored at ambient temperature. The unfavourable side of its use is its toxicity that requires very cautious procedures in handling it. The technology is not yet present in the market but the technological advancement for ammonia production is already existing. In a few years, appropriate engines are expected to be available [52].

8.1.3.2.3 Hydrogen

The eyes of the cruise and shipping industry are closely watching at the Hydrogen as alternative fuel being the main advantage of its use the zero emissions at the moment of use. The major concern is the fact that still the production of Hydrogen is made by intensive industrial processes making the fuel not yet a green fuel, characteristic that will be achieved only when its production will be 100% provided by RES. Difficulties that hydrogen development is facing are due to its low energy density and the need to be liquified and stored under high pressure making its transportation and storage complex.

8.1.3.3 Energy Storage

Energy Storage provided with electrochemical batteries is taking off for short distance passenger ships but yet this technology is not viable for powering large cruise ships [16].

8.1.3.4 Cold Ironing (CI)

Another option cruise ships, and different vessel types are adopting is Cold Ironing or On-Shore Power Supply, consisting in the provision of electrical energy required by ships at berth from shore.

ANNEX II Cruise Ships equipped to receive shore power

Table 26 lists the characteristics of the cruise ships equipped to receive shore power that visited the Port of Civitavecchia in 2019.

Table 26 CI equipped cruise ships visiting the Port of Civitavecchia characteristics

Ship Name	Passengers' capacity	Gross Tonnage	Length Over All	Estimated Power (MW)
MSC GRANDIOSA	4888	181000	331	12.76
MSC MERAVIGLIA	4488	167600	316	11.75
MSC BELLISSIMA	4488	171600	315	11.75
NORWEGIAN EPIC	4288	155873	329	11.24
MSC SEAVIEW	4134	1531	323	10.85
BRITANNIA	3647	14730	330	9.63
MSC DIVINA	3502	139072	333	9.26
MSC DIVINA	3502	139072	333	9.26
MSC FANTASIA	3274	137936	333	8.68
CELEBRITY REFLECTION	3046	125366	319	8.11
BRILLIANCE O.T.S.	2501	90090	292	6.73
NORWEGIAN STAR	2334	91740	294	6.31
COSTA LUMINOSA	2260	92720	294	6.13
AIDA SOL	2194	71304	253	5.96

ANNEX III Yearly Simulations monthly results

This annex shows the numerical results of the values of electricity purchased, sold, power charge, average power generation and load per month for each scenario visible from Table 27 to 34. These are the values used to create the bar charts of Figure 63 and 62.

Table 27 NoRes and S1 Yearly simulation monthly electricity purchase sale and power charge

NoRes				S1			
Time	**Energy Buy [€]**	**Energy Sale [€]**	**Power Charge [€]**	**Time**	**Energy Buy [€]**	**Energy Sale [€]**	**Power Charge [€]**
Jan	-133193	26189.86	-20340	**Jan**	-126021	31000.17	-20340
Feb	-96308.9	3738.56	-20340	**Feb**	-81562.5	6227.5	-20340
Mar	-106486	1121.48	-20340	**Mar**	-83290.8	2153.31	-20340
Apr	-80763.7	1413.98	-20340	**Apr**	-53474.4	1745.82	-20340
May	-84421.3	0	-20340	**May**	-54796	77.46	-20340
Jun	-91010.2	0	-20340	**Jun**	-55184.7	137.34	-20340
Jul	-142447	0	-20340	**Jul**	-108755	79.81	-20340
Aug	-120474	3655.29	-20340	**Aug**	-93809.3	4864.84	-20340
Sep	-112706	1022.36	-20340	**Sep**	-87000.7	1296.86	-20340
Oct	-65870.4	2065.65	-20340	**Oct**	-46067	2227.17	-20340
Nov	-59091.2	2869.36	-20340	**Nov**	-48583.6	2869.36	-20340
Dec	-88687.2	4216.99	-20340	**Dec**	-80331.1	4216.99	-20340

Table 28 S2 and S3 Yearly simulation monthly electricity purchase sale and power charge

S2				S3			
Time	**Energy Buy [€]**	**Energy Sale [€]**	**Power Charge [€]**	**Time**	**Energy Buy [€]**	**Energy Sale [€]**	**Power Charge [€]**
Jan	-114649	33901.17	-20340	**Jan**	-117564	35921.16	-20340
Feb	-73433.9	7280.99	-20340	**Feb**	-64672.5	8160.78	-20340
Mar	-77332.8	2355.9	-20340	**Mar**	-57224.9	2938.48	-20340
Apr	-51877.7	1745.82	-20340	**Apr**	-29609.2	7586.64	-20340
May	-52447.5	77.69	-20340	**May**	-28666.9	6343.11	-20340
Jun	-54392.4	150.88	-20340	**Jun**	-30258.6	13621.5	-20340
Jul	-105257	79.81	-20340	**Jul**	-74175.7	2354.99	-20340
Aug	-92598	4865.4	-20340	**Aug**	-64727.3	6167.65	-20340
Sep	-80537.5	1365.17	-20340	**Sep**	-60914.8	3884.54	-20340
Oct	-40277.1	2250.22	-20340	**Oct**	-25555.7	3416.65	-20340
Nov	-14028.8	3087.65	-20340	**Nov**	-37353.7	2959.11	-20340
Dec	-55358.6	4216.99	-20340	**Dec**	-71252	4256.15	-20340

Table 29 S4 Yearly simulation monthly electricity purchase sale and power charge

S4			
Time	**Energy Buy [€]**	**Energy Sale [€]**	**Power Charge [€]**
Jan	-106231	38758.81	-20340
Feb	-56702.8	9253.39	-20340
Mar	-51385	3216.71	-20340
Apr	-28259.9	7750.37	-20340
May	-26400.5	6397.7	-20340
Jun	-30039.6	14140.85	-20340
Jul	-70765.3	2357.01	-20340
Aug	-63536.3	6180.1	-20340
Sep	-54805.3	4152.94	-20340
Oct	-21204.3	4776.13	-12288.2
Nov	-11820.3	11540.78	-8253.72
Dec	-46469.6	4264.03	-20340

Table 30 Yearly simulation NoRes average generation and load values per month; values in kW.

Month	FG6MW Gen	Total Load	BESS Gen	BESS Load	FG6MW Load
Gen	2699	-1984	1405	-1711	-409
Feb	2157	-1846	1107	-1348	-70
Mar	2135	-1882	1089	-1326	-16
Apr	1716	-1503	860	-1048	-25
May	1721	-1535	852	-1037	0
Jun	1908	-1714	895	-1089	0
Jul	2845	-2566	1284	-1564	0
Aug	2457	-2135	1206	-1468	-60
Sep	2341	-2086	1094	-1332	-17
Oct	1387	-1208	673	-819	-32
Nov	1286	-1094	650	-792	-50
Dec	1809	-1540	900	-1095	-73

Table 31 Yearly simulation S1 average generation and load values per month; values in kW

Month	FG6MW Gen	Total Load	BESS Gen	BESS Load	PV1234 Gen	PV56789 Gen	FG6MW Load
Gen	2569	-1984	1381	-1681	148	60	-492
Feb	1829	-1846	969	-1180	247	100	-119
Mar	1683	-1882	947	-1153	312	126	-34
Apr	1131	-1503	649	-791	389	158	-32
May	1123	-1535	669	-814	398	161	-2
Jun	1158	-1714	587	-714	488	198	-3
Jul	2186	-2566	990	-1205	425	172	-2
Aug	1910	-2135	897	-1092	356	144	-81
Sep	1823	-2086	930	-1133	347	141	-22
Oct	969	-1208	436	-531	263	106	-35
Nov	1057	-1094	496	-604	139	56	-50
Dec	1635	-1540	785	-956	106	43	-73

Table 32 Yearly simulation S2 average generation and load values per month; values in kW

Month	FG6MW Gen	Total Load	BESS Gen	BESS Load	PV1234 Gen	PV56789 Gen	WSax Gen	REWEC3 Gen	FG6MW Load
Gen	2348	-1984	1363	-1660	148	60	94	174	-544
Feb	1655	-1846	956	-1164	247	100	71	121	-140
Mar	1560	-1882	913	-1112	312	126	26	93	-38
Apr	1096	-1503	634	-772	389	158	30	2	-32
May	1077	-1535	659	-802	398	161	12	33	-2
Jun	1141	-1714	581	-708	488	198	0	16	-3
Jul	2113	-2566	970	-1181	425	172	18	49	-2
Aug	1886	-2135	892	-1087	356	144	3	20	-81
Sep	1697	-2086	926	-1127	347	141	40	87	-23
Oct	847	-1208	402	-490	263	106	24	91	-36
Nov	304	-1094	247	-301	139	56	262	441	-54
Dec	1126	-1540	637	-776	106	43	166	311	-73

Table 33 Yearly simulation S3 average generation and load values per month; values in kW

Month	FG 6MW Gen	Total Load	BESS Gen	BESS Load	PV1234 Gen	PV56789 Gen	PV10-11 Gen	WSax Gen	REWEC3 Gen	FG 6MW Load
Gen	2189	-1984	1355	-1650	148	60	250	94	174	-636
Feb	1279	-1846	939	-1144	247	100	417	71	121	-184
Mar	1047	-1882	898	-1094	312	126	527	26	93	-55
Apr	592	-1503	699	-852	389	158	656	30	2	-170
May	542	-1535	703	-855	398	161	672	12	33	-129
Jun	631	-1714	745	-907	488	198	824	0	16	-282
Jul	1434	-2566	937	-1141	425	172	717	18	49	-46
Aug	1293	-2135	817	-995	356	144	601	3	20	-105
Sep	1153	-2086	866	-1054	347	141	586	40	87	-79
Oct	445	-1208	371	-451	263	106	444	24	91	-84
Nov	256	-1094	367	-446	139	56	235	262	441	-215
Dec	942	-1540	607	-740	106	43	178	166	311	-73

Table 34 Yearly simulation S4 average generation and load values per month; values in kW

Month	FG6MW Gen	Load EE Total	BESS Gen	BESS Load	PV1234 Gen	PV56789 Gen	PV10-11 Gen	FG6MW Load
Gen	2411	-1984	1379	-1680	148	60	250	-585
Feb	1453	-1846	964	-1174	247	100	417	-161
Mar	1168	-1882	931	-1133	312	126	527	-49
Apr	621	-1503	709	-863	389	158	656	-166
May	587	-1535	710	-865	398	161	672	-128
Jun	636	-1714	739	-900	488	198	824	-271
Jul	1504	-2566	951	-1158	425	172	717	-46
Aug	1317	-2135	820	-999	356	144	601	-105
Sep	1284	-2086	912	-1110	347	141	586	-73
Oct	537	-1208	379	-462	263	106	444	-59
Nov	812	-1094	442	-539	139	56	235	-52
Dec	1447	-1540	738	-899	106	43	178	-73