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

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Abstract— **Cold Ironing (CI) is progressively being more implemented to decrease berthed ships emissions in ports. Big sized Cruise Ships are the most energy-intensive vessels that commercial harbours can host. Providing shore power to them is so a complex task. The port of Civitavecchia is one of the top world's ranked for Cruise Ships traffic and shortly will need a CI infrastructure. The provision of shore power for Cruise Ships may request up to 14 MW while the most powerful power connection of the port can only deliver a max of 6 MW. To exclude installing a higher rated substation the opportunity of implementing a high power and large capacity Energy Storage System is studied. The first section of this paper consists in a literature review of the state of the art of CI. Successively, the port's grid is analysed along with the existing and additional Renewable Energy Sources (RES) available in the port. It follows the determination of the characteristics of the ESS and its dimensions (power and capacity). To finish the performance of the new designed port's grid will be examined with the help of an Energy Management Simulation Software (EMSS) developed by Falck Renewables – Next Solutions.**

I. INTRODUCTION

The rise of attention toward the problem of Climate Change and environmental degradation increasingly leads towards the implementation of actions to reduce them. In the last decades air pollution reduction has been controlled by the Montreal Protocol (1987), the Kyoto Protocol (1997), the Paris Agreement (2015) and many other regulations.

Maritime transportation is responsible of the 2.5% of the global greenhouse gas emissions and is expected to grow between 50% and 250% by 2050. Thus, in 2005 Annex V of the MARPOL Convention was introduced and became the first international regulation on ship emissions [1].

To reduce ships emissions different solutions are implemented and Cold Ironing (CI) represents one of the most effective when ships are at berth. CI consists in delivering electricity to ships from shore facilities in order to power onboard utilities turning off their auxiliary engines. This practice allows to cut of local air pollutants emissions and noise pollution generated from the ship's engines, generating a better liveability of the surrounding area.

The power to be delivered to the different vessel types varies according to their size and the on-board facilities. Cruise Ships are the largest vessels that commercial harbours can host and represent the most energy-intensive ship's type. While at berth their power request can reach up to 14 MW requiring the shore electrical infrastructure to be reasonably sized. Not every port can support such a high-power request, as it is the case for the port of Civitavecchia that only can provide 6 MW from its highest rated point of delivery (POD).

Civitavecchia's port is one of the world's most visited by Cruise Ships with up to 800 calls in a year. The ships traffic increased the surroundings air pollution pushing the port towards investigating the feasibility to implement a CI infrastructure.

To better understand the CI technique and its implementation this paper analyses as case study the Port of Civitavecchia. More particularly it researches how the port can implement it avoiding the adoption of a new High Voltage (HV) and high power rated substation, that would mean high investment and maintenance costs, new personnel and a large area, also risking underutilising the new electrical infrastructure when ships are not requesting power connection.

II. LITERATURE REVIEW

Cold Ironing can be studied from different perspectives:

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.

This section reviews relevant studies related to the CI implementation.

[2] Gives a clear overview of the technologies existing all over the world by 2008. The project has been written before the emission of the ISO 80005-1 (produced in 2012) and helped in its development. The work consists of a market review of the existing technologies, a technical survey where the power generation on board, power demand, frequency and voltage are analysed by ship type. Also includes 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 and simulations on the implementation of the CI infrastructure in a typical harbour.

[3] contains a deep literature review on port's emissions inventories, CI emissions reduction capacity and its historical roots. The study presents the status of CI in the world and successively highlights its challenges and opportunities providing an overview of the impact CI infrastructure can have economically and environmentally also analysing the problem with three different scenarios varying the fuel price. It results 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.

Calculating the precise power consumption profile of a ship is a very difficult task, and typically to obtain this data port authorities interview crew members of the boat or the shipowner. Anyway, accurate data is always difficult to obtain. Generally, ships energy consumption patterns are needed to prepare Port Emission Inventories, and [4] redacts which are the methodologies and the practices that port owners adopt to predict vessels air pollutants emissions.

The introduction of CI into an existing port is often taken as case study [5] does it for the Cruise port of Barcelona. The study describes the port's cruise terminal, the air pollution regulations, rules and design for the electrical infrastructure. It ends with the design of the CI infrastructure in the port and simulations 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. Results show that the adoption of such an infrastructure can bring 96% CO_2 emission reduction.

Similarly, [6] studies the port of Barcelona considering all type of ships visiting the port. The paper introduces CI state of the art and the regulations active in the port of Barcelona. Consequently, it proposes to implement CI to all ship types fully powered from RES. From the creation of a typical weak power curve, estimated from the sum of all the ships power demand, comes out that the average power request is of 221.9 MW. From simulations performed through Matlab-Simulink come out that the number of PV panels and Wind Turbines are to satisfy the vessels power request is 177 and 29 respectively.

Energy Storage is combined with CI in [7] where a Complex Compressed Air Energy Storage system in the harbour of Ancona to support CI to Ro-Ro ships. The system, composed of a cogeneration power plant, allows to increase the energy efficiency and decrease the cost of energy. It can deliver the waste heat to residential buildings next to the harbour and allows to reduce ships emissions showing how complex solution like this may bring environmental and economic benefits.

[8] Combines the CI technique with Smart Grids in ports as a solution to decrease port's environmental impact. The study affirms that from the integration of Smart Grids and CI facilities an environmental benefit must be expected but their feasibility needs to be evaluated. The paper shows three possible configurations for the electrical distribution for CI:

- 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.

The study follows by associating the topic to R&D aspects such as the integration with local RES or low carbon production, ESS, Power Management Systems (PMS), usage of power converters that can maximise the performance of interfaces. 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.

[9] Analyses ports 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. That require an Energy Master Plan, and their power systems need a comprehensive design. From the authors perspective port power systems are expected to be developed towards the introduction of information and communication technologies, environmental protection and the logic of liberalisation of markets. Business Continuity Management (BCM) is considered the solution to achieve the latter objectives. The proposed R&D points for ports proposed 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. Similarly, to [11] associates ports with Smart Grids to allow the decrease of chaotic phenomena of port utilities dispersion. The authors also underline how power flow could be inverted in CI infrastructure being the vessels a power source for the port's grid.

[10] consists into a previous work that was used as a starting point for this paper. 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.

III. COLD IRONING FOR CRUISE SHIPS

A. *Definition and Infrastructure*

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 [3].

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).
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 preferably electro-mechanically controlled to avoid handling of the cables.
f. Socket on board of the ship to connect the cables.
g. On-board transformer to adjust voltage according to ships requirements.

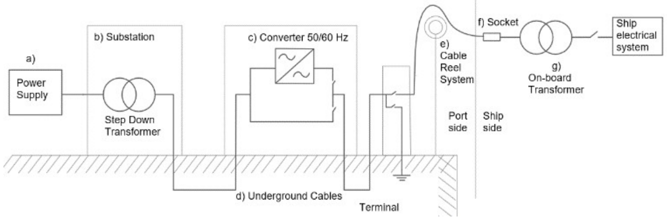

Fig. 1. Cold Ironing electrical infrastructure scheme

Cruise Ships electrical connection is performed through 4 cables and one neutral connection to support the high power required.

B. Benefits

CI allows ports and their surroundings to become more liveable areas by reducing air pollutants emissions and the impact of noise and vibration generated from ships engines. Most of the times inland power generation relies on more efficient and less polluting technologies than those used on board. Hence the overall energy consumption impact from ships can be reduced. Additionally, passengers' comfort is improved thanks to noise and vibration reduction as it occurs for conditions to perform maintenance or nearby port's operation. For shipowners and ports practicing CI public perception may increase and, in some cases, also receive incentives or rewards for being environmentally friendly.

C. Challenges

CI practice is not an easy task due to different reasons, technological and economic-related. Mainly represented by the high investment costs of onshore and on-board infrastructure. According to [11], onshore infrastructure can cost from 1 to 15 million dollars while ships retrofit ranges between $ 400.000 and $ 2.000.000 depending on vessel type and electrical system design. Incentives may help overcome this economic barrier. Furthermore, the cost of electricity produced onboard is, in most of the cases, extremely less expensive than that produced in land due to the low marine gas oil prices. This market unbalance pushes shipowners to prefer producing the required energy onboard rather than purchase it from ports. A solution already considered in the Council Directive 2003/96/EC [12] is the detaxation of electricity.

From the technical point of view powering large ships requires HV and high-power availability and ports power systems may need to be upgraded, resulting into complex and expensive infrastructures. Typically, the first explored solution to do so is developing a connection to the national HV network. Another issue is represented from the difference that may be encountered between ship and shore electrical operation frequency. In America most of the inland power system relies on 60 Hz frequency whereas in Europe and most of the countries in Africa and Asia use 50Hz. Nearly all the global ship fleet (99%) adopts 60Hz frequency. When harbour and ship grid frequency do not match a frequency converter is required, increasing the overall cost of the infrastructure.

D. Diffusion of the Infrastructure

The development of CI infrastructures was pushed by the introduction of ISO/IEC/IEEE 80005-1:2012 introduced in 2012 [13], the first international standard on High Voltage Shore Connection. In addition to the technological standard, the increase of restrictions on air pollutants emissions encouraged shipowners and ports to adopt the CI infrastructure or investigate its feasibility. The most important policy on emission reduction for maritime transportation, entered into force in 2005 is Annex VI of the MARPOL Convention [27] where limits on NOx and SOx emissions are imposed for maritime transport.

E. Cruise Ships CI

The power required at berth by vessels depends on their size, typology and onboard facilities. Table 1 shows the Typical power requirement of different ships type.

TABLE 1 TYPICAL VESSELS POWER REQUIREMENTS AND BERTHING TIME

Vessel Type	**Power Required (kW)**	**Berth time (hours)**
Auto/RoRo	800	24
Container	1400	48
Reefer	3000	60
Cruise	6000	10

Cruise ships are the largest passengers ship type of the world, capable to host up to 5 000 passengers reaching the overall length of 360 meters. Their high number of utilities on board makes them the most power-requiring vessels that combined with long time stays results in consistent energy consumption. To provide electrical energy from shore it is so required a high power rated infrastructure and the possibility to deliver a large amount of energy.

Modern cruise ships are equipped with diesel engines or gas turbines that power an electric propulsion (see Figure 3).

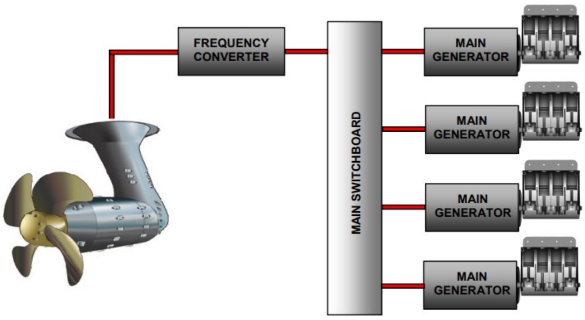

Fig. 2. Cruise Ships Power Train [5]

At berth only a few generators are kept on satisfying the ships on board load. The elevated power rating requires to operate at medium voltage levels typically 6.6 kV or 11 kV. The whole cruise fleet with a length over 200 meters adopt 60 Hz as electrical frequency.

The Onshore Power Supply infrastructure requirements are presented in the above mentioned international standard ISO/IEC/IEEE 80005-1:2012 [13]. The Ci infrastructure for cruise ships should be rated at 16 MVA and, when feasible, at 20 MVA. Even though, the standard allows also to adopt lower power ratings if the cruises calling at the port require less power capacity. The connection must be performed with 4 cables with standardised plugs.

F. Infrastructures around the World

The ports with CI infrastructure capable to power cruise ships are listed in Table 2.

TABLE 2 CRUISE SHIP COLD IRONING EXISTING INFRASTRUCTURES

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

* Only in shipyard

The first harbour to power a berthed cruise ships from shore has been the port of Juneau in Alaska in 2001 supplying for 10 hours a Princess Cruise Lines ship with the excess of energy produced from a hydro powerplant.

G. Policies

Policies on air emissions reduction for maritime transport promoted the diffusion of the CI infrastructure and often this technique has been suggested to comply with the emission reduction. It is the case for the first regulation on ships air pollutants emission entered into force in 2005 with the amendment of Annex VI of the MARPOL Convention [14].

The first attention EU towards CI came from the need of reducing ships emissions. In 2005, the EU Commission, anticipating the Annex VI (MARPOL Convention) restrictions, with DIRECTIVE 2005/33/EC [15] 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. However, this directive explicitly exempts from this restriction ships that receive electricity from shore.

Successively, in 2006 **Commission Recommendation 2006/339/EC** [29] "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. In 2014 **Directive 2014/94/UE** [16], on the deployment of alternative fuels infrastructure, was published. The Directive encourages states to implement policies to promote CI practice and put as a priority the adoption of CI infrastructures by 31st December 2025 for major EU ports.

For what concerns incentives to stimulate CI, article 19 of the directive of the **Energy Taxation Directive** [12] 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".

IV. THE PORT OF CIVITAVECCHIA

H. Description

The port of Civitavecchia is the biggest harbour of the Tyrrhenian Sea, founded by romans in 108 A.D. it is positioned 70 km north of Rome. The port operates under the Port Authority of the Central Northern Tyrrhenian Sea and its electrical infrastructure and energy contracts are managed by Port utilities S.p.A. The port is undergoing some renovations that when finished will allow the port to host boats up to 400 meters long. 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.

I. Port's electrical Grid

The port electrical grid has been designed to always offer the highest quality of and most reliable service to its users. It 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. The connected users in 2020 where 333 of which 7 in MV. The three MV POD ratings are listed in Table 3, with their consumption characteristics.

TABLE 3 MV POD POWER RATINGS, PEAK AND AVERAGE POWER CONSUMED

POD	A (Flavio Gioia)	B (Largo della Pace)	C (Varco Nord)
Rated (kW)	6000	3000	300
Peak (kW)	2090	618	60
Day - Time of Peak	14/08/2021 21:00	10/09/2021 21:00	25/02/2021 21:00
Avg (kW)	1155	168	29
MWh/year	10117	1473	252

The total capacity of the MV infrastructure is 9.3 MW and the highest peak reached in 2019 from the power request is 2386 kW on the 14th of August at 9 pm. From Table 3 is possible to see that POD A is the most used reaching a peak of 2 MW. This POD satisfies most of the loads in the central side of the port and in case of a CI infrastructure would be the one that will power it. The port's energy consumption in 2019 reached 11.8 GWh and is characterized by a strong seasonal pattern, with higher consumption in summer and lower in spring as visible in Figure 4.

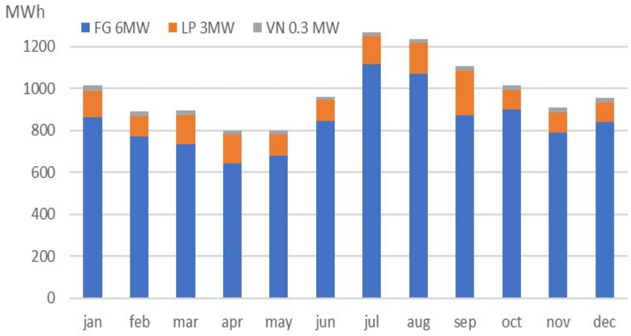

Fig. 3. Monthly Energy Absorption by POD

J. *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. As is determined by the law 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.

K. *Distributed Generation*

1) *PV Systems*

The harbour is in possess of 5 different PV systems whose capacity is listed in table 4.

TABLE 4 PV SYSTEMS CHARACTERISTICS

PV	PV1	PV2	PV3	PV4	PV5	Total
Power (kW)	115	583	1 100	15	75	1 889

Their yearly energy production is estimated to be 2 741 MWh. In addition to the existing PV systems other can be installed to increase the port's distributed generation capacity. Table 5 shows the power ratings of the installable PVs systems. With the addition of these PVs the total energy produced could increase to 8.17 GWh a year covering 63% of the port's energy consumption.

TABLE 5 INSTALLABLE PV SYSTEMS CHARACTERISTICS

New PV	PV6	PV7	PV8	PV9	PV10	PV11	Total
Power (kW)	180	102	200	300	1933	1666	4381

The monthly energy production of the PV systems is plotted in Figure 5.

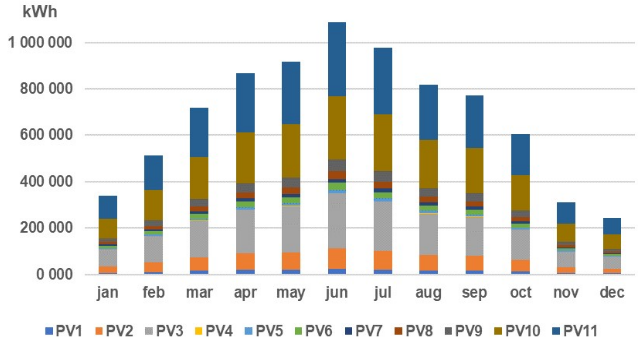

Fig. 4. PVs energy Production with additional PV systems

2) *Wave Energy Converters*

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. The conversion of wave energy can be performed with different devices, one of of the most reliable ones is 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 an 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 usually incorporated into breakwaters.

The port of Civitavecchia has installed a set of breakwaters with these characteristics, this consists of 17 caissons each provided by 8 semi-submerged chambers. The name of this OWC is REWEC3 Resonance Wave Energy Converter 3. To date the device has no turbines installed, but it is possible to equip each chamber with a 20-kW turbine allowing the whole OWC set to reach 2.72 MW of rated power.

Data on the energy production of this device where not available and so the following method has been used to estimate a yearly power curve:

- Determination of the generator power output by different sea conditions.

- Creation of a Time series of the sea conditions over a year (2019).
- Creation of the estimated hourly power curve of the turbine Generator.

For the first step Paper [17] has been consulted as it considers 12 different sea states characteristics of the REWEC3 location. The paper considered also gives the relative power outputs of the installable turbine generator in these sea states. By considering the yearly timeseries of the sea conditions and associating it with the different sea states and turbine power output it has been possible to create an estimated hourly power curve. The REWEC3 estimated energy production in a year is 1.1 GWh with the monthly energy production showed in Figure 6.

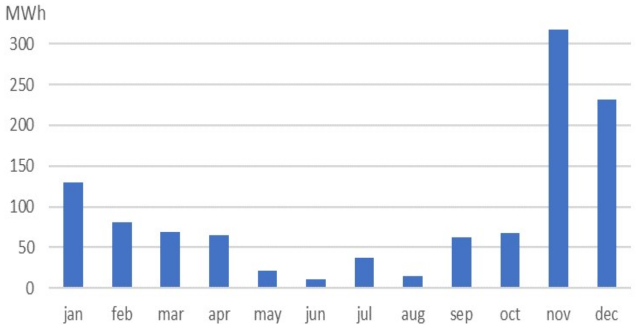

Fig. 5 Monthly estimated REWEC3 Energy Production

To exploit wave energy another device can be installed in the port and this is the WaveSax an OWC device developed by Gestore del Servizio Elettrico and Ricerca sul Sistema Elettrico S.p.A. Its turbine is located under the mean sea level and operates with sea water as a fluid [18]. This device is relatively small device and can be easily installed on the port's main breakwater. In the future, 500 devices are expected to be installed on the port's main breakwater. 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 yearly power curve estimation of the WaveSax has been obtained with the same methodology used for the one of the REWEC3. The power curve in [18] has been used.

L. Cruise Ships

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. 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 [19], resumed in Table 6. 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 6 CRUISE SHIP POWER DEMAND PER PASSENGERS CAPACITY

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

From these values, the power required by every ship in function of their passenger's capacity equation $P_{hot} = 2.5232 \cdot p + 428.33$ (1) has been computed. Where P_{hot} is the power required at hotelling by the cruise ship and p is the number of passengers.

The biggest ship visiting the port is Oasis of The Seas with 5592 passengers and an estimate power request of 14.53 MW. This value of power noticeably overcomes the capacity of the port's highest rated MV POD (6 MW) and will require a power upgrade of the port's delivery infrastructure.

Cruises calls increase during the summer months due to the increase of touristic traffic and the most visited quay is 12 BN with a total of 237 visits. For this reason, it is selected as the one that will host the CI infrastructure to increase its utilization factor. Of the 237 cruise ships calling at the pier only 44 are fitted to receive CI. From the schedule and the power request estimation a yearly power curve of the CI infrastructure is obtained.

V. ENERGY STORAGE SYSTEM

Typologies

Energy Storage Systems can store energy into a particular form and release it when requested. ESS can be classified into 4 main typologies:

- **Electrical Energy Storage (EES)**

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

- **Mechanical Energy Storage**

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

- **Chemical Energy Storage**

Electrochemical Energy Storage: Batteries;
Chemical Energy Storage: Fuel Cells; Metal-Air batteries
Thermochemical Energy Storage: Solar Hydrogen.

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

The main characteristics of the different ESS can be appreciated in Figure 7.

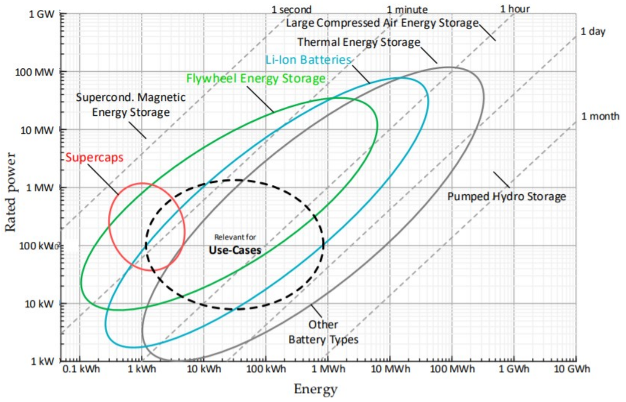

Fig. 6 Power rating and Energy capacity of ESS [20]

M. *ESS Functions*

ESSs can be used for different purposes at the different power system levels [20]. At the Generation level ESS can be used for different purposes such as commodity storage, contingency service, area control, frequency regulation and black start. At the Transmission and Distribution level ESS are used for system stability maintenance, voltage regulation maintenance and asset deferral consisting into the delay of the installation of new transmission lines, by installing an ESS the underusage and capital expenses of new lines will be avoided.

At the Energy Service level ESS allow a better energy management consenting to shift energy demand through peak shaving and so reducing the time of usage charges. also, a higher power quality provision. Moreover, power reliability will be increased permitting uninterrupted power supply, the capacity of delivering power with no interruption.

Intermittent generation of RES requires demand flexibility, backup power sources and ESS, the following practices are used to increase the res effectiveness. transmission curtailment time-shifting forecast hedge, grid frequency supports fluctuation suppression.

N. *ESS for the Port of Civitavecchia*

The purpose of use of the ESS in the Port of Civitavecchia is to fill the gap of power required from cruise ships that the port's grid cannot satisfy. Hence, the ESS requires to be of high-power and high-energy capacity, relatively fast charge, a daily discharge rate with an elevated number of life cycles.

From the above-mentioned typologies, the most suitable for the port's scope and the required features are PHES, CAES, Fuel Cells and BESS. The first two are large area requiring and the absence of a basin or a cave where to store water or air respectively excludes these two types of storage systems. Fuel Cells technically represent a very good solution, but its high costs lead to the exclusion of it. Hence, the selected typology to be used for the study is based on batteries particularly Li-ion as it is the most efficient and flexible of this technology.

VI. SIMULATIONS

O. *The Energy Management Simulation Software*

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.

P. *Simulation Data*

The CI infrastructure is expected to be connected on the Flavio Gioia POD rated 6 MW and with a 10 GWh of yearly consumption. The energy contract of the utility company of year 2019 has been consulted and used into the simulations. The purchase of energy is made according to band rates being the peak equal to 82.733 €/MWh, standard 79.268 €/MWh and off-peak 63.756 €/MWh. Electricity is sold to the grid at the zone price that in this case is the Centre-South of Italy's energy market found at [50].

Q. *Sizing the ESS*

The BESS must supply enough power to the port system to satisfy the estimated total load. It is required to determine the BESS power rating and total capacity. The BESS is going to be of Li-ion technology, maximum and minimum State of Charge (SoC) will be of 90% and 5% respectively of its nominal capacity. The Depth of Discharge (DoD) will be set to 85% of its nominal capacity. The capital investment cost is considered to be 297.5 €/kWh.

The BESS is sized over a year time perod in the worst-case scenario occurring when no RES are available in the port's grid and only the BESS and the Grid can provide power to the loads.

The minimum power of the BESS to satisfy the given loads has been determined as follows. It has been chosen as starting point the value of P_1 corresponding to:

$$P_1 = P_{\_peak\_Load} - P_{Grid} \tag{2}$$

$$P_1 = (14.23 - 6)\ \mathrm{MW} = 8.23\ \mathrm{MW} \tag{3}$$

Where $P_{\_peak\_Load}$ is the peak reached from the total load over a year (14.23 MW) and P_{Grid} is the power that the Flavio Gioia's POD can deliver (6MW). From this value simulations have been performed increasing the BESS power by 100 kW and keeping its energy capacity constant. The power to be selected from the simulation is the minimum obtained that allows to satisfy the loads without requiring any extra power to do it. The real capacity of the BESS for these simulations was set to 110 MWh. This value has been chosen as does not interfere with the power determination considering that the longest continuous power request higher than the grid capacity occurring on December 29th requires from 7 AM to 7 PM a total energy equal to 165 MWh. As during this period, the port's grid with a constant power output of 6 MW is capable to provide 72 MWh the remaining energy to be supplied at the same time would be 93 MWh a value way lower than the one considered, this confirms that the energy capacity given to the BESS in these simulations will not interfere with the power determination results.

To determine the BESS capacity, it has been proceeded similarly to what was done for the power. Keeping the power of the BESS constant to the previously determined value, while the real capacity of the BESS was decreased by 1 MWh in each performed simulation until it was found the last feasible value according to which the load was satisfied without requiring extra energy. So, starting from 110 MWh the minimum value of the real capacity of the BESS with the power of 8.73 MW 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 so 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 €.

R. Yearly Simulations Analysis

To evaluate the BESS and RES integration into the port's grid 5 different scenarios have been studied. The difference between each scenario resides in the RES available, their characteristics are exposed in Table 7.

TABLE 7 CHARACTERISTICS OF THE SIMULATION'S SCENARIOS

Simulation	**NoRes**	**S1**	**S2**	**S3**	**S4**
Port Load	x	x	x	x	x
CI 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 previously sized BESS, excise duty for large customers, sale of energy at the zone price, a yearly fixed total cost of 981.75 € for the connection to the National Grid a monthly peak power cost of 3.4 € /kW. Capex of the new PV technologies are considered to be 1 000 € /kW, for the REWEC3 and the WaveSax 6 756 € /kW and 7 000 € /kW respectively. While Opex costs for the three technologies are 21 € /kW/year, 85 € /kW/year and 51 € /kW/year respectively in order. Capex will only be considered in multiyear simulations. The yearly simulations main results are listed in Table 8 & Table 9.

TABLE 8 YEARLY SIMULATIONS MAIN RESULTS

	Purchased Energy [MWh]	Sold Energy [MWh]	Res share	Res Gen [MWh]	BESS NCycle
NoRes	17 752	462	0%	0	79.15
S1	13 934	691	15%	3 711	64.97
S2	12 316	751	22%	5 301	61.25
S3	8 626	1 501	38%	9 759	62.03
S4	10 065	1 291	32%	8 169	64.53

The port yearly load reached a maximum of 26 GWh in *NoRes* and a minimum of 24.3 GWh in *S3* in all the simulations ranged around 25 GWh. It varied depending on the BESS utilisation as load while in charging mode. Sold and Purchase energy varies depending on the RES available. Sale of energy increases as RES share rises while is the opposite for the energy purchased bringing an economic benefit to the system. The BESS number of cycle 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. These results show how the BESS is predominantly used to satisfy the high load of the CI infrastructure as when operating only for the port's users load it result to be oversized.

TABLE 9 ECONOMIC YEARLY SIMULATIONS MAIN RESULTS

	Cost of operation [k€]	Buy [k€]	Sale [k€]	Grid Tot Cost [k€]	Opex [k€]
NoRes	2 015	462	38	1 379	635
S1	1 795	691	56	1 106	689
S2	2 220	812	61	995	1 224
S3	1 954	568	113	678	1 275
S4	1 552	662	98	808	743

Over a year the less expensive configuration concerning the port's grid operation is *S4* 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 8). 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.

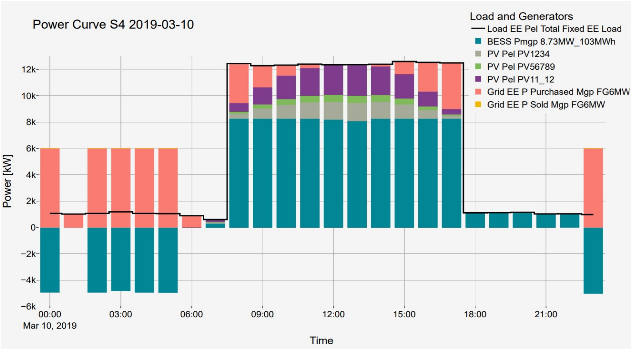

Fig. 7 10th of March power Curve

S. *Port's Grid Performance*

The 21st 22nd and 23rd of December are considered as a case study. 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 (S3 in Figure 9). 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.

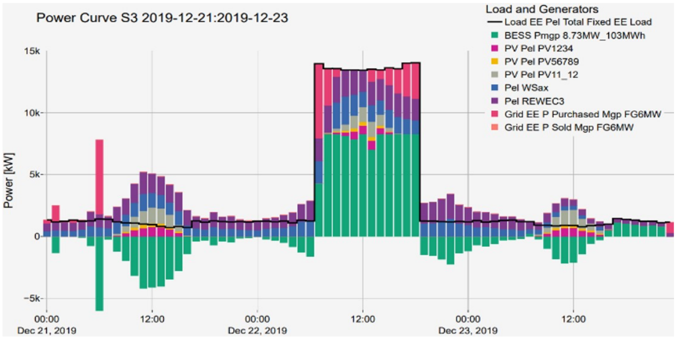

Fig. 8 December 21st to 23rd power curve *S3*

T. *Multiyear Results Analysis*

Multiyear simulations are run over a 20-year period to evaluate the performance of the system over the years. These are done with a hurdle rate of 7% to compute Net Present Value (NPV), additionally Capex of the RES are considered. Main results are in Table 10.

TABLE 10 RESULTS OF MULTIYEAR SIMULATIONS BY SCENARIO

	Total [k€]	LCOE [k€]	NPV [k€]
NoRES	75 097	11.9	-58 199
S1	71 153	10	-56 294
S2	121 503	19.8	-102 676
S3	117 962	4	-101 795
S4	67 946	2.5	-55 611

From the results emerges that *S4* is the less expensive scenario with approximately 68 billion € spent in 20 years, followed by *S1* and *NoRes*. The LCOE related to the different scenarios is highly influenced by the presence of PV systems, it is the lowest in S4 (2.5 k€/MWh), followed by S3 (4.06 k€/MWh). S1 and NoRes have an LCOE of 12 k€/MWh and 10 k€/MWh respectively while S2 is the highest with approximately 20 k€/MWh. The LCOE highly decreases in *S3* and *S4* as PV 10 and 11 allow to reduce drastically the purchase of energy from the grid. Contrary, the introduction of WECs at this high Capex and Opex costs rises the LCOE as it can be seen comparing S1 with S2.

Concerning NPV, all resulted to be negative. Anyway, they can be used to compare the different scenarios economic attractiveness, being the lower in absolute value the best. The most economically attractive scenario that is *S4* with -56.6 billion € a few points less than *S1* and *NoRes*. *S2* and *S3* almost double these amounts reaching -102.7 billion € and -101.8 billion € 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.

Over the analysed period it comes out that the BESS SOC is expected to decay of a maximum of 10% (in *NoRes*). This decrease of real capacity does not influence the performance of the system where the loads can still be fully satisfied. The maximum number of cycles reached are in *NoRes* being 1 636 and the minimum in S4 with 1333 cycles in 20 years. Theoretically the BESS could operate still for different years as Li-ion batteries are characterised by 6 thousand life cycles.

VII. CONCLUSIONS

This study consists of two parts: the description of cruise ships CI technique and the case study of the port of Civitavecchia. Cruise ships CI is exposed giving an outlook on the state of the art, the policies and the international standard in the initial chapters. Advantages of its implementation are the reduction of local GHG emissions and compliance with regulations on air pollutants emission. Difficulties occurs in providing from the port's electrical system the adequate power to these high-energy consuming vessels. To satisfy the high loads involved for the case study of the Port of Civitavecchia it is proposed solution to implement a large-scale ESS to increase the port power capacity and RES infiltration potential. 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.

This study is the first one in the literature consider the usage of Wave Energy in port's areas to power CI infrastructures analysing its performance.

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 5.27 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 9 & 10, 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 maximum number of cycles expected from the BESS designed in a year are 79, when no RES are considered. 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.

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

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

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

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

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

[6] 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.

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

[8] 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.

[9] 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.

[10] 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.

[11] IMO Train the Trainer (TTT) Course on Energy Efficient Ship 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]

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

[13] 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.

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

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

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

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

[18] 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].

[19] 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.