Optimal Management of a Port considering Shore-side Power and Electrical Vessels

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***Abstract*— Maritime ports play a vital role in global economic activity and international trade, with shipping being the most efficient and widely used method for cargo transportation. Given this significance, the sector is facing increasing challenges due to national and international decarbonization targets. One of the key solutions being implemented is the Shore-Side Power (SSP)—the connection of ships to the port's electrical grid while docked—which fundamentally transforms the role of seaports and demands new approaches to power and control infrastructure. This paper proposes linear optimization considering two scenarios. Both scenarios address energy management within a port, incorporating SSP alongside internal distributed energy resources such as controllable loads, photovoltaic (PV) generation, battery energy storage systems (BESS), and a fleet of electric vehicles. The scenarios differ in the number of ships that are docked in the Port. In the first Scenario it is assumed that three cruise ships are docked (full capacity). In the second Scenario it is assumed that no Cruises ships will use the Port. The scenarios were developed considering the application in Port of Funchal in Portugal.**

Keywords—Maritime Transportation, Shore-Side Power, Ramping, Flexibility management

I. Introduction

A. Motivation

Maritime ports are an important hub for passengers and marine transportation, playing a vital role in economic and international trading [1]. Shipping is the most efficient and common method for transportation of any cargo. In the era of globalization and the rapid expansion of world trade, ports are crucial links in contemporary supply chains and logistics processes, serving as transport hubs with their inter-modal transport networks (sea, road, rail and inland shipping) [2].

International shipping, particularly maritime transportation, is a significant contributor to global greenhouse gas emissions arriving at 2% of CO_2 emissions [3]. As over 80% of global trade by volume is carried by sea, the sector emits substantial amounts of carbon dioxide (CO_2), along with other pollutants such as sulfur oxides (SO_x) and nitrogen oxides (NO_x). These emissions primarily result from the combustion of heavy fuel oil in large cargo vessels. Despite being more energy-efficient than other transport modes per ton-kilometer, the sheer scale of global shipping leads to a considerable environmental footprint. The International Maritime Organization (IMO) has recognized this impact and is working to reduce emissions through regulations and initiatives, including the introduction of cleaner fuels, improved vessel designs, and enhanced operational efficiency [4]. However, achieving significant reductions remains a challenge due to the sector's complexity and the international nature of its operations. Additionally, other port operations such as trucks and cargo handling equipment make the seaport a considerable source of pollution for air and marine ecosystems nearby.

The main sources of energy supply come from the utility grid and diesel generators, constantly emitting greenhouse gas emissions [5]. However, there are many not electric equipment, like cranes. Also, usually seaports tend to be located relatively close to urban communities, subjecting them to increased health risks [6], specially when considering the fact that docked ships also release greenhouse gases.

Despite its importance, it is the least regulated regarding energy efficiency and emissions, something that slowed down its energy transition. To meet these concerns, the IMO reached an agreement in July 2023 to address the maritime transport's emissions. The following goals were aligned between the 175 member states [7]: *i)* carbon neutrality of the sector until 2050; *ii*) reduction of C02 emissions by at least 40% in 2030, comparing with 2008 values; *iii)* Develop clean propulsion technologies, to meet the goal of 10% renewable from the total energy consumed by 2030; *iv)* implement improvements regarding energy efficiency of new ships.

From the seaport perspective, electrification, the replacement of fossil fuel-based energy with new advanced technologies through the use of electricity, is the key for the energy transition topic in seaports [8]. The connection between ships and ports play a crucial role for that process. The future of the ship port relationship will define the reduction of pollutants' emissions. Also, some of the other port areas, like use of automated cargo handling system, energy optimized cargo handling, electrification of railroad and vehicles in and around the port area are also a necessary path towards the energy transition in this infrastructure [9].

However, with the high energy requirement for all this port operation proposals regarding electrification, reliance on power from the grid alone is not enough. With the development of microgrid and smart grid technologies, more renewable energies are integrated which lead the power systems to be more clean, efficient and reliable. A port's geographical location can provide a strong base for RES production.

It has an area with a large flat surface that is suitable for solar panel installation, such as on the rooftop of a warehouse, a storage area, or a flat roof from a building [10]. According to [11], because of the low efficiency of energy production as well as losses related to transmission and distribution of energy in the hierarchical structures, a significant part of the primary energy is wasted in these structures. To have a better idea, in a typical coal thermal power plant, only 28% of primary energy reaches residential consumers. That leads us to Distributed Energy Resources (DER): power generation resources (electrical and thermal energy) near the consumption site, at Medium Voltage (MV) and Low Voltage (LV) level, rather than being connected to bulk transmission systems, which result in lower energy costs, reduced transmission and distribution losses and higher energy efficiency. It reduces the investment costs in both utility grid expansion and long distribution cables [12].

B. Main Contributions

This paper introduces a methodology allowing the optimal management of a Port considering the energy needs of the ships when they are docked. In the proposed model it is assumed that several DERs are connected to the port and can be managed by the Port authorities. Considering the energy provided by the Port to the ships by the Port should be "green" energy, it is expected the installation distributed generation based on wind and or photovoltaic (PV) systems. Considering the potential of the Port of Funchal, PV was selected in the proposed model.

From a system perspective, one of the main challenges is the impact of Port in global power demand, including the high variations in power consumption and production. Taking this aspect into account, the proposed method will consider ramping up and down services considering the needs of Madeira Island.

In summary, the main contributions are:

- Propose a methodology allowing the energy management of a Port considering Shore Side Power as well as the management of internal distributed energy resources such as active loads, PV production, battery energy storage systems (BESS) and a fleet of electric vehicles (EVs);
- Evaluate ramping up and down services mitigating the impact on the grid;
- Evaluation of the use of BESS and EVs fleet as a source of ramping and flexibility.

C. Paper Organization

After this introductory section, Section II describes the proposed methodology considering two different use cases. Section III presents the obtained results considering a realistic scenario in Port of Funchal and in Section IV the main conclusions are discussed.

II. OPTIMAL ENERGY RESOURCES SCHEDULING IN SEA PORTS

The main aim of the present methodology is the optimal scheduling of the energy resources existing in a Sea Port, including SSP. The energy resources considered in the methodology include PV production, BESS, active loads, EV fleet and SSP. The global vision of the resources is presented in the Fig.1.

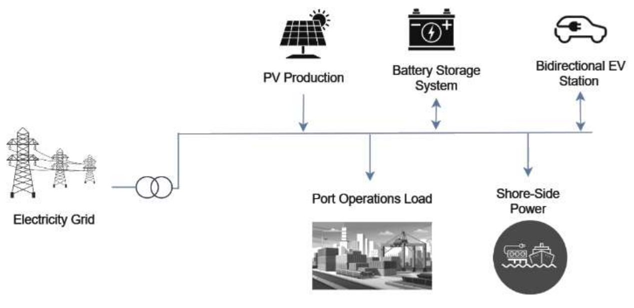

Fig. 1. High-level optimal scheduling for UC1

The optimization was modelled as na mixed integer linear programing model considering a cost minimization funaction as presented in Equation (1).´

$$minF = \sum_{t=1}^{T} \Big(C_{buy}(t) \times E_{imp}(t) - C_{sell}(t) \times E_{exp}(t) + C_{DegBESS}(t) \times E_{DchBESS}(t) + C_{DegEV}(t) \times E_{DchEV}(t) \Big) + C_{Penal} \times P_{Penal} \tag{1}$$

where the parameters $C_{buy}(t)$ and $C_{sell}(t)$ are the buying and selling prices per kWh considering that the values can be different in each period *t*. The variable $E_{imp}(t)$ is the energy that is imported from the grid (supplyed by retailers) and the $P_{exp}(t)$ the one that is injected in the grid. According to the Portuguguese regulation, this energy is payed based on the spot market price. The parameters $C_{DegBESS}(t)$ and $C_{DegEV}(t)$ refer to the degradation cost of BESS and Evs, respectively. The values are normally computed per cycle. However, in the present model, these values are computed per kWh. Taking this assumption into consideration, the values of $E_{DchBESS}(t)$ and $E_{DchEV}(t)$ are variables corrsponding to the enegy discharged from BESS and EVs respectively. Finally, P_{Penal} is a variable representing a penalty cost related with the contracted power. According to the regulation, the when the consumers exced the contracted power during 15 minutes (a period *t* in the present methodology), the contract is updated during a year.

Several constraints have been included in the model related with:

- Power import/export: The power suplpyed by the grid or injected in the grid is subjected to hard constraints related with installed capacity of the power transformers and with cables thermal limits. Soft constraint is related with the contracted power. As already mentioned, this limit can be surpassed under the payment of a penalty.
- Power generation: The only technology considered in the present methodology is the PV. In that case, it is considered that all the energy produced is consumed in the Port or injected in the main grid.
- BESS: BESS is limited by the nominal power of the inverter that limits the power charge and discharge of the battery. Additionally, it is considered an efficiency in the charging and discharging processes. Concerning the battery itself, are considered the maximum capacity as a hard constraint and a minimum limit as a soft constraint. In that case, a penalty factor should be included in the objective function. A constraint imposing that the state of charge in the end of the simulation should be similar to the one in the beginning is also included.
- EVs: The model of EVs is similar to the BESS where constraints in power and energy are applied. However, in the case of EVs, it is important to consider only the periods where the EVs are connected to the Port and the needs for trips. Considering the use of the EVs, it was defined that the EVs should be at 90% of their capacity when the users will rent the EVs. Addicionally, due to the OCPP specification, the charging/discharging

should be higher than 4.1 kW corresponding to 6A in a three phase system [13].

- SSP: In the present model, SSP is considered as a load without flexibility. This means that all the power required by the Cruise Ship should be delivered by the Port. This is an extreme case because the Cruise can also have internal BESS that can supply some of the energy required by the services [14]. It is also important to mention that the energy required by the Cruise is only the one required by the "hotel" zone.
- Active loads: Port is modelled considering the consumption of partial electric boards. Nowadays, the Port have 31 partial electric boards that are monitored. The real profiles are used to validate the proposed methodology. Depending on the type of loads, power curtailment (on/off) or power reduction are included in the constraints.

To mitigate the impact of the cruises in the main grid, specific constraints related with ramping have been included as presented in Equation (2) and (3). In the equations, $dPmax$ represent the maximum variation up and down between two consecutive periods.

$$\left|P_{imp}(t) - P_{imp}(t-1)\right| \leq dPmax \quad \forall t\epsilon T \qquad (2)$$

$$\left|P_{exp}(t) - P_{exp}(t-1)\right| \leq dPmax \quad \forall t\epsilon T \qquad (3)$$

III. Results

This section presents the results obtained using the methodology presented in Section 2 and considering two extreme scenarios. In Scenario 1, it is considered the use of full capacity of the Port of Funchal where three cruise ships can be docked at the same time. In Scenario 2 it is assumed that the Port is not used during all day.

A. Characterization of Port of Funchal (Cruise Terminal)

Port of Funchal – Terminal 1 is mainly used by cruise ships. The capacity of the Port depends on the size of the ships but, in the maximum, three Cruise ships can be docked. Other ships can be docked but using other terminals that are connected to the main grid using different connection points. This means that the limits and constraints are independent.

Nowadays, the Port have an installed capacity of 1MW through a MV/LV secondary substation with a single power transformer. The Port also have a capacitor bank and an emergency group to ensure the continuous operation of the Port. However, this power is not enough to accommodate the needs of SSP. In this context, it is expected a significant increase of the installed power. Considering the consumption of a single cruise ship this value can arrive to more than 30MW.

In the present this capacity is limited to 10MW due to the use of a BESS with an inverter of 10MW and with a capacity of 10MWh. The BESS will be used for two main purposes. First, allows the reduction of installed capacity of the Port increasing the utilization factor of the infrastructure. The second goal is to mitigate the impact of the cruise ships ensuring a ramping up and ramping down services.

Beyond the challenge of providing energy to Port, this energy should be "green" energy. In the present scenarios it is considered that 10 MW of PV will be installed to be used in self-consumption by the Port. Finally, to consider not only the Maritime transportation but also the road transportation, it is expected that tourists can use EVs for their trips in the city [15]. In this regard it is considered a fleet of 100 EVs that are used exclusively by the passengers of the cruise ships. This means that when the Port is not used (Scenario 2), the EVs can be seen as stationary batteries considering V2X capability. Table I presents the parameters considered in both Use Cases.

TABLE I. Scenarios parameters

Parameter type	Scenario 1	Scenario 2
Contracted Power [MW]	10	
Exported Power limit [MW]	10	
PV rated power [MW]	10	
BSS [MW/MWh]	10/10	
EV station rated power [kW]	50x22 (2x11)	
EVs	100 x40kWh	
Ship 1 Peak Power [MW]	6.5	-
Ship 2 Peak Power [MW]	6.5	-
Ship 3 Peak Power [MW]	8	-

Considering the mentioned values of the installed capacity, 10MW, and comparing the peak consumption of the cruise ships presented in Table I, 21 MW, it is possible to understand the challenge imposed to the model. On the other hand, if no cruise ships are docked the port should be managed in order to take advantage of the electricity prices to make some profits. In that case, then EVs will have a very negligible use and can be seen as stationary batteries that can be operated by the port.

Beyond the technical characteristics it is important to present the scheduling of the cruise Ships. The scheduling is presented in Fig. 2. The use of EVs is correlated with the arrivals and departures of the Cruise ships. This means that they are normally parked in the port and are used when the Cruise chips arrive. Finally, it is assumed that the Port can sell energy to the grid. In Portugal the buying tariffs are defined by the retailers based on Time-of-Use tetra-hourly imposed by the regulator. However, the excess of energy sold to the grid is defined based on the hourly price of spot market namely the one of OMIE [16]. The buying and selling prices are presented in the Fig. 3.

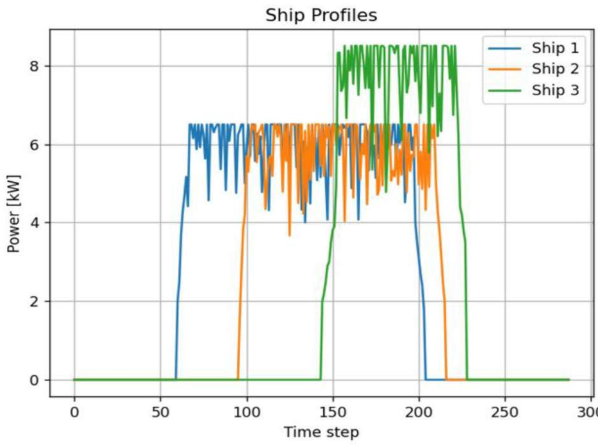

Fig. 2. Scheduling of Cruise ships

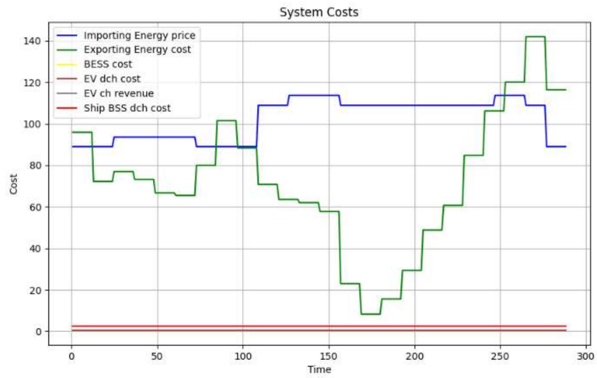

Fig. 3. Electricity Prices

B. *Scenario 1 – Use at full capacity of the Port*

In Scenario 1, it is considered the use of the maximum capacity of the port namely when three cruise ships are docked. In that case, the aggregated consumption is presented in Fig. 4 and the aggregated production in Fig 5. In the figure, it is possible to observe the huge compensation of the batteries and EVs to guarantee the power ramp requirements imposed by the method. This compensation can be seen in the arrival and departure periods, namely between period 4 and 5, 7 and 8 11 and 12, 19 and 20. To allow this compensation, the battery and EVs are discharged between the mentioned periods. In the beginning of the day, the EVs are charged to take advantage of the lower prices.

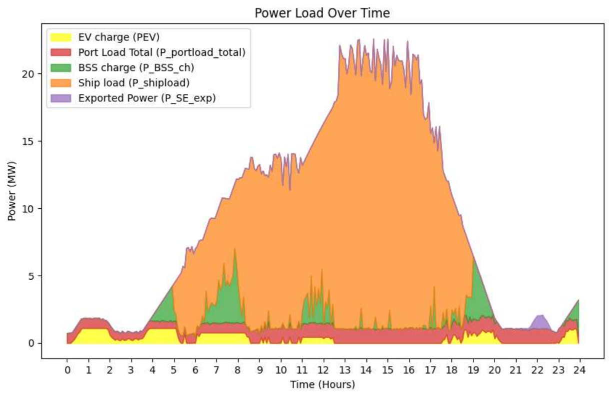

Fig. 4. Power Consumption in Scenario 1

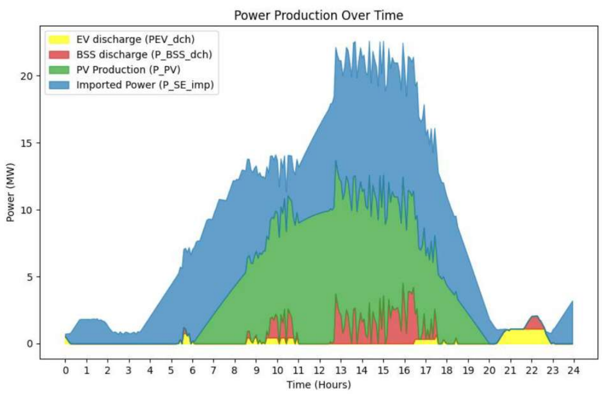

Fig. 5. Power Production in Scenario 1

Additionally, the EVs and batteries are discharged in the end of the day, mainly because of the electricity prices. In fact, in the end of the day the selling prices (based on the spot prices) are higher than the buying prices. Finally, it is important to notice the important limitation in the contracted power that is defined at 10 MW. To guarantee this limit (see Fig. 6) the scheduling needs to discharge the battery during several periods. Again, some oscillation behaviour (charge and discharge in consecutive periods) can be seen mainly due to the very constrained scenario in terms of imposed constraints.

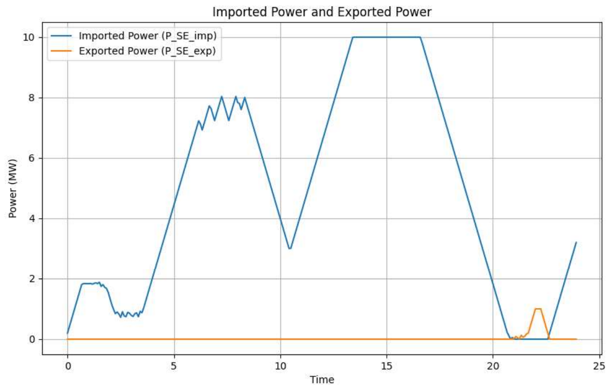

Fig. 6. Imported and Exported Power in Scenario 1

C. *Scenario 2 – Without Use (Cruise Ships) of the Port*

As previously mentioned, Scenario 2 is the opposite of the Scenario 1 meaning that no cruise ships are planned to be docked in the port. The aggregated consumption is presented in Fig. 7, the aggregated production in Fig. 8 and the imported and exported power in Fig. 9.

Analysing the figures it is possible to see that the port only imports electricity during around 5 hours exporting during all the other periods. Considering the high production of the PV systems, the BESS will discharge before the sunny periods showing the effectiveness of the method. Afterwards, both BESS and EVs are charged around 15:00 because is the period when the selling price is lower, resulting in a higher profit by selling in other periods. It is also important to notice that the ramping is also active when the port is exporting imposing that the BESS also follows a ramping in their charging and discharging. Finally, the in the end of the day the energy charged during the day is injected in the grid due to the high selling prices.

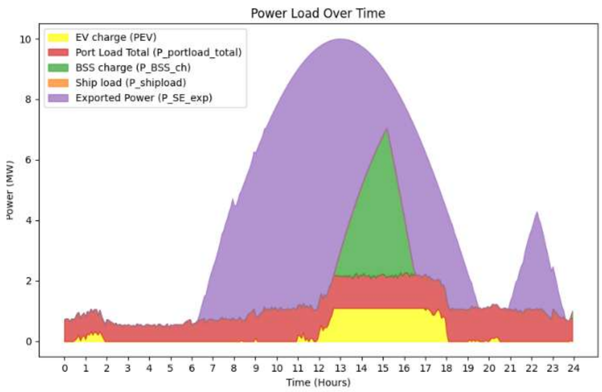

Fig. 7. Power Consumption in Scenario 2

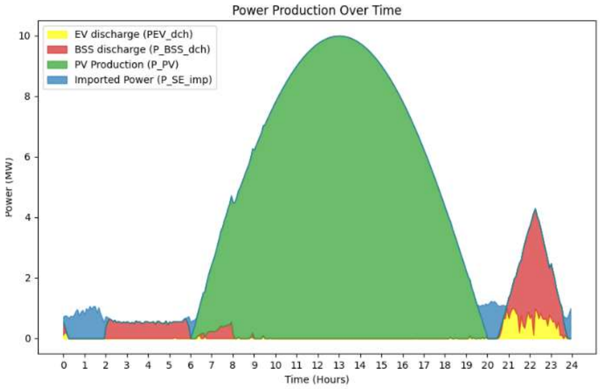

Fig. 8. Power Production in Scenario 2

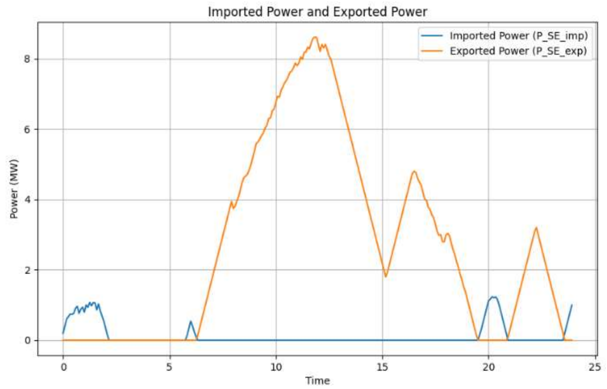

Fig. 9. Imported and Exported Power in Scenario 2

CONCLUTIONS

Taking into consideration the objectives defined in the early stages of this document, it is possible to conclude that they were successfully met. Formulating the optimal scheduling method as a Mixed-Integer Linear Programming (MILP) problem enabled effective management of energy resources in two extreme scenarios: when three cruise ships are docked (full capacity) and when no cruise ships are docked. In both cases, the proposed method demonstrated its advantages by leveraging electricity price variations and meeting the energy demands of all loads, including cruise ships and EVs.

Another important aspect incorporated into the method was the limitation of power ramping, both in increases and decreases. This feature is particularly significant in mitigating the impact of loads on the power system. It becomes even more critical in isolated systems, such as the island setting of the present study. Once again, the model showed strong performance, maintaining a maximum power variation of 0.2 MW every 10 minutes (the simulation time step). This behaviour was made possible through the optimized management of the BESS and EVs. However, achieving this required multiple charging and discharging cycles, which may accelerate battery degradation.

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