Funchal Port as an Energy Hub

Optimal Resources Management

Afonso Teixeira Diniz Antunes Barradas

Thesis to obtain the Master of Science Degree in

Electrical and Computer Engineering

Supervisors: Prof. Hugo Gabriel Valente Morais
Dr. Cindy Paola Guzman Lascano

Examination Committee

Chairperson: Prof. Célia Maria Santos Cardoso de Jesus
Supervisor: Prof. Hugo Gabriel Valente Morais
Member of the Committee: Prof. Lucas Pereira

November 2024

This work was created using LaTeX typesetting language
in the Overleaf environment (www.overleaf.com).

Declaration

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.

Acknowledgments

Firstly, I would like to thank my parents and siblings for their unconditional support, encouragement and caring throughout my life, without whom this academic path and project in particular would not be possible.

I would also like to acknowledge my dissertation supervisor prof. Hugo Morais, for his magnificent sharing of knowledge and orientation that has made this Thesis possible, as well as the opportunity to follow along the SHIFT2DC Project, allowing me to get even more insight and absorption of information. Therefore, also a word of appreciation for the attention and time that other project members provided to me.

Last but certainly not least, to my girlfriend and friends, for always being there for me.

To each and every one of you – Thank you.

Abstract

Maritime ports represent a vital role in the economic and international trading across the world, considering shipping is the most efficient and common method for transportation of any cargo. Given such importance, it is facing challenges due to targets being defined by countries related with decarbonization of the sector. The main one being OnShore Power Supply, the connection of the ship to the port during the periods where the ship is docked, completely changing the role of seaports and how its power and control infrastructure should be developed and installed. This thesis proposes a top-level methodology with four sequential Use-Cases. It will allow the energy management of a Port considering the Onshore Power Supply (OPS) as well as the management of internal distributed energy resources, such as solar production, electric vehicle to grid charging station, battery storage system and the seaport demand itself, for the Funchal Port case in particular. The Use Case 3 will propose bidirectional batteries to electric vessels. All that so in the final Use Case 4, the model can include a Hydrogen network, with onsite generation and storage of Hydrogen, turning the whole system into a Energy Hub, with this final network working as additional power backup and storage. Simultaneously, services to the grid operator are being considered. The results obtained were that Funchal Port meets the goals defined in every Use Case, enabling the path towards decarbonization, as well as considerable financial gains attainment, from the possiblity to safely reduce the contracted power.

Keywords

Energy Hubs; OnShore Power Supply; Electric Ships; Grid Services

Resumo

Os portos marítimos representam um papel vital no comércio económico e internacional em todo o mundo, considerando que o transporte marítimo é o método mais eficiente e comum para o transporte de qualquer carga. Dada esta importância, enfrenta desafios devido às metas definidas pelos países relacionadas com a descarbonização do sector. A principal delas é o OnShore Power Supply, a ligação do navio ao porto durante os períodos em que o navio fica atracado, mudando completamente o papel dos portos marítimos e a forma como sua infraestrutura de energia e controle deve ser desenvolvida e instalada. Esta tese irá propor uma metodologia de alto nível com quatro Use Cases sequenciais. Permitirá a gestão energética de um Porto considerando o fornercimento de energia aos navios, bem como a gestão dos recursos energéticos distribuídos internamente, como a produção solar, a estação de carregamento de veículos eléctricos para a rede, o sistema de armazenamento de baterias e a própria demanda portuária, para o Caso do Porto do Funchal em particular. O Use Case 3 irá propor baterias bidirecionais para navios elétricos. Tudo isto para que no Use Case 4 final, o modelo possa incluir uma rede de Hidrogénio, com geração e armazenamento de Hidrogénio no local, transformando o sistema num Energy Hub, com esta rede final a funcionar como backup e armazenamento de energia adicional. Os resultados obtidos foram que o Porto do Funchal cumpre os objetivos definidos em cada Use Case, possibilitando o caminho da descarbonização, bem como a obtenção de consideráveis ganhos financeiros, através da possibilidade de reduzir a potência contratada de forma segura.

Palavras Chave

Hub Energético; OnShore Power Supply; Navios elétricos; Serviços para a Rede

Contents

List of Figures

List of Tables

Acronyms

BSS	Battery Storage System
CI	Cold Ironing
CHP	Combined Heat and Power
CCHP	Combined Cooling Heat and Power
DC	Direct Current
DER	Distributed Energy Resources
EL	Electrolyzer
EH	Energy Hub
ESS	Energy Storage System
FC	Fuel Cell
HES	Hydrogen Energy Storage
HVAC	Heating Ventilation and Air Conditioning
IMO	International Maritime Organization
LV	Low Voltage
MV	Medium Voltage
NPV	Net Present Value
NG	Natural Gas
OPS	Onshore Power Supply
P2G	Power to Gas
RES	Renewable Energy Sources
SPB	Simple Pay-back
SNG	Synthetic Natural Gas

List of Nomenclatures

The present section aims to work as a source for clarification regarding all sets, parameters and variables used in the optimization model.

0.0.1 List of Sets definitions

t - set of simulations during one day

ev - set of EV vehicles

n_switchboards - set of partial switchboards

0.0.2 List of Parameters

$P_{contracted}$ - Contracted Power [MW]

$P_{contracted\_new}$ - New Contracted Power if current exceeded [MW]

$P_{transformer}$ - Substation Power transformer [MW]

max_ramp_rate - Threshold for maximum variation for importing and exporting between each simulation [MW]

$n_{simulations}$ - Number of daily simulations

time_step - Each simulation's hourly time step

P_{PV_max} - PV rated power [MW]

E_{BSS_max} - Maximum energy to be stored in the Battery Storage System (BSS) [MWh]

E_{BSS_SOC0} - Energy stored in the BSS in the beggining of the simulation [MWh]

BSS_eff_ch - Efficiency from BSS charging process

BSS_eff_dch - Efficiency from BSS discharging process

min_BSS_regulation - BSS's lower energy envelope for frequency regulation

max_BSS_regulation - Higher BSS's energy envelope percentage for frequency regulation

n_evs - Number of EVs in the station

$E_{trip}(ev)$ - Energy consumed by each ev in a trip [MWh]

$E_{tripn}(ev;t)$ - Energy consumption proportionally distributed for the entire day [MWh]

EVs_eff - Efficiency from EV charging and discharging process

E_{EV_max} - Maximum energy stored in the EV battery [MWh]

$P_{EV;chmax}$ - Maximum power injected to and from the EV [MW]

$S(ev;t)$ - Trip is starting for vehicle ev at instant t

$portload\_factors(i;t)$ - Matrix size $i \times t$ that stores load for each partial switchboard at instant t [MW]

$P_{portload\_total}(t)$ - Total port natural load at instant t [MW]

$final\_ev\_soc$ - Percentage of maximum EV energy value that will be present in the end of the day

$Price_{buy}(t)$ - Electricity acquisition price at instant t [€/MW]

$Price_{sell}(t)$ - Electricity selling price at instant t [€/MW]

$Transformer\_penalty$ - Penalty of exceeding substation transformer power [€/MW]

$extra\_contr\_penalty$ - Additional cost for the new contract after exceeding contracted power [€/MW]

n_ships - Number of ships at dock

$P_{shipn\_load}(t)$ - OPS demand for each n ship, at instant t [MW]

$frequency\_regulation$ - Binary input to define if frequency regulation service should occur

P_{island_limit} - Limit of power the system can export to the island [MW]

tn_init - Docking arrival time for ship n

tn_final - Departure time for ship n

$ship\_initial\_percentage$ - Initial ship's BSS percentage

$ship\_final\_percentage$ - Final ship's BSS percentage

$P_{BSS;shipmax}$ - Maximum charging and discharging power associated with the ship's BSS [MW]

$E_{ShipBSS\_max}$ - Maximum energy stored in the ship's BSS [MWh]

$ship\_degcost$ - Ship's BSS discharge degradation cost [€/MW]

$ship\_dch\_pay$ - Ship's BSS discharge revenue to vessel owners [€/MW]

pr_{H2}^{max} - Maximum H2 pressure in the tank [Pa]

pr_{H2}^{min} - Minimum H2 pressure in the tank [Pa]

$pr_{H2}(initial)$- Initial H2 pressure in the tank [Pa]

LHV_{H2}- Lower Heating Value of Hydrogen [MWh/mol]

V_{H2}- Volume of H2 tank [m^3]

T- Temperature in the system [K]

N_{H2}^{chmax} - Maximum H2 charging flow rate [mol]

N_{H2}^{dchmax} - Maximum H2 discharging flow rate [mol]

eff_EL- Electrolyzer device efficiency

eff_FC- Fuel Cell device efficiency

pv- Binary flag to control if PV generation is to occur that day, to impose Scenario type

enable_ships- Binary flag to control if ships are docked in that day, to impose Scenario type

0.0.3 List of Variables

$P_{SE;imp}(t)$ - Imported Power from the grid at instant t [MW]

$P_{SE;exp}(t)$ - Exported Power to the grid at instant t [MW]

$V_{transf\_imp}(t)$- Relaxation variable for importation of power at instant t [MW]

$V_{transf\_exp}(t)$- Relaxation variable for importation of power at instant t [MW]

$P_{extra\_contracted}(t)$ - Extra contracted power necessary to meet demand [MW]

$X_{imp}(t)$- Binary variable to store if power is being imported to the grid at instant t

$PV\_factor(t)$- PV production factor at instant t

$P_{PV}(t)$- Total PV power generated at instant t [MW]

$P_{BSS\_ch}(t)$- BSS charging power at instant t [MW]

$P_{BSS\_dch}(t)$- BSS discharging power at instant t [MW]

$X_{BSS\_ch}(t)$- Binary activated if charging occurs at instant t.

$X_{BSS\_dch}(t)$- Binary activated if discharging occurs at instant t.

$E_{BSS\_SOC}(t)$- Energy stored in the BSS [MWh]

$E_{EV}(ev;t)$- Energy in each ev at instant t [MWh]

$P_{EV;ch}(ev;t)$- EV charging power for each ev at instant t [MW]

$P_{EV;dch}(ev;t)$- EV discharging power for each ev at instant t [MW]

$C_{buy}(t)$- Cost of buying electricity at instant t [€]

$C_{sale}(t)$- Cost of selling electricity at instant t [€]

$E_{ship\_socn}(t)$- Energy in the n ship's BSS at instant t [MWh]

$P_{ship\_chn}(t)$- n ship's BSS charging power at instant t [MW]

$P_{ship\_dchn}(t)$- n ship's BSS discharging power at instant t [MW]

$P_{FC}(t)$- Fuel Cell Output power at instant t [MW]

$P_{EL}(t)$- Electrolyzer Input power at instant t [MW]

$P_{H2}^{ch}(t)$- Power charging of Hydrogen storage at instant t [MW]

$P_{H2}^{dch}(t)$- Power discharging of Hydrogen storage at instant t [MW]

$pr_{H2}(t)$- Level of H2 pressure in the tank at instant t [bar]

$N_{H2}^{ch}(t)$- Quantity of H2 charged to the tank at instant t [mol]

$N_{H2}^{dch}(t)$- Quantity of H2 discharged from the tank at instant t [mol]

$X_{H2}^{ch}(t)$- Binary variable for Hydrogen charging power at instant t

$X_{H2}^{dch}(t)$- Binary variable for Hydrogen discharging power at instant t

$X_{FC}(t)$- Binary variable for fuel cell activation at instant t

$X_{EL}(t)$- Binary variable for electrolyzer activation at instant t

1

Introduction

Contents

1.1 Motivation

Maritime ports are an important hub for passengers and marine transportation, playing a vital role in economic and international trading. Due to increasing global trade, transport of goods through ports has been steadily increasing and will likely continue to increase in the future [12].

Currently, the marine transport network accounts for more than ninety percent of global trade, and according to the International Maritime Organization (IMO) annual report, it is predicted to be tripled by 2050. Seaports have become complex hubs due to the multi functional operations that need to comply with various factors such as marine regulations, technologies, transportation, operational, and policy requirements. Hence, high investment is required to expand ports facilities and infrastructure and to enhance their operation management and maintenance in order to boost all marine operations [13].

The demand for energy in the maritime sector is significant and keeps increasing over time because of the expanding infrastructure, increasing size and number of seaport transportation, need for handling multi functions, and increase in global demand for logistics and ports' daily operation due to lack of energy efficiency. Also, a port area is where emission sources are currently least regulated. Therefore, this infrastructure may play a key role in energy transition and its development is a must. However, it still has not gained the appropriate attention [4].

Transforming a sea port into a Energy Hub (EH) leading to its electrification, is a crucial step towards its sustainability, energy efficiency and economic growth, potentially leading to a nearly zero energy port (nZEP), benefiting the environment, air quality and also the health of nearby communities, since ship emissions can travel up to 500 km of land and green house gases impacts are associated with cardiovascular diseases and asthma [14].

1.2 Objectives and contributions

This dissertation aims to outline a structured approach for the energy transition of Funchal Port, ultimately demonstrating the feasibility of operating the port as an Energy Hub (EH). Through four distinct Use Cases, this study examines the integration of renewable energy sources (RES), storage solutions, and bidirectional power systems, assessing their impact on energy efficiency and flexibility. The research culminates in an analysis of hydrogen onsite generation and storage, highlighting its potential for reducing both energetic and financial costs.

The project employs Pyomo, a Python-based optimization modeling language, to create a high-level optimization model that connects the diverse energy components into a cohesive system.

In summary, the main objectives of this present work are to:

- Obtain load curve for Funchal Port.

- Integrate Renewable Energy Sources (RES) and Storage in the Seaport context.
- Identify and formulate useful services to be provided to the grid operator.
- Tackle the challenge of integrating Onshore Power Supply (OPS) demand in the Funchal Port.
- Define a mathematical formulation for bidirectional electrical ships integration.
- Propose an on-site Hydrogen generation and storage mathematical formulation and sizing.
- Validate a high-level optimization model to properly connect all the previous components.

The Research Questions this work aims to address are the following:

- Can a port be operated as an EH?
- Can a seaport provide services to the grid?
- Can Funchal Port provide OPS without disrupting its network?

1.3 Organization of the Document

This document is structured as follows:

- Introduction (1)- Current chapter, that introduces the main motivations, objectives and contributions of this thesis, as well as the research questions it aims to address.
- Literature Review (2)- Exposes key concepts associated with the thesis, while exploring existing literature regarding the topic.
- Methodology (3)- proposes a step by step solution approach, through four sequential Use Cases, to ultimately have the port as a working EH.
- Results and Discussion (4)- presents the most important results and relevant discussions obtained through them.
- Conclusion (5)- points out the most important conclusions of the work as well as system limitations and future work.

2

Literature Review on Seaport Energy scope and on Energy Hub concept

Contents

2.1 Background context and motivations

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) [15].

When it comes to global impact, it is also responsible for 3.3% of global carbon dioxide (CO2), 14% of anthropogenic nitrous oxides (NOx), 7% of global sulfur oxides (SOx) emissions. Even though the statistics of 27% CO2, 42% NOx, and 10% SOx for the whole transport sector make the shipping numbers seem neglectable, they represent a considerable slice of the cake and improvements are necessary and attainable [16]. 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 [17], specially when considering the fact that docked ships also release greenhouse gases.

Despite this, emissions from this sector are the least regulated ones and several studies point towards the need for more and more precise international regulations on ship emissions [18].

To meet these concerns, the International Maritime Organization reached an agreement in July 2023 to address the maritime transport's emissions. The following goals were aligned between the 175 member states [19]:

- Carbon neutrality of the sector until 2050
- Reduction of C02 emissions by at least 40% in 2030, comparing with 2008 values
- Develop clean propulsion technologies, to meet the goal of 10& renewable from the total energy consumed by 2030
- 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 [20]. 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 [16].

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 [4].

According to [2], 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 this 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 [21].

In [22], it is explained that the growth of Combined Cooling Heating and Power (Combined Cooling Heat and Power (CCHP)) is related to the emergence of DER. CCHP systems integrate a power generation unit, a waste recovery system, a back-up boiler, cooling system and heating system as a whole to implement the energy cascade utilization, reduce carbon emission and meet the cooling, heating and electricity demands simultaneously [23]. This concept of typical CCHP however today does not contain renewable energy sources nor energy storage systems [24].

In the next section it will be exploited the previously explained concepts and motivations, with the use of the EH concept.

2.2 Energy hub definition and background context

The EH concept was presented by a research team at Power Systems and High Voltage Laboratory at ETH Zurich within the framework of the project called “a vision of future energy networks (VOFEN)”, aimed to create a picture of future energy systems in the 20 to 30 year scope [1]. Their concept was to generate Synthetic Natural Gas (Synthetic Natural Gas (SNG)), that would either be injected in utility's natural gas system or converted into electricity and injected to the electrical grid, and heat from wood chips. Waste heat would be absorbed by the heating district network [25]. That project helped define an EH as a multiple energy carrier infrastructure, serving as an interface between consumers, producers, storage devices and transmission devices in different ways: directly or via conversion equipment, handling one or several carriers, like [3] specifies. The requirements are some input of energy, an energy