Design Project Report

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“An energy model of OG’s hybrid integration proposing the Ocean Battery as deployable on-site storage profitability optimizer for offshore renewable production plants.”

Master Design Project

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Abstract

In the last decades, the renewable energy market has attracted revived interest as global response against incumbent climate change concerns. Peculiarly, European authorities and governing bodies have recently urged for the continent to become carbon neutral before 2050, thus encouraging both technological development as well as innovative projects related to renewable sources to flourish. Within such habitat operates the Dutch start-up company Ocean Grazer B.V., which aims to disrupt the energy storage market for offshore renewable production farms with its unique design of pumped hydro storage solution: the Ocean Battery. Nonetheless, in order to assess the profitability improvement allowed by the Ocean Battery deployment within offshore farms, Ocean Grazer requires a basic and comprehensive techno-financial model. This would allow the company to strengthen and justify its business model, which rotates around the Ocean Battery deployment, thus captivating a wider spectrum of investors. Consequently, the company assigned the student with the task to fill such a technical gap: a modular and versatile model assessing the profitability improvement, implied in the Ocean Battery deployment as on-site storage device for offshore farms, has been implemented during the design project. Such a financial assessment culminates with the evaluation of two selected key performance indices: namely, the farm LCOE and the LCOG, both described in section 4. Therefore, the present report aims to introduce and examine the Techno-financial Model, designed to satisfy Ocean Grazer demand. As the problem context is depicted, the involved stakeholders as well as the followed methodology are discussed. Subsequently, the designed Techno-financial Model is presented through a differentiated analysis of its two main constituents, namely: the Power Model and the Cost Model. Although the former has been implemented in Simulink, the latter has been realized in MATLAB. Once the structure of the Model is illustrated, the report presents the Model response to a selection of market scenarios. In particular, sensitivity analyses are conducted with the Model on a 600 MW plant, containing a mixture of solar power production, wind power production and wave power production, for the location of offshore Eemshaven, in the Netherlands. Furthermore, a 600 MW grid presenting wind power production exclusively is also used to validate the Model with regards to both the locations of Eemshaven and Bayonne, in France. This is key in order to certify the Model adaptability to project site changes. Finally, as an in-depth discussion is conducted on the attained results, a set of sensitivity analyses are conducted by measuring both the LCOE and LCOG for changing: expected power output from the farm, energy storage capacity, number of deployed WEC arrays, number of deployed floating solar arrays.

Acknowledgements

The design project was fully conducted during a period marked by diffused tribulations and concerns. Unfortunately and understandably, it was never possible to attend the office for the whole project duration. However, the clear guidance provided by my supervisors was always crucial for achieving the project target. Therefore, I wish to express my gratitude to my first supervisor, dr. G. K. H. Larsen: her precise instructions were key in order to fulfill the project milestones. Moreover, I wish to express my gratitude to my second supervisor, Prof. dr. A. Vakis, for always being present and supportive at the same time. The feedback, backing and encouragement he provided during the project stages was invaluable for the target achievement. Furthermore, I wish to express my gratitude to my company supervisor, dr. M. van Rooij: his support and critical feedback were always constructive, and his belief in the project relevance was of great motivation. Together with Prof. dr. A. Vakis, dr. M. van Rooij was always aware of the dimension of the task confronted by the student, if compared to the design project time window, and provided crucial guidance. I wish to express my gratitude to dr. A. Bechlenberg: she always kindly offered support during the artifact validation. I wish to express my gratitude to Ocean Grazer B.V., for having welcomed me in their great journey of success.

I would also like to thank my family, to whom I devote the effort I dedicated.

Andrea Di Modugno

Glossary

CTO	Chief Technical Officer.
IOCs	Inputs, outputs and controls.
LCOE	Levelized Cost of energy - Cost to produce each MWh of energy. [EUR/MWh]
LCOG	Levelized Cost of Ocean Grazer - Cost to produce each MWh of energy if the Ocean Batteries are used as storage devices. [EUR/MWh]
MW	Mega Watt - Power unit measure.
MWh	Mega Watt hour - Energy unit measure.
PHS	Pumped Hydro Storage - Hydro-electrical energy storage device.
WEC	Wave Energy Converter

Contents

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1 Introduction

During the last decades, a renowned interest has been focused on the renewable energy market. As multiple international regulators and organizations urged on a global response against climate change by highlighting the harmful implications which non-renewable energy production exerts on the environment, new technologies allowing higher renewable energy production efficiencies have flourished world-wide [1][2]. In particular, amongst these institutions the European Union has assumed the leading role within such energy conversion process, by aiming to become carbon neutral by 2050 [3]. Although fossil fuel remain the most diffused source of energy [4], their finite nature continues to concern [5]. Consequently, due to both non-renewable resource scarcity as well as to their related carbon footprint, it is required to pursue the replacement of non-renewable sources with renewable ones on a wider scale. Although the global energy demand is previewed to drop by 5% *circa* during 2020 as shown in figure A.1, energy investments are expected to plunge by 18% during the same period, as institutions turn their attention to health and financial concerns [4]. Nonetheless, the contribution of renewable energy production throughout 2020 has continued to increase.

In order to accomplish such ambitious carbon neutrality goals [6] [7], no compartment of the energy sector is allowed to display inertia to technological advancement. Since, in 2018, the Netherlands and France were highlighted as the furthest away, in Europe, from their respective goals of renewable energy supply [6], the Dutch government recently deliberated that by 2050 the country's emissions of greenhouse gases shall be brought to zero [8]. Consequently, the low-carbon energy sources of solar energy, onshore wind energy, offshore wind energy and biomass energy will be exploited [9]. Specifically, the Dutch government has elected offshore wind energy production as the direction to pursue, by promoting a technological innovation habitat amongst which companies such as Ocean Grazer B.V. emerge as pioneer avant-gardes.

Although it must be underlined that offshore wind energy generation continues to require considerable financing [10], leading to higher investments, it must also be noted that these allow to exploit more stable, uniform and continuous wind speed patterns, whilst compared to those experienced onshore [11]. Nonetheless, the key challenge remains the conversion of renewable sources' intrinsic fluctuating and unstable origination into an adequately constant energy supply [12]. Therefore, in order for renewables to diffusely replace non-renewable sources, the power output uniformity shall be improved, as the farms must provide the grid with a stable power output. This issue has been addressed and tackled by associating, to renewable energy production farms, devices devoted to energy storage. As these can accumulate power during periods of production excesses, such reserves can afterwards be provided to the grid during periods of power deficits. Moreover, to deploy storage solutions on-site allows to reduce capital expenditures related to cabling [13]. Therefore, it is clear how to complement production offshore renewable production farms with on-site storage devices implies an added value in terms of increased efficiency, reliability, profitability and output quality [14].

Consequently, Ocean Grazer B.V. has developed and refined a unique design of pumped-hydro storage (PHS) device, named Ocean Battery, to be deployed on-site within offshore renewable energy farms. Ocean Grazer B.V. is a Dutch start-up, founded in 2018 and based in Groningen (Netherlands), composed of a management board and four employees, both supported by a scientific advisory board, thus producing an efficient, solid and organized structure. The company envisions a future where offshore *hybrid integrations* are complemented with on-site energy storage. *Hybrid integrations* are farms presenting both production as well as storage modules. Key players of the energy market such as TNO are currently investigating options for diverse renewable energy production modalities pairing [15]. Therefore, Ocean Grazer B.V. is firmly determined to assess the profitability improvement allowed by the Ocean Battery deployment within offshore farms, regardless of their composition (wind, solar, wave energy production), as it will be profoundly discussed in Chapter 2. In fact, the Ocean Battery's one-of-a-kind design allows to store power production excesses in form of potential energy, by moving a given volume of still water amongst two reservoirs, precisely from a rigid to a flexible one. On the other hand, during production deficits the Francis turbine hosted in the Battery converts such potential energy into electrical energy by draining the flexible reservoir in favor of the rigid one, as represented in figure 2.1, thus providing the grid with additional energy. As the device is intended to operate offshore by being partially buried under the seabed, the Battery takes advantage of the pressure imbalance between atmospheric pressure and hydrostatic pressure. In fact, one reservoir is constrained at atmospheric pressure through an umbilical chord, whereas the other is subject to the pressure of the water column placed above it [16] [13].

Since the Ocean Battery represents the core of Ocean Grazer's vision, to accurately assess and estimate the Battery's potential, whilst associated to any possible renewable source combination, has recently captivated the company's focus [17]. In fact, the next steps for Ocean Grazer involve to captivate and engage a wider spectrum of investors, alongside already acquired business partners, including Ørsted, TNO and TenneT. In order to do that, Ocean Grazer must first strengthen its business model by assessing the profitability improvement allowed by the Ocean Battery deployment. Although previous investigations [16][13] demonstrated that the device adds value to offshore production plants, as it will be discussed in Chapter 2, such researches either took advantage of outsourced models or referred to outdated literature for input data acquisition. On the other hand, Ocean Grazer requires a more accurate, comprehensive and updated model for presenting to investors the business case improvement allowed by the deployment of Ocean Batteries within offshore renewable energy production plants, as it will be discussed in Chapter 2. Consequently, the company needs a more accurate techno-financial model representing the Ocean Battery alongside renewable energy sources in order to justify its business model, which rotates along the vision perceiving the Ocean Battery as deployable device granting higher profitability to investors.

Therefore, the design project contribution is represented by the design, implementation and validation of such model, as it will be profoundly discussed in chapter 2. Moreover, the rest of the report is structured as follows: as the problem context is discussed in section 2.1, the scope of the system as well as its description are reported in section 2.2. Consequently, both the problem statement and the problem owner are clearly defined. This is key in order to define a design project goal, which is highlighted in section 2.5. In order to achieve such target in the limited time span available, a specific methodology has been implemented within the path of the Design Cycle, as presented in section 2.6: the process is guided by both the research and design questions enlisted in section 2.7. Therefore, as the problem analysis is performed in chapter 2, the depiction of the designed Techno-financial Model is discussed in chapter 3, where the architecture of the implemented artifact is examined in detail. Finally, a new performance index, more accurately capable of capturing the profitability improvement allowed by the Ocean Battery(ies) deployment, is introduced in chapter 4. Therefore, the Model is tested and validated on a set of selected scenarios in chapter 4, whereas sensitivity analyses on the profitability improvement are conducted in chapter 5.

2 Problem Analysis

2.1 Problem Context

As consequence of the unilateral effort discussed in chapter 1 towards global emission reductions, the offshore Wind European market is projected to triple during the current decade. Such an increase would require for storage capacity in Europe to grow up to almost 2 GW [4]. In particular, the capacity of installed pumped-storage solutions around the continent is set to increase from the actual 45 GW to 112 GW before 2030 [18]. The Ocean Battery, as on-site storage solution for offshore production plants, has started to capture investors focus, thus allowing the company to subscribe key strategic business partnerships with crucial market players such as Ørsted, TenneT and TNO. To acquire further insights on the interactions between the Battery and offshore production farms would enable investors to assess the profitability improvement implied by the deployment of Ocean Batteries within offshore plants, as anticipated in chapter 1.

On a higher level, recent investigations have confirmedly elected energy storage devices as supply stabilizers to be used during periods of production deficits [12], thus allowing an optimized energy management [19]. Consequently, energy storage devices are capable of providing financial returns, since these allow to store, and afterwards sell, energy likely to be wasted. In particular, storage devices in form of pumped hydro storage solution (PHS) already proved to grant higher financial returns, given their cheaper nature whilst compared to most storage designs [20]. Additionally, storage devices prove to resolve the intermittent and fluctuating nature of the renewable energy sources, by more efficiently accommodating the energy demand [12]. PHS solutions allow to store production excesses in form of potential energy by maneuvering the displacement of a certain volume of water amongst two reservoirs connected by a rotational component. During production excesses, the rotational component acts as a pump by obliging the water to migrate, typically, towards the high pressure reservoir; on the other hand, during production deficits such reservoir gets emptied in favor of the other tank, thus allowing the rotational component to behave as a turbine and generate electrical energy. The Ocean Battery pertains to PHS category as well. Although PHS' activity is relatively straightforward, their performance still requires more profound and comprehensive understanding [21]. Therefore, during the present design project the behavior of the Ocean Battery was modelled, so that the investigation of a realistic offshore farm integrated with the Batteries is now allowed.

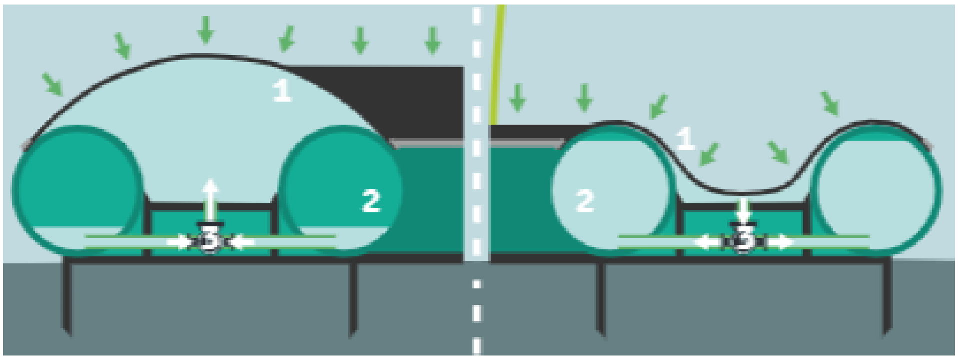

Figure 2.1: Basic model of the Ocean battery, presenting the flexible reservoir (1), the rigid reservoir (2) and the pump-turbine system (3) [22].

2.2 System Description and Scope

In order to design such a comprehensive model, it is first required to outline the perimeter of the system under scrutiny. The system in analysis is Ocean Grazer's current design of a hybrid integration, itself composed by two modules. Firstly, the production module harvests energy from wind, the Sun and waves. Secondly, the energy storage module (the Ocean Battery) collects production excesses in order to satisfy the energy demand during production deficits. As anticipated in section 2.1, Ocean Grazer' storage device solution for offshore renewable production farms (the Ocean Battery, presented in figure 2.1) belongs to the realm of PHS. Nonetheless, it presents a unique design, since it is designed specifically to be deployed offshore. In fact, as the structure of the Ocean Battery shall be anchored to the sea bed, the Battery features one rigid reservoir, hosted in the engine room, and a flexible reservoir, as shown in figure 2.1. Additionally, the Ocean Battery is provided with an umbilical cord, granting connection with the atmospheric environment.

Consequently, two different pressure patterns are exerted on the device: atmospheric pressure is exerted on the rigid reservoir, whereas the flexible tank is subject to hydrostatic pressure. Therefore, the water is moved reciprocally amongst the two reservoirs based on need, thanks to such pressure imbalance. The Battery is conceived as deployable device for offshore renewable production farms. An instance of integration between renewable energy production modules and the Ocean Batteries is provided in figure 2.2. Therefore, the Ocean Battery design developed by Ocean Grazer offers a deployable storage solution for offshore hybrid integrations.

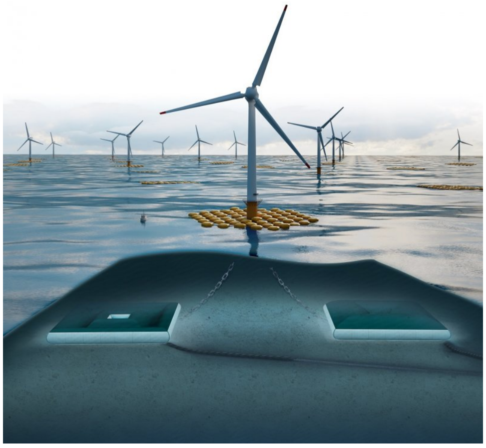

Figure 2.2: Model of Ocean Grazer's hybrid integration.

Finally, it is therefore clear that the scope of the design project focuses on offshore hybrid integrations presenting the Ocean Battery as storage solution on-site. As previously explained, these could include any possible combination of production modules associated to the Ocean Battery as on-site storage device.

2.3 Problem Statement

As the problem context has been introduced in section 2.1, it is now possible to present the problem statement, which recites as follows:

> *As Ocean Grazer B.V. lacks a comprehensive energy model capable of representing the Ocean Battery adjacent to renewable energy production sources, the company is now unable to fully present to investors the added value implied with the Ocean Battery deployment within offshore hybrid-integrated system, thus being unable to justify its business model.*

Consequently, the company demands for a multifaceted project, which then needs to account for both technical and financial aspects with respect to hybrid integrations featuring Ocean Batteries. Therefore, the problem owner of the project is a preeminent company's profile, Marijn van Rooij, Ocean Grazer's CTO. By being one of the co-founders, the professional has contributed to build solid information databases concerning the designed device by both promoting and directing technical investigations as well as by coordinating and supervising financial assessments related to the device. Consequently, the professional holds major stake in the present project. Nonetheless, further stakeholders maintain focus on the project development and output, as it will be discussed in section 2.4. The CTO requested to the student to develop a basic and modular tool capable of portraying the Ocean Battery alongside any hybrid integration characterization. Consequently, the company expected the model to be versatile, in order for it to be applicable to a wide spectrum of future projects analyses.

2.4 Project Stakeholders

As previously underlined, multiple stakeholders relate to the present project. Such an acknowledgement is critical in order to subdivide recognitions of all stakeholders' power and responsibility, which heavily influences the achievement of the desired strategic goals [23]. Firstly, the scientific advisory board represents a main stakeholder. Peculiarly, Prof. dr. A. Vakis, who supervised the project and provided invaluable guidance, aims for his research team to use the design project artifact (described and discussed in chapter 3) to scrutinize and validate a wide set of analyses to be conducted on wave energy conversion as a mean of renewable energy production alongside the Battery. Peculiarly, two PhD fellows maintain the project under periodical scrutiny, since both the pricing results, in one case, and the generated integration model details, in the second case, will phagocytise their future higher case investigations. Secondly, drs. W.A. Prins provided an energy management perspective on the model given his co-founder and advisor status within the company. Both stakeholders were crucial for identifying and translating the functional requirements of the design into both technical and technological model features. In particular, Prof. dr. A. Vakis involvement in terms of advise, navigation and supervision was crucial. Furthermore, although to interpellate the company's CEO was highlighted by the student as crucial, in order to acquire detailed information concerning the energy market for implementing a more refined market behavior, it was never possible to reach the professional.

2.5 Design Goal

The SMART goal of the design project is the following:

To design and build an integrated, basic model representing the interaction amongst the Ocean Battery and offshore power plants displaying any combination of these three production sources: wind, solar and wave conversions. Additionally, the model shall present a cost analysis, so that the business case improvement (LCOE), allowed by the Ocean Battery deployment within offshore renewable power plants, is investigated.

Therefore, the tool must present modular nature, so that easy switches across combination of production sources are allowed. Such flexibility would allow the company to adopt and use the same model independently from the business partners' investments plan to be analyzed.

The proposed design project goal displays the complete five characteristics spectrum intrinsic for SMART goals. In fact, it is *specific* since it refers precisely to the need of representing offshore renewable energy plants complemented with the Ocean Battery. Furthermore, it is *measurable* since the target is achieved only once hybrid integrations featuring the Batteries are both modelled as well as financially analysed in order to evaluate the farm LCOE and LCOG. In addition, the output of the designed Techno-financial Model displays a measurable profitability improvement in terms of LCOE reduction [24] for the case of Battery(ies) deployed compared to the case of absent Batteries. Thirdly, such business case improvement is both *achievable* and *realistic* since the pumped-hydro storage technology has already proven to be helpful in terms of costs reduction and revenues increase for production plants. Finally, the project's *duration* allowed the student to develop an accurate enough design, in accordance to the company demands.

2.6 Methodology

The project started on the 3^{rd} of September 2020, and throughout its development it has followed rigorously the framework indicated by the Design Cycle [25]. In fact, such methodology was immediately identified as both adequate and pertinent for the case under scrutiny. In particular, the Design Cycle presents a specific characterization of the Engineering Cycle. Therefore, the former was preferred to the latter since the treatment implementation was not possible during the project time window: the design validation was performed as last stage. The present section reflects on the echo of the Design Cycle's phases onto the conducted project.

Firstly, the chosen framework demands for a thorough period of *Problem Investigation*, which was guided by the Research questions reported in section 2.7. For the case of analysis, this stage was conducted through a precise sequence of investigations. After the key problem was assessed by addressing the lack of a comprehensive and accurate techno-financial model, the investigation moved towards the definition of both physical as well as functional requirements to be superimposed on the model. Consequently, the scrutiny turned towards a profound inspection of the most appropriate software(s) allowing to reach the project target: namely, to design a comprehensive Techno-financial model of the hybrid integration proposed by Ocean Grazer, as discussed in section 2.5.

Secondly, since the software MATLAB and its featured environment Simulink were selected for the modeling stage, the *Treatment Design* was performed by scanning the available literature in order to find already available MATLAB models relatively to the production modules. Consequently, a heuristic approach was applied to model the Ocean Battery in such engineered environments. Direct contact with the stakeholders involved was constantly maintained, in order to preserve the design pertinence to the company requirements. In fact, precise requirements and parameters, such as the Battery capacity and the power of the pump, were superimposed on the design, after multiple targeted interviews with the stakeholders. Both the production and the storage components were designed by the first week of October 2020. As the Power Model (described and circumstantiated in section 3) was designed and refined, the focus moved, during the first week of November 2020, towards its complementing with the financial counterpart (the Cost Model, as from section 3) by adding the pricing components for each of the elements operating within the Power Model. In such way, the comprehensive techno-financial model was allowed to provide the required overall business case assessment related to exactly the offshore farm characterization established within the Power Model, as it will be precisely discussed in chapter 3.

Finally, the *Design Validation* was conducted since the last days of November 2020 by assessing whether the developed artifact actually efficiently represented the behavior of the hybrid integrations modules. Furthermore, during the *Treatment Validation* phase the student and the company assessed whether the design was capable of attaining the project target. As, peculiarly during the initial stage, the Techno-financial model presented few fragilities, improvements were realized. Additionally, a more accurate profitability index was defined in order to fully capture the business case improvement: the LCOG, to be compared with the LCOE. Both are defined and discussed in section 4.1. Consequently, the design was posed under stress tests, where analyses of realistic offshore farm characterizations were conducted, in order to verify the model response. Since the

Techno-Financial Model produced, as output, LCOE values aligned to those found in literature, as will be discussed in chapter 4, the validation was determined and concluded by appraising the Model capability to provide accurate results for different hybrid integration characterizations. Additionally, the validation was also performed by comparing the attained LCOE results with the conclusions achieved in previous researches [13], as it will be discussed in chapter 4.

2.7 Research Questions

Since both the design project goal as well as the followed methodology have been discussed (in sections 2.5 and 2.6, respectively) it is possible to highlight the research questions which led the investigation throughout the project development. Due to the fact that the main motivation leading to the design may be synthesized as follows: "How could Ocean Grazer accurately justify its business model to investors?", the necessity of a more advanced and accurate model capable of capturing the business case improvement allowed by the Ocean Battery was identified as crucial, as discussed in section 2. Therefore, the project target was pursued through an obedient sequence of research questions, which are here reported divided amongst design (D) and knowledge (K) themes, in order of display.

- (K) Does a techno-financial model solve the company's problem?
- (K) Would such model satisfy all stakeholders' requirements?
- (D) Which software/program supports best the achievement of the project's target?
- (K) Why were the models previously used by Ocean Grazer ([13] [16]) inaccurate? Which of their aspects could be improved?
- (K) Is there already available literature related to the production components models within the selected software?
- (K) Is there available literature depicting a pumped hydro storage model within such software?
- (D) Model the hybrid integration within such software/simulated environment.
- (K) Does the design accurately represent the hybrid integration?
- (D) Build the cost model related to the developed hybrid integration model.
- (K) Which KPI would assess the profitability of hybrid integrations more accurately than the LCOE does?
- (K) Does the developed model correspond to and satisfy the company's requirements?
- (K) Which are the most suitable scenarios for model validation?
- (K) Is the developed model prone to the planned validation (as from chapter 4?
- (D) Does the designed model assess the business case improvement implied by the Ocean Battery deployment?

These sub-questions have been confronted, in the reported order, throughout the project development during both individual investigation as well as meetings with the involved stakeholders.

3 The Techno-financial Model

The present chapter proposes and discusses the nature of the designed Techno-financial Model. Here, not only its inputs, outputs and controlling parameters are scrutinized, but also its two major constituents are examined. These are: the Power Model, simulating the power production components, engineered in Simulink; the Cost Model, which has been implemented in MATLAB. The latter receives, from the Power Model, as inputs the produced power from each production module. This allows to perform the required financial assessment, as it will be discussed in section 3.4. It must be immediately stated that the power production trends, attained during the power simulation, are dependent on given inputs data sheets representing critical parameters, as it will be explained in section 3.2. Additionally, the demand trend as well obviously influences the overall financial assessment.

3.1 Model Structure

The structure of the designed Techno-financial model is crucially composed by two constituents: the Power Model, modelled in Simulink; the Cost Model, designed within MATLAB, as anticipated.

In particular, the Power Model was built in MATLAB's environment Simulink. In order to do that, blocks available within Simulink libraries were associated in order to reproduce the power generation processes. Peculiarly, with respect to the wind power generation, models available in the Mathworks library were re-adapted. As Ocean Grazer demanded for the to-be-designed model to present complete modularity with respect to the power generation components, the Power Model is composed of three main blocks: *Solar Power Production*, *Wind Power Production* and *Wave Power Production*. Each of these receives the relevant data from a *Data Acquisition* block, which acquires databases from the Excel as described in section 3.2. For instance, the solar production block receives the trend of the Sun irradiation throughout the year, whereas the wind power production block collects the data concerning the wind speed trend during the same time span. Both these data extraction and subsequent acquisition are performed through the Simulink blocks *From Spreadsheet*, *GoTo* and *From*. As such databases are acquired by the respective power production blocks, these information are afterwards processed by the power production blocks, which generate the trend of the power produced by each module. Further details related to each power production blocks are reported in section 3.3. The power simulation performed by the Power Model is required to be completed as first step of the comprehensive Techno-financial Model's execution.

As the Power simulation is performed, the blocks *To workspace*, featuring each of the production modules of the Power Model, send the simulated power production trends to the Cost Model, which is entirely coded within MATLAB. The Cost Model combines a wide set of inputs, entered by the user from the file *input.m*, with the produced power and demand trends attained from the Power Model. Such integration allows the Cost model to rely on multiple functions in order to, in the end, assess the levelized cost of energy (LCOE), which displays the profitability of the offshore hybrid integration. Crucial inputs for the Cost Model to produce the business case assessment are, for instance, the farm characterization (namely the number of wind turbines, solar panels, buoys, Ocean Batteries and grid hubs to be considered), the type of turbine featured within the Ocean

Battery, and the simulation time window. The Cost Model must be run after the Power Model simulation has stopped and the Cost Model inputs have been set. Evidently, in order to attain the LCOE, the Cost Model performs a sequence of intermediate steps of investigation, ranging from the calculation of the stored power to the price of energy per time step. These information are stored into relevant arrays and displayed to the user in order to grant a detailed motivation of the overall result. Further detailing of the functions allowing the Cost Model to run is reported in section 3.4.

It must be clarified that the distinction amongst Power and Cost Models was required in order to produce and maintain the highest possible level of accuracy and modularity throughout the overall Techno-financial assessment. In fact, although Simulink is a MATLAB-based environment, it did not support a considerable set of MATLAB functionalities, key for accurately modelling the Ocean Battery interaction with the production modules. On the other hand, these were supported by MATLAB. Therefore, it became immediately necessary to perform the more detailed analysis regarding the business case improvement within MATLAB, only. On the other hand, since Simulink is a programmable modeling environment simulating engineered systems, the latter was the most appropriate platform for hosting the modeling of the power production blocks. As the general structure of the Techno-financial model has been discussed, it is now possible to progress to the analysis of its inputs, outputs and controls, in section 3.2.

3.2 Input, Outputs and Controls (IOCs)

The present section examines the characterization of the designed model in terms of describing its inputs, outputs and controls, the so-called *IOCs*. As shown in figure 3.1, the developed model has the purpose to produce a profitability assessment of an offshore hybrid integration based on both the farm's geographical location as well as on the farm characterization.

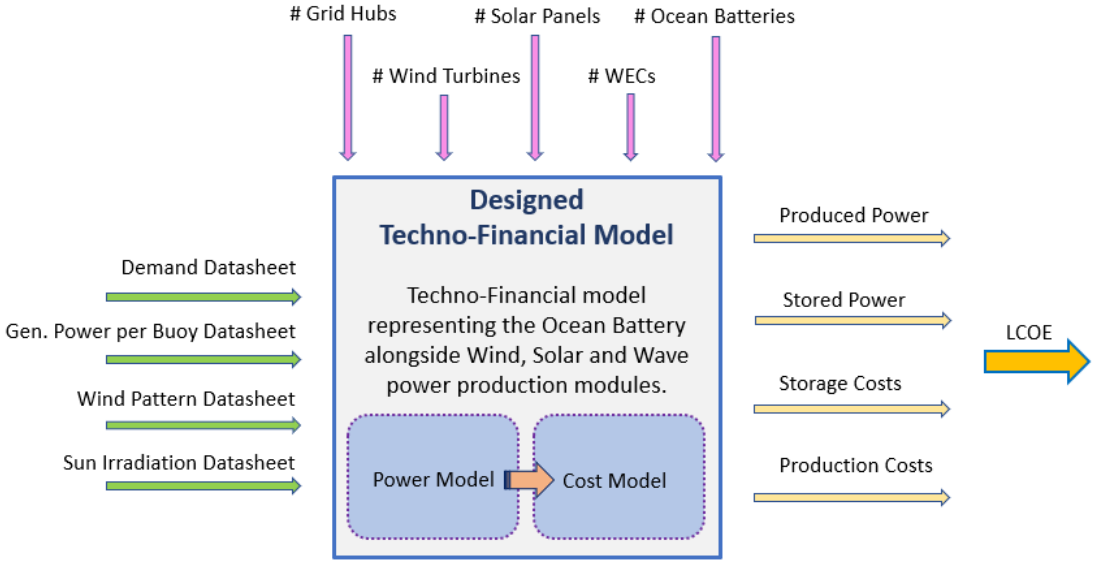

Figure 3.1: Scheme displaying input, outputs and controls of the designed Techno-financial Model.

First of all, it is possible to note that the developed model acquires as inputs four datasheets: the power demand, the generated power per buoy given a certain wave height, the average wind speed pattern and the sun irradiation. These data sheets are dependent on the selection of a specific location. For instance, the average value related to the sun irradiation ($[W/m^2]$) may differ across geographical domains. Furthermore, it is key to note that these four input databases are two-columns, 35151 lines arrays. As the first column represents the simulation time step, it is built with a 0,05 s time step. The latter value is chosen for a specific reason. In fact, as the Power Model performs a discrete simulation with a time step of 0,05 s (identical to the time step used for the Excel datasheets) and has a stop time of 1756,5 s, it is immediate to calculate that 35151 steps are analysed. If 15 minutes in reality are compared to 0,05 s in the simulation, the total simulation time of 1756,5 s would equal approximately 365 days. This allows the Power Model to simulate and produce yearly power outputs. In particular, the time step of 15 minutes is selected since it was addressed in previous investigations as the most appropriate to analyze the Battery's behavior with [13]. On the other hand, the second column of each of these datasheets contains the relevant characteristic values: wind speed, solar panel voltage, power per buoy and sun irradiation. It must be specified that the Power Model expects the generated power per buoy database to contain the power generated per buoy, to be previously calculated based on the wave height for the given location. This is motivated by the fact that the *Wave Power Production* block was left as a *black box*, as requested by the stakeholders. All the mentioned datasheets have been handcrafted based on documented pivot values, one for each characteristic, for the area of offshore Eemshaven, which is realistically the region where the Battery would be first tested. Peculiarly, further discussion on datasheets' nature are reported in chapter 4.

Moreover, since the Techno-Financial model's objective is to produce a profitability assessment of the selected grid characterization, the LCOE of the farm is the overall output of the model. Nonetheless, such results may vary based on the type of farm. Therefore, the Techno-financial Model allows to accurately pre-select the farm characterization based on the project to be investigated. In fact, as shown in figure 3.1, the cardinality of each farm component is set as control of the model: by changing these values, the attained LCOE results may differ. This feature allows the Model to display complete modularity and versatility, as requested.

As the IOCs of the comprehensive Techno-financial model have been introduced, it is possible to deepen the discussion of the Techno-financial Model by further reviewing the Power Model and the Cost Model, separately. In fact, as it was anticipated within section 3.1, the Techno-financial model is composed of two main constituents: the Power Model which is in charge of generating the produced power trends for the simulated time window; the Cost Model, which receives the data produced by its counterpart and performs the financial assessment by integrating the Ocean Battery in the analysis. Such digression will be conducted throughout the next two sections, in sections 3.3 and 3.4, respectively.

3.3 The Power Model

As anticipated in section 3.1, the Power Model is modelled in Simulink. It encapsulates the three production modules (shown in figure A.3), and it calculates the power generated by each wind turbine, solar panel and wave energy converter based on the discussed set of Excel datasheets, which shall be defined before starting the power simulation. In particular, the datasheets must be structured as defined in section 3.2, and must refer to, namely: wind speed, sun irradiation, solar panel voltage, wave energy per buoy and power demand. Such information may differ based on both the region where the farm shall be located as well as on the type of solar panels to be used. Once these information are gathered and the input spreadsheets are built, the Power Model simulation may be initiated.

Concerning the three power production blocks, the first unit (shown in figure A.5) reproduces the behavior of a single 8 MW windmill subject to the stimulus of the wind speed pattern reported in the wind speed Excel spreadsheet. It is important to note that further parameters such as nominal voltage, magnetization and blade pitch angle may be easily modified from within the *Wind Power Production* block, based on physical constraints. Secondly, the *Solar Power Production* module (shown in figure A.6) reproduces the current intensity flux generation by simply replicating the formulas reported in the literature, referred to a 12 V solar panel at environmental temperature [26]. Once more, further parameters involved in current intensity calculations may be easily modified within the block. Finally, the *Wave Power Production* (shown in figure A.4) is maintained, as requested by the stakeholders, as a *black box*: a mere data acquisition from the respective Excel datasheet is performed.

As the Power Model simulation runs, the three generated power production trends as well as the demand trend are sent to the Cost Model through *To workspace* blocks, where either 0,05 s or -1 (corresponding, in Simulink, to *inherited* from the spreadsheets) shall be set as time step value. This grants consistency across simulation. As the Power simulation ends, MATLAB's workspace receives these trends as 1-D arrays, allowing the Cost Model to process them as described in section 3.4.

3.4 The Cost Model

The Cost Model is designed entirely in MATLAB, which was selected since it granted the desired accuracy of investigation. As discussed in section 3.1, the Cost Model must run after the Power Model, since the former makes use of the power production trends generated by the latter. In fact, once the Power Model has run, such four produced trends will be available in the Cost Model's workspace within the standardized variable allocator *Out*. Once the user has selected the farm characterization whose profitability shall be analyzed, the desired inputs shall be set from function *input.m*. Such function grants the model's complete modularity and versatility towards different projects. Once the inputs are filled, the Cost Model requests the user to locate the production elements across the desired grid. Immediately afterwards, the Cost Model starts the autonomous assessment by taking into account, namely: each of the user inputs, ranging from the physical requirements of component to the cost categories; the four power trends from the Power Model; the grid characterization. In order to attain the overall profitability of the project, the Cost Model performs a sequence of intermediate steps of analysis, such as: the cables utilization per element across the grid during the simulation, in order to show the user any eventual cables' over-dimensioning; the comparison amongst power demand and power production; the stored power per iteration and the drained power per iteration, in order to present the Battery(ies) charge and discharge. The last intermediate step towards the profitability assessment is the calculation of the cost categories, namely: capital expenditures (CAPex) and operational expenditures (OPex). Obviously, as these depend on the nominal power production as well as on the power capacity of storage, it is strictly required that such stage is performed as from the designed sequence: namely, after both the Power Model has run as well as the grid characterization has been defined.

Once each of these intermediate steps are autonomously executed by the Cost Model during the simulation, the overall synthesis is achieved by condensing the attained information within the desired KPI: the levelized cost of energy (LCOE) [27]. The LCOE displays the cost involved, in €, in the production of a single MWh of energy. Finally, it must be noted that the presence of Ocean Batteries allows to generate additional revenues, since power excesses, which may be lost due to physical constraints of cables, may be stored and sold in a second instance. Such added value represents alleviation capital for operational expenditures. It is key to underline that the Cost

Model analyzes the selected grid for both the scenarios of Battery(ies) deployed and Battery(ies) not deployed. This provides immediate evidence to the investor regarding the profitability change involved by considering either one scenario or the other.

4 Results and Validation

The present chapter discusses the results attained by using the Techno-financial Model on selected scenarios. Firstly, the key assumptions characterizing the model and the simulated grid scenarios are examined, thus allowing a clear depiction of the fundamentals behind the results. Furthermore, the results of the validation process are here depicted, as anticipated in section 2.6. The pseudocodes of the formula governing the Model's processes are reported in Appendix C. On the other hand, a set of sensitivity analyses related to the scenarios here described are provided in chapter 5.

4.1 Modelling Assumptions

As for any model of dynamical systems, a precise set of assumptions were designated, ranging from the Ocean Battery's components to the price of energy. In order to grant complete modularity towards future model implementations, the present section enlists these assumptions, since these influence the attained results.

Firstly, the spreadsheets which are provided as input to the Power Model obviously influence the overall techno-financial assessment. In fact, an evidence of the difference in power generation, whilst diverse location are considered, is provided in the following sections. Peculiarly, it is critical to build the spreadsheets within Excel by acquiring precise and up-to-date data on the parameters enlisted in section 3.3. During the project, two locations were analysed: offshore Eemshaven, in the Northern Netherlands, and offshore Bayonne, in Western France. These were selected in order to provide instances of Model compliance and accurate response to a project location modification. Peculiarly, the spreadsheets contain information on sun irradiation $[W/m^2]$, wind speed $[m/s]$, solar panel voltage $[V]$ and wave power produced per buoy $[W]$ for both Eemshaven ([28] [29] [30] [31]) as well as Bayonne ([32] [33] [30]). In addition, the power demand $[W]$ was modeled by adapting the power load October 2020 trend to a yearly seasonal tendency [34]. Moreover, the voltage trends were built by selecting the type of solar panel to be considered: here, 12 V solar panels are used. Nonetheless, such parameter is easily modifiable in the Power Model from the *Solar Power Production* block. Therefore, these spreadsheets were manufactured by both taking documented and literature based values as pivots as well as by building a seasonality in order to represent realistic power generation and consumption. Nonetheless, these spreadsheets may be updated and changed at will a based on the project area to be examined with complete Model compliance and adaptation.

In addition, relatively to the *Wind Power Production* block in the Power Model, a three phase asynchronous 8 MW wind turbine is considered and used. Physical parameters of the wind turbine are available for consultation and modification within the respective block of the Power Model, as these respect those available in the literature [35]. Moreover, related to the *Solar Power Production* block in the Power Model, the processes, available in the literature [36], describing the current intensity generation procedure have been followed precisely in order to build the model of the solar panel. Additionally, an environment temperature of 25 Celsius degrees is used, and the list of used constant values is certifiable from the model, as it respect those in the literature [36]. Furthermore, concerning the trend of the power demand, it must be highlighted that a precise yearly trend was not discovered, peculiarly with such a time step accuracy. Therefore, the most reliable power demand trend available [34] was used and a seasonality was implemented, as evident from scanning the respective spreadsheet. Since such data regards the power demand for the Netherlands, the demand trend was afterwards reduced by a smart coefficient, which is changeable from function "inputs.m" based on grid characterization, in order for it to be comparable to the power production of the farm. Seasonalities were also implemented for the other built spreadsheets. Overall, a farm lifetime of 15 years has been selected, although the model allows to make use of different lifetimes for each of the deployed modules.

Furthermore, regarding the Ocean Battery a set of assumptions were implemented. Firstly, the Model allows to change the ratio (and specifically the two values as well) between energy capacity and power capacity from function "inputs.m". In particular, as previous investigations were conducted on this value [13], the optimal ratio of 0,75 was considered. This means that the full energy capacity is either filled or drained in 75% of an hour. Furthermore, the considered turbine is a Francis Turbine. Moreover, the energy capacity of the single Ocean Battery is set at the optimal value of 2,44 MWh [13] throughout the simulations. Since, as agreed with the stakeholders, the Model shall maintain a basic depiction of the Ocean Battery behavior, the charging and discharging of the Battery(ies) is only dependent on both the up-told ratio as well as on the difference amongst demand and the production. These information influence the dynamics behind the Battery(ies). Moreover, the price of energy has been set to the value used in previous investigations [13]: 40,05EUR/MWh, converted in EUR/W. Moreover, the AFRR energy market has been heuristically modelled, as forecasts on demand and production for the day consecutive to data production are calculated with the same time step used for the simulation: namely, 15 minutes. Nevertheless, to implement further market characterization and to base the Battery dynamics on a sell-on-price-based business case are easily allowed by the Model, since only two new respective functions shall be designed to replace or complement those now present. Finally, the farm lifetime is set at 25 years [37].

4.2 New Key Performance Index: the LCOG

As anticipated, the key performance indices actually available to assess the profitability of renewable production plants do not capture the added value of hybrid integrations presenting storage modules. In fact, two are the key performance indices available in the literature: the LCOE [27], and the LCOS [38]. In particular, the former evaluates the cost involved in the production of each MWh of energy for a renewable power production farm. On the other hand, the latter measures the cost per stored energy unit (MWh) with respect to the storage module only. Therefore, these do not capture the profitability of the comprehensive integrated system containing both production as well as storage. Viceversa, these are only accurate whilst describing each component, separately. Further investigation towards the definition of a more indicative index has progressed [13]. In such perspective, the present report introduces a new index: the levelized cost of Ocean Grazer (LCOG), expressed in EUR/MWh. In particular, the LCOG is defined as follows:

$$LCOG = \frac{CAPex + \sum\limits_{i=1}^{n} \frac{(OPex-R)}{(1+WACC)^i}}{\sum\limits_{i=1}^{n} \frac{P}{(1+WACC)^i}}, \tag{4.1}$$

where:

- CAPex = capital expenditures for the hybrid integration
- OPex = operational expenditures for the hybrid integration
- R = yearly revenues attained from Battery(ies) draining
- P = total power produced yearly by the production component of the hybrid integration
- n = lifetime of the hybrid integration
- WACC = weighted average cost of capital, calculated as from table A.7

By contrast, it is important to recall that the LCOE is constructed as follows:

$$LCOG = \frac{CAPex + \sum_{i=1}^{n} \frac{(OPex)}{(1+WACC)^i}}{\sum_{i=1}^{n} \frac{P}{(1+WACC)^i}}, \tag{4.2}$$

where:

- CAPex = capital expenditures for the hybrid integration
- OPex = operational expenditures for the hybrid integration
- P = total power produced yearly by the production component of the hybrid integration
- n = lifetime of the hybrid integration
- WACC = weighted average cost of capital, calculated as from table A.7

The Techno-Financial Model, as it is designed, provides an instant comparison, for a given wind farm characterization, amongst the case where the Ocean Batteries are deployed and the scenario where merely the production module is present. This allows investors to immediately visualize the profitability improvement allowed by the Ocean Battery(ies) deployment. Therefore, both the LCOG as well as the LCOE are assessed by the Techno-Financial Model for the selected scenarios, as discussed in chapter 5.

4.3 Investigated Scenarios

The Techno-financial Model's modularity grants unlimited grid customization, thus allowing to investigate the widest possible set of scenarios. the report presents the results related to a key grid scenario. In particular, a diversified offshore renewable production plant proposing not only wind, but also solar and wave power production is examined with the Techno-Financial Model in section 4.3.1. Afterwards, an offshore wind power production farm has been scrutinized, since it represents the most likely circumstance in which the Ocean Battery(ies) could be deployed, given the fact exposed in chapter 1. As two hosting sites for the plant are investigated: offshore Eemshaven and offshore Bayonne. With respect to both, the LCOE and LCOG are evaluated for an increasing number of wind turbines. The results are presented in sections 4.3.2 and 4.3.1.2, respectively, and discussed in chapter 5. Additionally, the location of Eemshaven is further investigated since it hosts the actual testing site for the device. Peculiarly, as the most profitable farm in terms of wind turbine deployed was assessed in the previous stage, such characterization is scrutinized through multiple sensitivity analyses based on, respectively: the ratio amongst energy storage capacity and expected power output, the number of added wave energy converters and the number of added solar panels.

Since the two locations are characterized by different relevant values (wind speed, sun irradiation and wave height), the next two sections presents the average values of these characteristics, which are pivotal for constructing the discussed spreadsheets to be provided as input to the Power Model. The following values have been acquired from relevant literature, as presented in section 4.1.

Input Spreadsheets for Offshore Eemshaven Firstly, the Model is tested relatively to the location of offshore Eemshaven, which is a critical location for Ocean Grazer, as it hosts the company's base hub and testing. The average values, for each specific parameter analysed, used to build the spreadsheet are:

- average wave height = 3,25 m
- average sun radiation = 0,72 W/m^2
- average wind speed = 10,98 m/s

A display of the attained results for the location of Eemshaven is proposed in section 4.3.2.

Input Spreadsheets for Offshore Bayonne Secondly, the report verifies the Model adaptation to location changes by analysing a site offshore the Western coast of France, whose key parameters recite as follows:

- average wave height = 4,87 m
- average sun radiation = 0,94 W/m^2
- average wind speed = 6,5 m/s

Evidence of the power simulation results for such location is provided in section 4.3.1.2.

4.3.1 Diversified Offshore Hybrid Integration

The current scenario analyses a 600,2 MW renewable production plant characterised by the presence of all three discussed renewable power production modules. In particular, the grid presents:

- 75 8MW wind turbines
- 25 solar panels
- 10 wave energy converters type Ocean Grazer WEC [39]
- 25 Ocean Batteries (Energy capacity 2,44 MWh; Turbine power 3,25 MW)
- 1 grid hub
- 324 km^2 grid

organized as presented in figure 4.1. The location is relevant since the model takes into account the location for calculating cables CAPex and OPex costs. Such grid plot is analysed for both the location of Eemshaven as well as for the location of Bayonne, as it will be presented in the next two sub-sections.

As evident from figure 4.1, the grid was organized by organizing the wind turbines at a precise inter-distance of 2 km, which is the minimum distance for wind speed recovery with respect to offshore wind farms [40]. Moreover, the solar panels have been condensed in a specific domain, which could correspond to the position of highest exposure to sun irradiation. Equivalently, the wave energy converters shall be located on the perimeter exposed to highest waves.

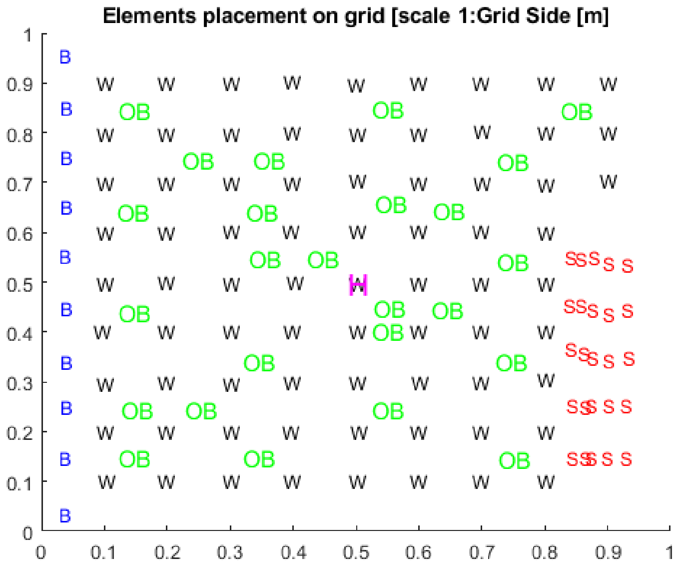

Figure 4.1: Scrutinized grid composition for the scenario presenting diversified production modalities. "W" labels wind turbines, "S" represents a solar panel, "B" stands for wave energy converter buoy, "OB" labels Ocean Batteries and "H" stands for grid hubs.

4.3.1.1 Northern Netherlands: Offshore Eemshaven - Results

Firstly, for the case in analysis it is key to underline that the location presents strong wind speed patterns throughout the whole year, as the average value of wind speed displays. As evident form figure A.9, the strength of the winds allows the wind turbine to produce the maximum amount for most of the simulation duration, namely 8 MW reduced by its intrinsic efficiency, which is modifiable from the Power Model. The initial transitory, evident from figure A.15, is required for the start-up of the wind turbine. From figure A.9, where it is evident how wind speed reductions imply plunge in power production. As, in the simulated scenarios, the wind speed datasheets never present a value triggering the cut-off speed control, this feature is not evident from these plots. An analogue display of yearly and daily trends are also provided from figure A.10 to figure A.13. In particular, it is evident from figure A.10 how the solar power production falls to zero whilst the sun irradiation does not at least equal a certain value.

From the yearly plots, it is possible to appreciate the seasonality implemented: as wind speed decrease are mostly present during middle part of the year, such period displays the highest instances of wind power production reductions. On the other hand, solar power production is amplified during summer periods, whilst wave height are reduced, compared to colder months. These factors display the accuracy in the power output as well as its relevancy to the provided input spreadsheets. Figures A.15 and A.17 present the difference amongst the sum of the power produced by the three modules and the power demand, as the daily (identical time window as before) trends are provided in figures A.14 and A.16. From the total power production plots it is key to point out how the wind turbine output critically represents the highest contribution. The demand as well presents an implemented seasonality, which influences the Battery(ies) usage. A comparison amongst production and demand across the selected day is provided in figure A.18.

In order to perceive the Ocean Battery(ies) behavior, it is possible to analyse figure A.18. Here, moments after the beginning of the 115th day, the demand exceeds the power production by around 50 MW. By contrast, slightly before day 115,3 the power production exceeds the demand by around 100 MW. Consequently, one would expect that after the beginning of the 115th day 50 MW were drained, whereas at moment 100 MW were stored slightly before day 115,3. As the expected draining is confirmed by figure A.21, it must be also taken into account that the Model takes into consideration the available capacity inside the battery at the previous moment as well as the turbine efficiency in order to calculate such amounts. In fact, from figure A.19 it is evident that the stored quantity is much less than 100 MW slightly before day 1153th, since both the available capacity left (shown in figure A.23) as well as the pump efficiency are taken into account in order to assess the stored power per iteration. Additionally, the Model assures that the maximum battery capacity is never surpassed. For the present case, 25 Ocean Batteries characterised by 2,44 MWh of energy capacity each were used. Thanks to the previously mentioned optimal value, 2,44 MWh correspond to 3,25 MW of turbine power. Therefore, the limit of $81,25MW$ of power capacity times the efficiency of the pump (0,9) must not be surpassed during the simulation. This is confirmed by figure A.24, where 74 MW is the ceiling level. Furthermore, from figures A.24 and A.26 it is possible to appreciate that the seasonality of the production and demand influences the quantities which are stored and drained as well as the total capacity available within the Battery(ies). In fact, from figure A.24 it is evident that the stored capacity is more readily available in overages during the summer period. on the other hand, during the other periods, the production is more often overwhelmed by the demand, leading to a more rare availability of stored power. On the other hand, from figures A.22 and A.26 it is possible to appreciate how during summer period the draining is occasional, since the demand is low, whereas during the other months the grid relies heavily on power draining from the Battery(ies).

As the cables capability to accept the produced power depends on the physical requirements of the cables themselves as well as on the produced power quantities, the mapping plots of such feature are provided in figures A.27 and A.28 for the cables connecting each production element with each Ocean Battery and for the cables connecting each production element with each grid hub, respectively. These values as those previously discussed influence the revenues attained during the simulation, since the cables can accept up to a maximum value of power, based on the parameters set in function "inputs.m", as presented in Chapter C.

The results attained by the Techno-financial Model concerning the profitability of such a configuration recite as follows:

$$\begin{aligned} LCOG &= 48,04EUR/MWh; \\ LCOE_{withoutstorage} &= 48,97EUR/MWh. \end{aligned} \tag{4.3}$$

These mean that an investor planning on a farm presenting production components only requires 61,26 EUR to produce one MWh energy to be provided to the grid. On the other hand, to deploy the Ocean Batteries within the plant allows to save more than 5 EUR/MWh. Such results are also, as expected, slightly higher than those reported in sections 4.3.2 for wind farm characterized by wind power only within the same production site. As such results refer to the location of Eemshaven, the next section presents the results attained by displacing the same farm characterization to offshore Bayonne.

4.3.1.2 Western France: Offshore Bayonne - Results

As discussed in section 4.3, the simulation has been performed also based on data relatively to a different location, in order to display that the model would also display pertinence to the spreadsheets provided as inputs. Consequently, the area of offshore Bayonne, in Western France, was considered. As expected given the average values presented in section 4.3, the 8 MW wind turbines rarely, if not never, reach their stable output value, since the wind speed is never stable and high enough, as shown in figures A.30. On the other hand, both the solar power production as well as the wave power production presents more significant trends throughout the year, as evident from figures A.31 and A.32. This reflects to the total produced power, plotted in figure A.33.

The results attained by the Techno-financial Model concerning the profitability of such a configuration correspond to:

$$\begin{aligned} LCOG &= 51,04 EUR/MWh; \\ LCOE_{withoutstorage} &= 51,47 EUR/MWh. \end{aligned} \tag{4.4}$$

Such a difference in profitability whilst compared to the previous location is motivated by the fact that the site of Bayonne does not exploit the high power density characterizing the wind power production, thus implying lower produced power amounts compared to the expected power output of the plant.

4.3.2 Wind Offshore Hybrid Integration

The current scenario analyses a grid characterised by the presence of exclusive wind power production as a generation mean. In particular, the grid presents:

- 75 wind turbines
- 25 Ocean Batteries (Energy capacity 2,44 MWh; Turbine power 2,44/0,75 MW)
- 1 grid hub
- 324 km^2 grid

Such scenario is highly more likely than a grid characterization featuring three production modules simultaneously, given the discussion performed in chapter 1. The following picture shows the elements disposition across the grid for the case of analysis.

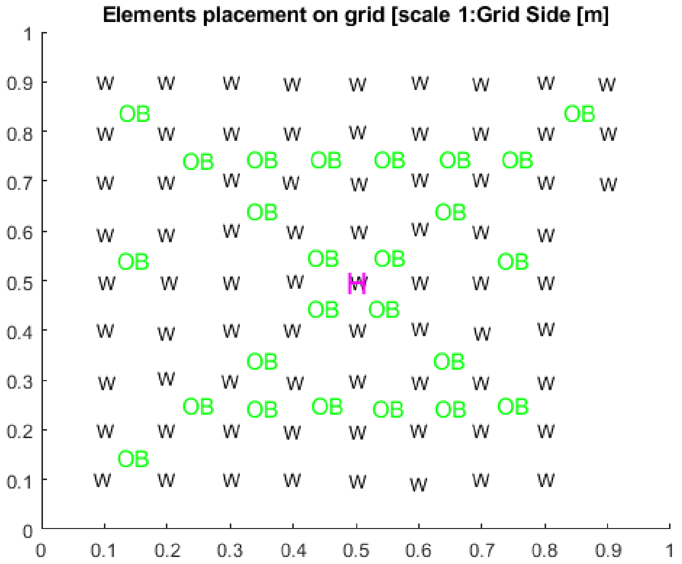

Figure 4.2: Scrutinized grid composition for the scenario of exclusive wind power production. "W" labels wind turbines, "OB" labels Ocean Batteries and "H" stands for grid hubs.

Since in chapter 1 the focus was placed onto the investments towards offshore wind farms planned by the Dutch government, and given the fact that Ocean Grazer's testing hub is located in Eemshaven, such grid investigation has been conducted relatively to the site of offshore Eemshaven. Therefore, the pivotal values around which the input spreadsheets initiating the Model simulation are built correspond to those reported in section 4.3.

4.3.2.1 Northern Netherlands: Offshore Eemshaven - Results

Here, analogue considerations to those performed in the previous sections may be conducted, stemming from the difference amongst demand and power production, represented in A.41. Moreover, it is possible to note from figure A.45 that the maximum quantity stored per iteration equals around 68 MW, whereas from figure A.47 the maximum level of total stored power across the simulated period never exceeds the same level discussed previously. This is due to the fact that 25 Ocean Batteries characterised by 1 MW of turbine power and 2,44 MWh of energy capacity each are deployed, leading to 2,44/0,75 = 3,25 MW times the pump efficiency of power stored per Battery. This results in an available power capacity of around 73,5 MW, which is indeed the maximum amount of stored power reached in figure A.47. On the other hand, figures A.49 and A.47 represent the drained and stored power amounts across the simulation, which are dependent on the difference amongst the production and the demand. Once more, the same analysis performed in section 4.3.1.1 may be conducted on figures from A.41 to A.49. Finally, both the annual trends represented in figures A.47 and A.49 present a seasonality, as expected.

The results attained by the Techno-financial Model concerning the profitability of such a configuration correspond to:

$$\begin{aligned} LCOG &= 47,81 EUR/MWh; \\ LCOE_{withoutstorage} &= 48,72 EUR/MWh. \end{aligned} \tag{4.5}$$

As obvious, the profitability of the current scenario is slightly higher than the profitability of the scenario discussed in section 4.3.1.1. This is motivated by the fact that the capital and operational expenditures involved in the deployment of low power density devices, such as solar panels in particular, is here non existent. On the other hand, the grid is composed completely of high power density devices, the 75 8 MW wind turbines, which interact with the 25 Batteries to grant a higher plant profitability.

4.4 Results Validation

AS described in section 2.6, the validation process involved two diverse stages. Initially, the Power Model quality was questioned. In fact, to attain precise results from the Power Model was crucial in order to execute a precise financial simulation as well, as explained in chapter 3. Nevertheless, the quality of the Power Model's outputs was continuously scrutinized. Secondly, the Cost Model quality, sub-section by sub-section, was questioned: the objective of such stage was to verify the pertinence between the results attained from the simulation and those reported in the literature for analogue cases. Such comparison was supported by helpful meeting with the stakeholders involved as well. Furthermore, the overall results of the techno-financial assessment was analysed with the same target, in order to verify the comparability with data available from both academic as well as industry-based literature. The following two paragraphs provide precise depiction of the operated design validation process.

Firstly, the sub-results obtained were verified step by step autonomously and presented with periodical cadence to the stakeholders, whose more experienced and non-biased judgement provided key feedback and allowed crucial improvements. Values ranging from the capital expenditures for the production modules, and from the operational costs for the storage component to the stored power amounts, were subject to progressive questioning and verification, continuously. In fact, to attain a certain level of precision on such intermediate steps would have granted an accurate overall techno-financial assessment, based on the assumptions (section 4.1). Therefore, for instance, the cost categories for the wind power production modules were acquired from relevant literature and compared with values there reported. The same procedure was operated with respect to the solar power production module as well as to the wave power production component. Secondly, the result of the overall techno-financial assessment, namely the LCOG and the LCOE [27], were compared with those presented in the literature for comparable grid scenarios [41] [42] [43] [44] [45] [46] [47] [48] [49] [50] [51] [52] [53] [54] [55] [56] [57] [58] [59] [60]. Peculiarly, the attained assessment on the LCOE for the scenario of wind farm located at offshore Eemshaven are in range with those reported in the literature for analogue grid characterizations in the North Sea.

Moreover, the Techno-Financial Model versatility and modularity were assessed in order to validate its usability. Throughout the whole design project, both the supervisors as well as the interested stakeholders highlighted a correct direction of the Model. Furthermore, the Model was addressed as crucial for further investigating the profitability of future projects involving the presence not only of the Ocean Batteries, but also of wave energy converters alongside the more diffused wind power production module. Nonetheless, alongside such positive response, the stakeholders maintained a critical perspective on the Model's design, so that constructive and helpful feedback was always granted. Such an improvement process was crucial in order to identify design weaknesses as well as to progressively improve the Model output by refining its behavior.

Since the Model represents an idealized replica of a highly dynamical system inserted into a complex context, it obviously required to set a sequence of assumptions which overall influence the Model response (section 4.1). Unfortunately, given the reduced time window of the design project, few modelled behavior were not implemented as precisely as they shall realistically behave. Although the problem owner highlighted in one of the last online meetings the basic nature of the requested tool, an increased level of accuracy in details, such as the modelling of the energy market as well as of the Ocean Battery behavior during charging and discharging, is here highly suggested by the researcher as an important step towards the Model improvement. Additionally, the more scoped scrutiny of the cost components related to the storage module (to be expected from P. S. Dijkstra's research) shall be immediately performed in order to insert in the Techno-Financial Model the most up-to-date data from the literature. Overall, the here presented and designed Techno-Financial Model accomplished the target of representing the Ocean Battery alongside production components within an offshore wind farm, by also producing a comprehensive financial assessment on projects including the device. Additionally, the Techno-Financial Model also grants complete modularity, as it was initially agreed with the company. Even though the results attained from the Techno-Financial analysis are within reasonable range from those reported in up-to-date literature, the student approach has always been focused towards continuous Model improvement. consequently, the previously suggested implementation are considered as key in order to refine the Model's response.

5 Discussion

The present chapter discusses the results attained in the techno-financial assessment for the scenarios examined in section 4.3. Furthermore, sensitivity analyses were performed with respect to these scenarios by tracking the performance indices (namely, the LCOE and the LCOG), for a selection of changing parameters. It is important to recall that the obtained results are influenced by the assumption discussed in section 4.1. The next paragraphs discuss the results attained from the sensitivity analyses, in particular.

Firstly, a sensitivity was performed on an offshore wind farm by increasing the expected power output from the plant: namely, by increasing the number of 8 MW wind turbines deployed. Here, the optimal amount of wind turbines granting the lowest cost per energy unit was investigated. Therefore, the LCOE exclusively was evaluated, since only the wind power production module is deployed within the plant. Such scrutiny was conducted for both the locations of Eemshaven as well as Bayonne, as evident from figures 5.1 and 5.2, which refer to tables A.52 and A.53, respectively. By analysing these plots, it is immediately possible to certify an expected outcome. In fact, offshore Eemshaven is characterised by stronger wind patterns on average whilst compared to offshore Bayonne, as presented in section 4.3. Consequently, for identical amounts of 8 MW wind turbines to produce one MWh of energy is more expensive in Bayonne than in Eemshaven. This is motivated by the fact that, thanks to the wind intensity in the analysed Dutch region, the wind turbines often provide the grid with the maximum expected power output. On the other hand, identical 8 MW turbines located in offshore Bayonne never reach the maximum expected power output, thus leading to lower yearly produced power amounts for the same capital expenditures, which represent the highest pricing share. As a consequence, the costs per energy unit in Bayonne are consistently higher than those for Eemshaven, for the same amount of deployed wind turbines, as evident from figures 5.1 and 5.2. Therefore, the Techno-Financial Model would here suggest to either relocate the French project or to make use of smaller wind turbines. Moreover, these plots allow to visualize the economy of scale, since for increasing number of wind turbines the cost per energy unit decreases until a minimum is reached. Afterwards, the cost per energy unit starts to slowly invert the trend. The expected power output allowing the minimum cost per energy unit is, with respect to 8 MW wind turbines: 760 MW, corresponding to 95 wind turbines. Nonetheless, as the average expected power outputs of either functioning or planned European wind farms is equal to *circa* 600 MW [?], such grid characterization is investigated in the next sensitivity analyses.

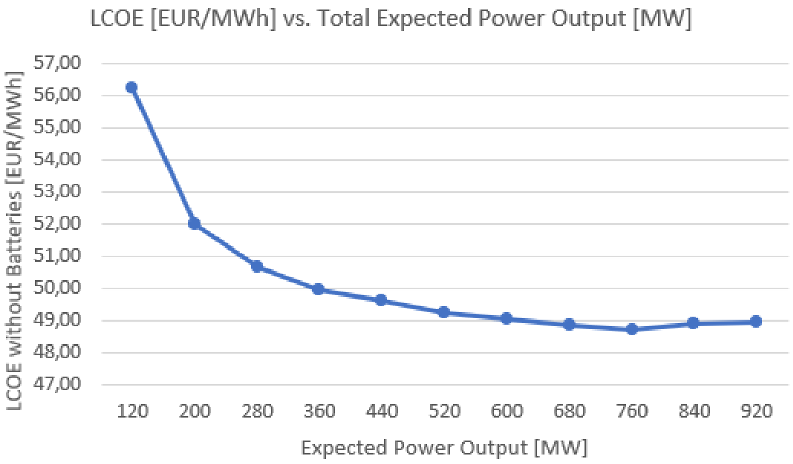

Figure 5.1: Plot of the sensitivity analysis on the number of wind turbines with respect to the location of Eemshaven.

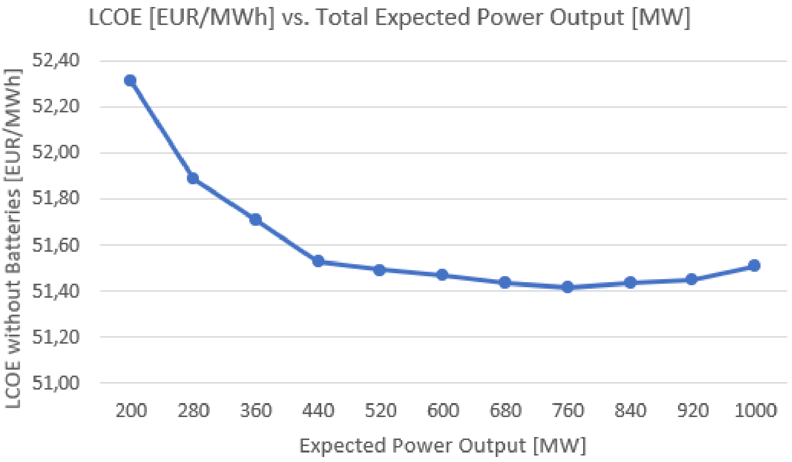

Figure 5.2: Plot of the sensitivity analysis on the number of wind turbines with respect to the location of Bayonne.

As the expected power output of 600 MW is set, the optimal ratio between the installed energy storage and the expected power output (in [MWh/MW]) is assessed, as evident from figure 5.3 and table A.54. Here, two factors must be recalled. Firstly, the optimal energy capacity value of 2,44 MWh [13] was set for each Ocean Battery. Secondly, to deploy the Ocean Batteries as on-site storage devices not only grants higher returns in terms of drained energy based on need, but also requires more significant expenditures. As the technology development with respect to PHS has in the last decade reached a plateau [61], both capital as well as operational expenditures per storage energy unit are recently subject to modest decrease, whilst compared to further technologies. As evident from figure 5.3, to deploy the Ocean Battery as on-site storage devices immediately grants lower price per energy unit. In fact, the LCOG is, for low values of the ratio, increasingly lower than the value of the LCOE. Nonetheless, as the ratio and thus the number of Batteries increase, CAPex and OPex progressively surpass the profits granted by the draining of the Batteries. In fact, the delta in LCOG value from one ratio value to the following slightly increases. Although to increase the amount of energy storage leads to an increase in costs, the sensitivity analysis suggests that, until the energy storage capacity of the farm equals 30% of the plant expected power output, the Battery(ies) deployment is profitable. This is motivated by the fact that the drained energy generates returns which mitigate the operational expenditures. By contrast, above a ratio of 0,3 for a 600 MW wind farm, the cost involved for the storage module surpasses the benefits attained through energy draining. As future research, to further examine the relation amongst plants expected power outputs and the optimal ratio, between expected power output and energy storage capacity, is key. The Techno-financial Model would support such investigation, given its complete modularity.

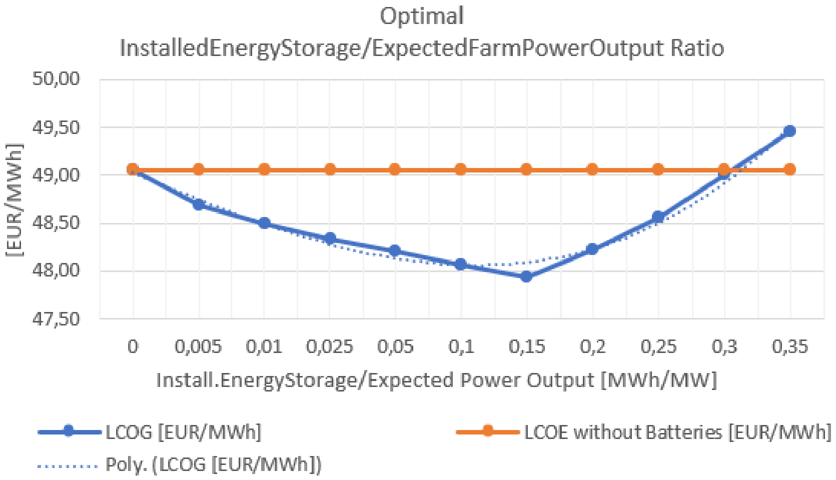

Figure 5.3: Plot of the sensitivity analysis on the optimal (energy capacity of storage - expected power output) ratio with respect to the location of Eemshaven.

Now, the inclusion of further renewable power production means is discussed. In particular, the sensitivity to a progressively increasing presence of wave power production components is firstly measured on the performance indices (LCOG and LCOE). Afterwards, the same scrutiny is performed with respect to floating solar arrays.

The results concerning the deployment of an increasing number of Ocean Grazer WEC arrays, within a 600 MW offshore wind farm, are plotted in figure 5.4 and reported in table A.55. As wave energy converters are typically high power density devices, their influence on the overall LCOG and LCOE assessment is modest. Here, Ocean Grazer wave energy converters are considered [39]. In fact, although the cost per array is significant, the high amount of produced power grants an overall stability to both indices, which slowly increase from the case where 1 arrays are deployed to the scenario where the 600 MW wind farm is complemented with 10 arrays. From table A.55, it is possible to quantify the effect on the LCOE and LCOG, with regards to a 600 MW offshore wind hybrid integration, as follows: the addition of 10 additional WEC arrays only accounts for a $+3,76\%$ on the LCOG and for $+4\%$ on the LCOE.

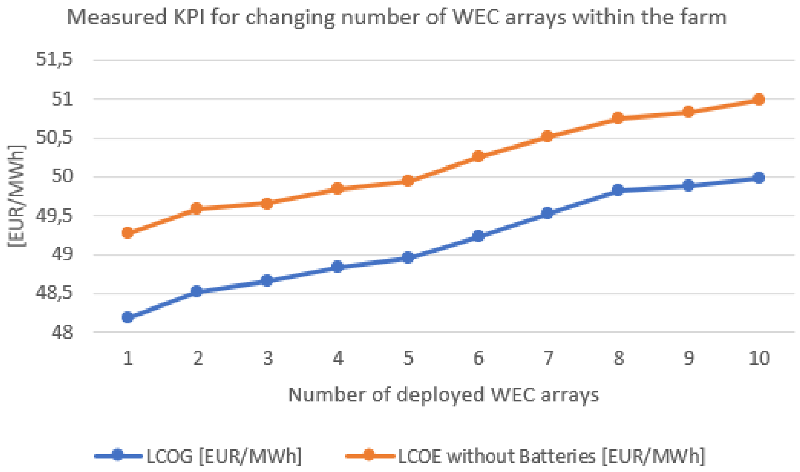

Figure 5.4: Delta from the sensitivity analysis on the number of WEC arrays with respect to the location of Eemshaven. Each Ocean Grazer WEC array contains 16 buoys [62]

Multiple considerations may be extracted. Firstly, the impact of the addition of each WEC array reflects, on both the LCOE and LCOG, the economy of scale, as the trends' slope tend to reduce. Additionally, it is motivated by the fact that the high cost per device, combined to the high power output density per device, progressively balance itself on a plant characterized by medium to high expected power output. In fact, it must be recalled that the power produced through waves would still account for a modest share if compared to 600 MW, even in the case where 10 arrays are deployed.

On the other hand, the results of the deployment of an increasing number of solar panels within a 600 MW offshore wind farm, are plotted in figure 5.5 and reported in table A.56. Similarly to the considerations examined in the previous paragraph, the economy of scale is also evident. Whilst analysing plot 5.5, it must be recalled that, differently from the wind turbines and WECs, solar panels are low power density components. For instance, since wind turbines produce higher power outputs, the 2,24 MWh Batteries are more efficiently employed in terms of charging and draining. As higher energy capacity is available and higher power is produced, increased overall stored and drained amounts are possible in such scenarios, leading to an increase in revenues attained from draining. Consequently, components as such more decisively balance the increase in capital and operational expenditures involved in storage nominal capacity increase. Therefore, since on average, with respect to offshore Eemshaven, each floating solar array produces 1000 W at peak [63], larger amounts of solar arrays are required in order to provide a 600 MW plant with relevant produced power shares balancing the increase in capital and operational expenditures. In fact, as the number of floating solar arrays increases, both the LCOG as well as the LCOE stabilize, as the LCOE inverts the trend. This is motivated by the fact that the increase in revenues, granted by a more stable and distributed Battery draining processes, more efficiently balances the expenditures.

Finally, although the most relevant scenarios were here discussed, the complete modularity granted by the designed Techno-financial Model allows to perform the widest possible set of sensitivity analyses. For instance, although during the present scrutiny, as discussed, a set of optimal values (identified from previous investigations [13]) were used, the ratio between energy capacity and power output with regards to each Battery may be changed, and analyses may be conducted on such values based on need. The Techno-financial Model allows the user to select more than 90 inputs, ranging from physical requirements to pricing categories. Such complete Model versatility towards parameters modification was initially demanded by the company, so that the implemented tool could be used to perform assessments on the most diverse projects.

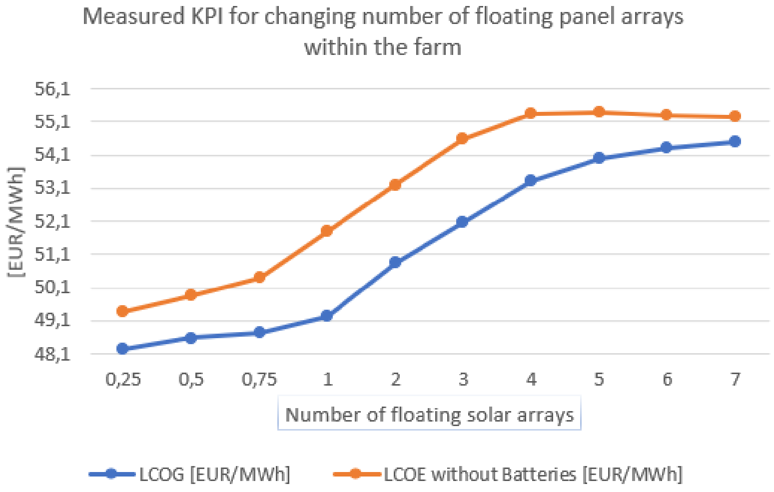

Figure 5.5: Delta from the sensitivity analysis on the number of floating solar arrays with respect to the location of Eemshaven. Each floating module contains 100 solar panels. [63]

6 Conclusions

The report aimed to propose a detailed overview of the artifact implemented during the design project conducted at Ocean Grazer B.V. from September 2020 to January 2021. As delineated in section 2.3, the company requested for a basic, modular tool for conducting techno-financial assessments on offshore hybrid integrations displaying their device, the Ocean Battery, as on-site storage solution. Ocean Grazer requires such a comprehensive model in order to present to investors the profitability improvement allowed by the Ocean Battery deployment within offshore renewable energy production plants. This is crucial to strengthen the company's business models, which rotate alongside the Ocean Battery. Consequently, once the problem statement was identified as presented in section 2.3, the project goal was provided in section 2.5. Afterwards, a precise project methodology was delineated and described in section 2.6: namely, the Design Cycle [25]. Such process was guided by a precise set of both research and design questions, enlisted in section 2.7. To follow such procedure was key in order to design and implement a tool presenting both accuracy as well as pertinence to the company's requirements.

Therefore, chapter 3 examines the structure of the designed Techno-financial Model. Peculiarly, here its two key constituents were introduced and described in detail, namely: the Power Model and the Cost Model. Once the nature of the designed artifact was outlined, a set of elected energy market scenarios was chosen and discussed. Such scenarios represent grid characterizations likely to host the Ocean Batteries as on-site storage devices. The Techno-Financial Model was tested and validated by assessing the profitability of these grid compositions, as discussed in chapter 4. In particular, not only a 600,2 MW offshore renewable plant presenting the three different production modules (solar power, wind power and wave power production) was analyzed for two different locations (offshore Eemshaven, in the Netherlands, and offshore Bayonne, in France), but also a 600 MW wind farm featuring the Ocean Batteries as on site storage devices was investigated for the former location. As discussed in chapter 4, the Techno-financial Model produces an overall profitability assessment by evaluating the costs involved in the production of each energy unit.

Peculiarly, given a specific farm characterization the Model calculates: the LCOE [27] of the farm; the LCOG (introduced in section 4.1) of an identical plant, but complemented with a given set of Ocean Batteries as on-site storage solution. This allows investors to immediately visualize the overall profitability improvement allowed by the Ocean Batteries deployment. As the results concerning the discussed scenarios were attained and presented, sensitivity analyses were conducted on the 600 MW wind farm characterization, as examined in chapter 5. During such stage, the variations of the mentioned performance index (LCOE and LCOG), induced by both physical constraints as well as grid parameters modifications, were observed. Peculiarly, both the LCOE and LCOG for a 600 MW wind farm were recorded and discussed in chapter 5 for changing: grid homogeneity, energy capacity of the Ocean Batteries versus expected power output of the plant ration, number of solar panels, cardinality of wave energy converters

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List of Figures

A Appendix - Diagrams, Tables and Plots

- Power trends
- Used Demand
- Cable capacities per type of connection (Element to hub, element to storage, hub to shore)
- Battery charging and discharging

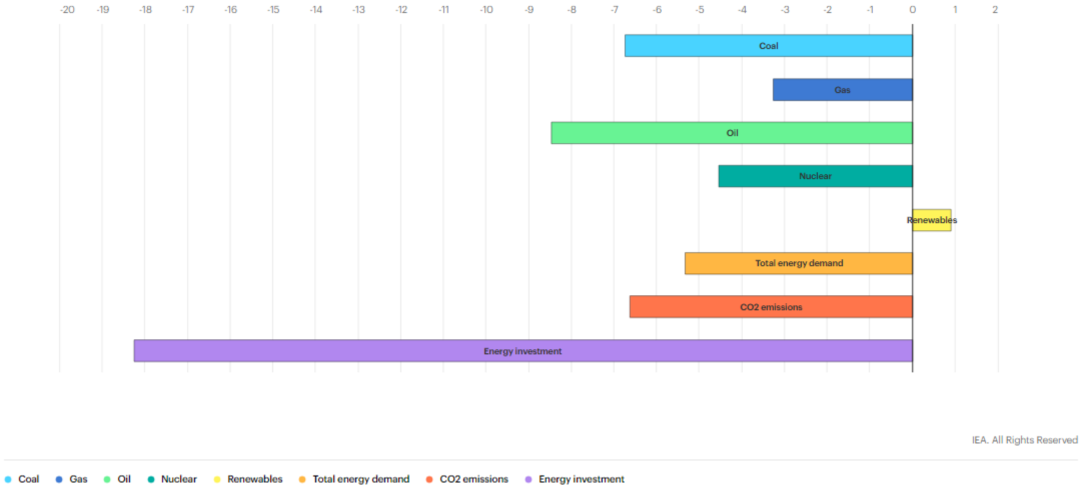


Figure A.1: Percentage variations of investment indices and of other key index for 2020, compared to 2019, relatively to the energy sector [4].

A.1 Power Model Blocks

Figure A.2: Power Analysis block of the Power Model in Simulink.

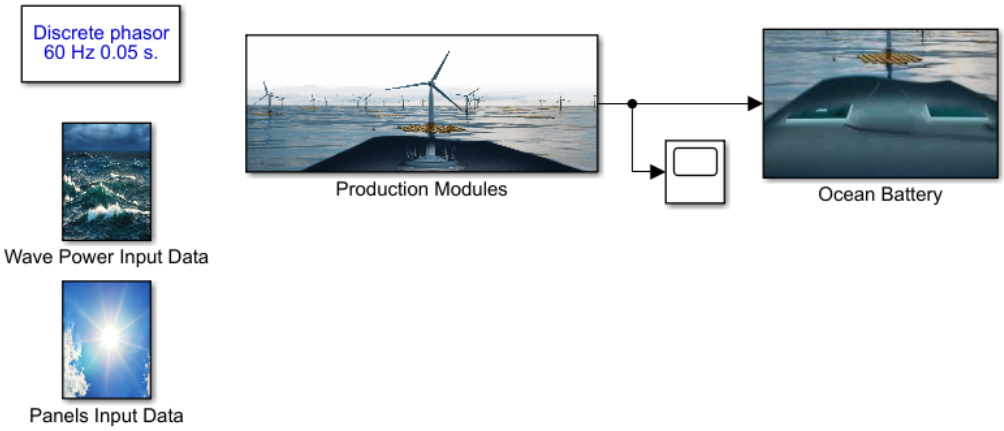


Figure A.3: First level decomposition of the Power Analysis block of the Power Model in Simulink.

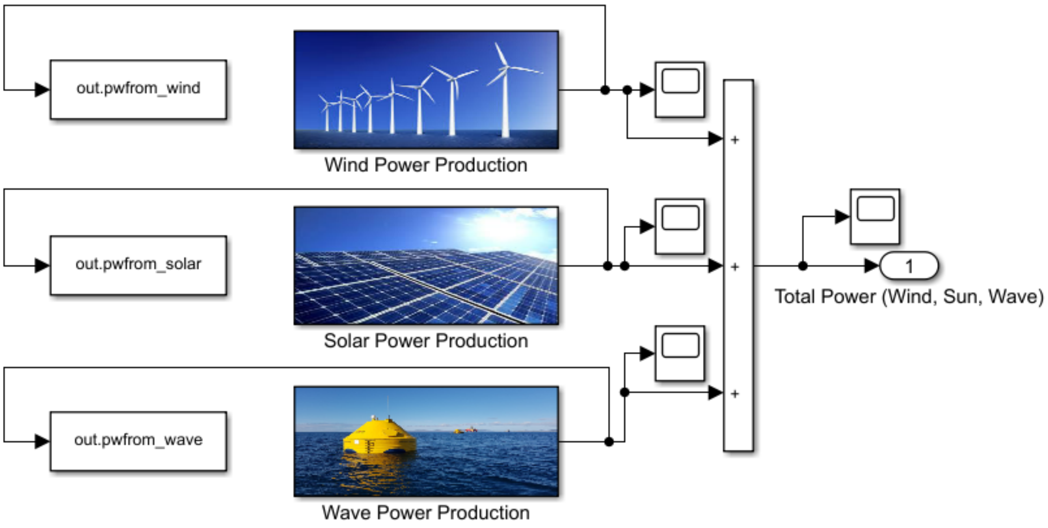


Figure A.4: Second level decomposition of the Power Analysis, Production Modules block of the Power Model in Simulink.

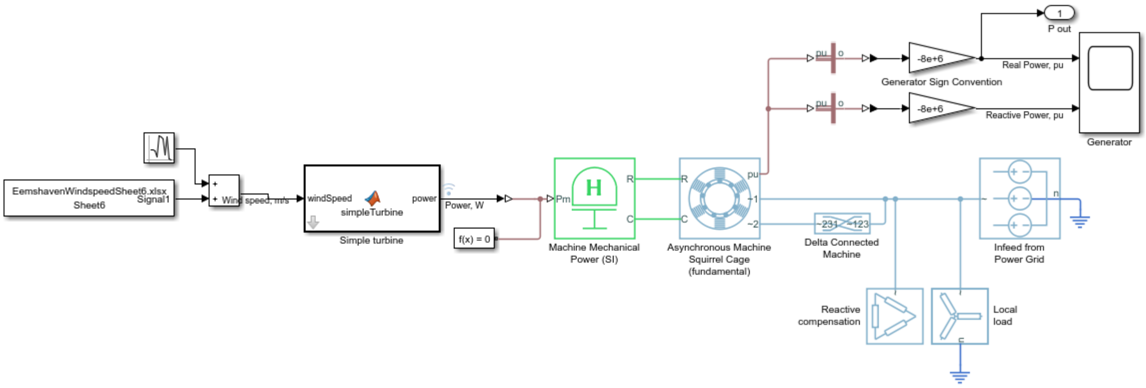


Figure A.5: Third level decomposition of the Power Analysis, Production Modules, Wind Power Production block of the Power Model in Simulink [35]

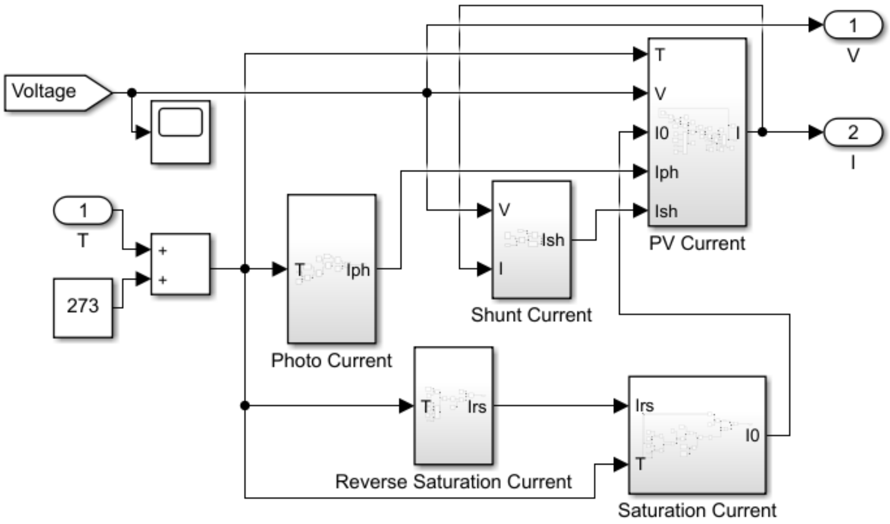
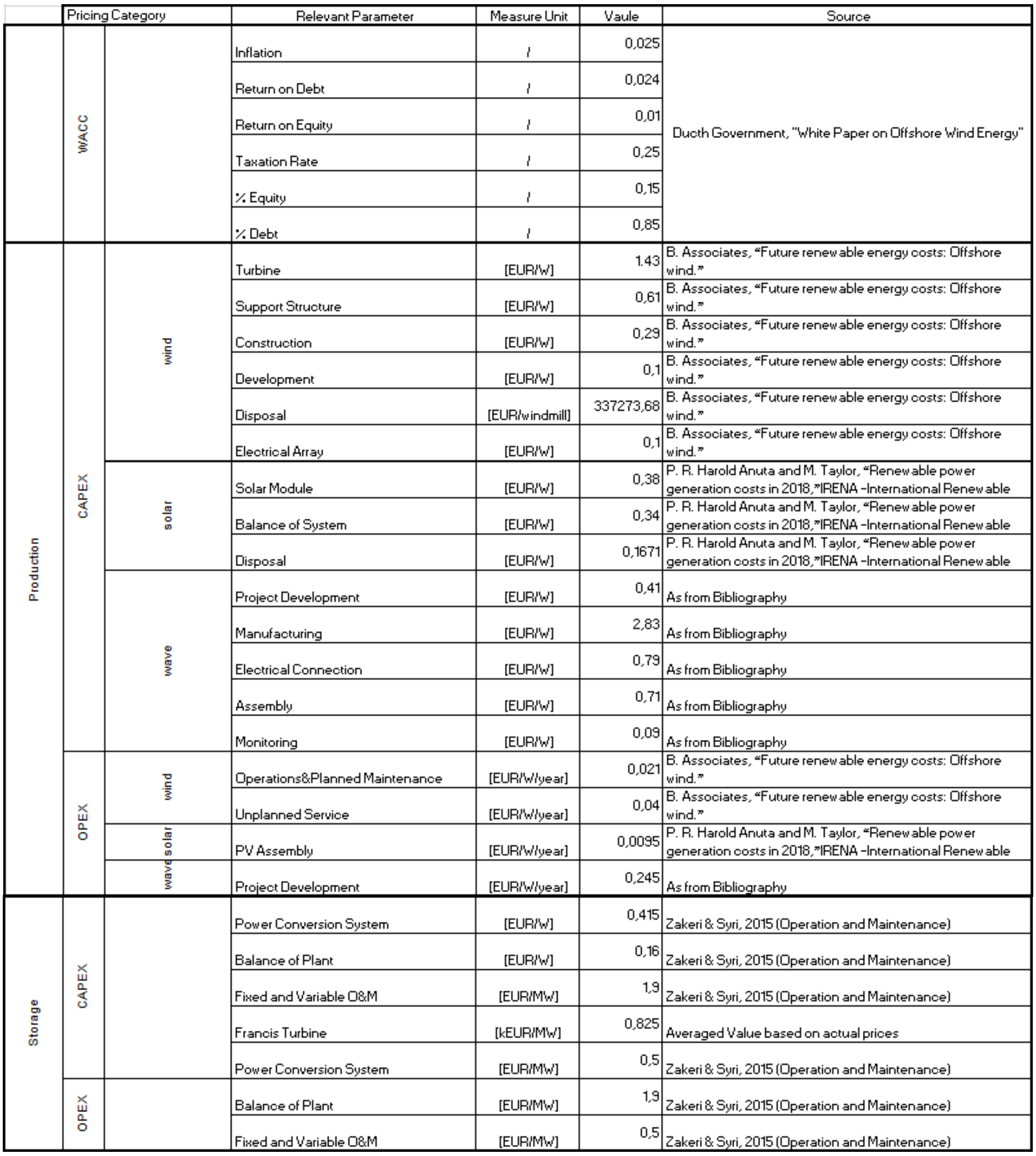


Figure A.6: Third level decomposition of the Power Analysis, Production Modules, Solar Power Production block of the Power Model in Simulink.

A.2 Cost Categories



Pricing Category			Relevant Parameter	Measure Unit	Vaule	Source
Production	WACC		Inflation	/	0,025	Ducth Government, "White Paper on Offshore Wind Energy"
			Return on Debt	/	0,024	
			Return on Equity	/	0,01	
			Taxation Rate	/	0,25	
			% Equity	/	0,15	
			% Debt	/	0,85	
	CAPEX	wind	Turbine	[EUR/W]	1.43	B. Associates, "Future renewable energy costs: Offshore wind."
			Support Structure	[EUR/W]	0,61	B. Associates, "Future renewable energy costs: Offshore wind."
			Construction	[EUR/W]	0,29	B. Associates, "Future renewable energy costs: Offshore wind."
			Development	[EUR/W]	0,1	B. Associates, "Future renewable energy costs: Offshore wind."
			Disposal	[EUR/windmill]	337273,68	B. Associates, "Future renewable energy costs: Offshore wind."
			Electrical Array	[EUR/W]	0,1	B. Associates, "Future renewable energy costs: Offshore wind."
		solar	Solar Module	[EUR/W]	0,38	P. R. Harold Anuta and M. Taylor, "Renewable power generation costs in 2018,"IRENA -International Renewable
			Balance of System	[EUR/W]	0,34	P. R. Harold Anuta and M. Taylor, "Renewable power generation costs in 2018,"IRENA -International Renewable
			Disposal	[EUR/W]	0,1671	P. R. Harold Anuta and M. Taylor, "Renewable power generation costs in 2018,"IRENA -International Renewable
		wave	Project Development	[EUR/W]	0,41	As from Bibliography
			Manufacturing	[EUR/W]	2,83	As from Bibliography
			Electrical Connection	[EUR/W]	0,79	As from Bibliography
			Assembly	[EUR/W]	0,71	As from Bibliography
			Monitoring	[EUR/W]	0,09	As from Bibliography
	OPEX	wind	Operations&Planned Maintenance	[EUR/W/year]	0,021	B. Associates, "Future renewable energy costs: Offshore wind."
			Unplanned Service	[EUR/W/year]	0,04	B. Associates, "Future renewable energy costs: Offshore wind."
		solar	PV Assembly	[EUR/W/year]	0,0095	P. R. Harold Anuta and M. Taylor, "Renewable power generation costs in 2018,"IRENA -International Renewable
		wave	Project Development	[EUR/W/year]	0,245	As from Bibliography
Storage	CAPEX		Power Conversion System	[EUR/W]	0,415	Zakeri & Syri, 2015 (Operation and Maintenance)
			Balance of Plant	[EUR/W]	0,16	Zakeri & Syri, 2015 (Operation and Maintenance)
			Fixed and Variable O&M	[EUR/MW]	1,9	Zakeri & Syri, 2015 (Operation and Maintenance)
			Francis Turbine	[kEUR/MW]	0,825	Averaged Value based on actual prices
			Power Conversion System	[EUR/MW]	0,5	Zakeri & Syri, 2015 (Operation and Maintenance)
	OPEX		Balance of Plant	[EUR/MW]	1,9	Zakeri & Syri, 2015 (Operation and Maintenance)
			Fixed and Variable O&M	[EUR/MW]	0,5	Zakeri & Syri, 2015 (Operation and Maintenance)

Figure A.7: Pricing categories implemented in the Cost Model.

A.3 Diversified Offshore Hybrid Integration: Offshore Eemshaven

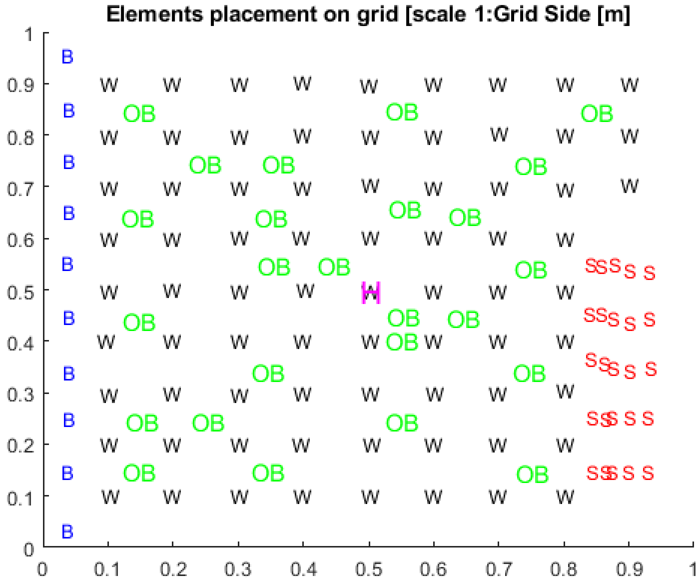


Figure A.8: Scrutinized grid composition for the scenario of diversified production modalities.

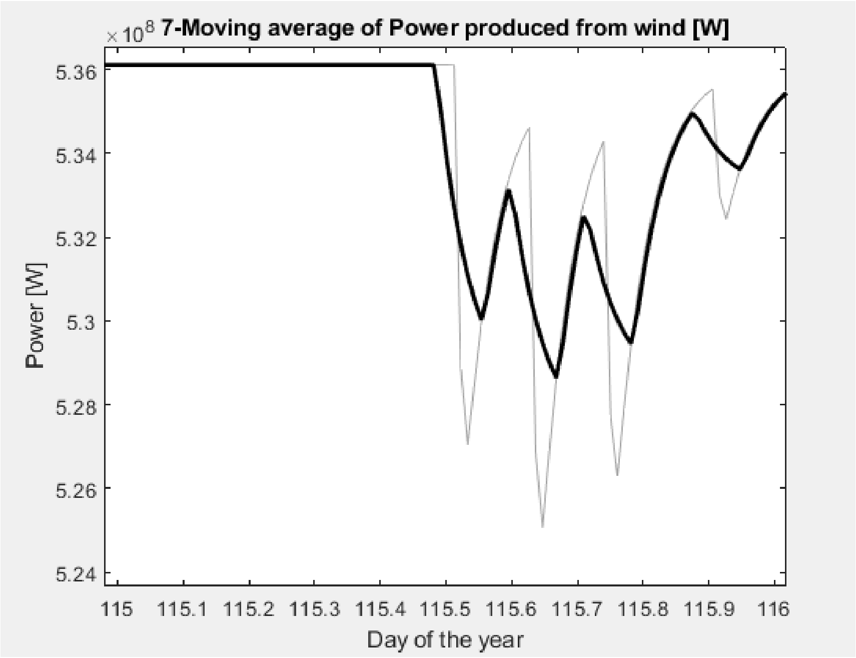


Figure A.9: Focus on day 115th for the wind power production yearly trend.

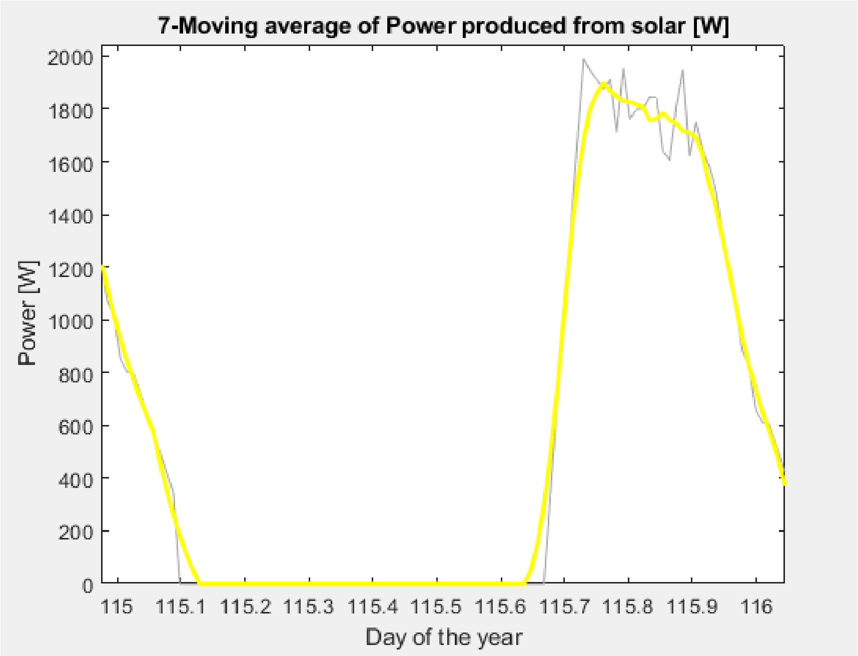


Figure A.10: Focus on day 115th for the solar power production yearly trend.

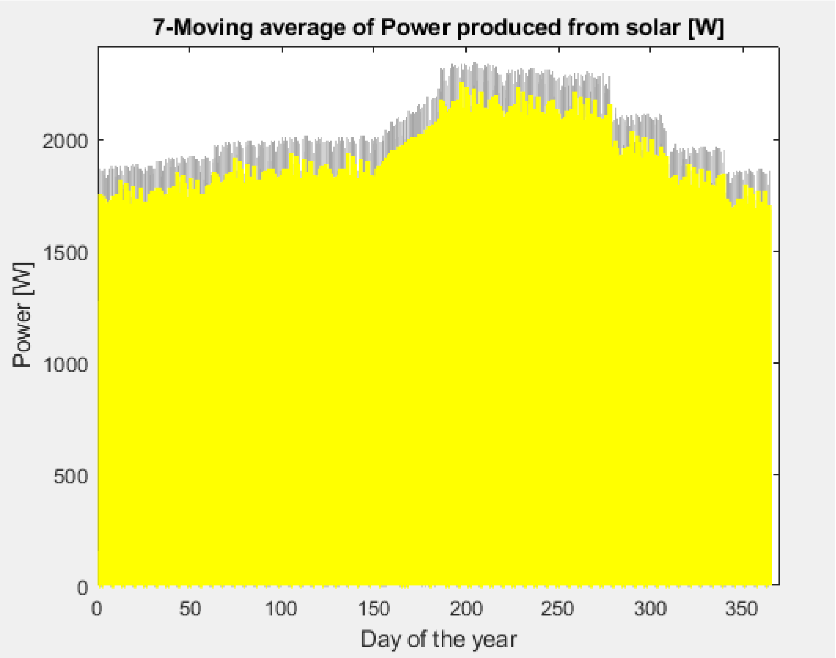


Figure A.11: Solar power production yearly trend.

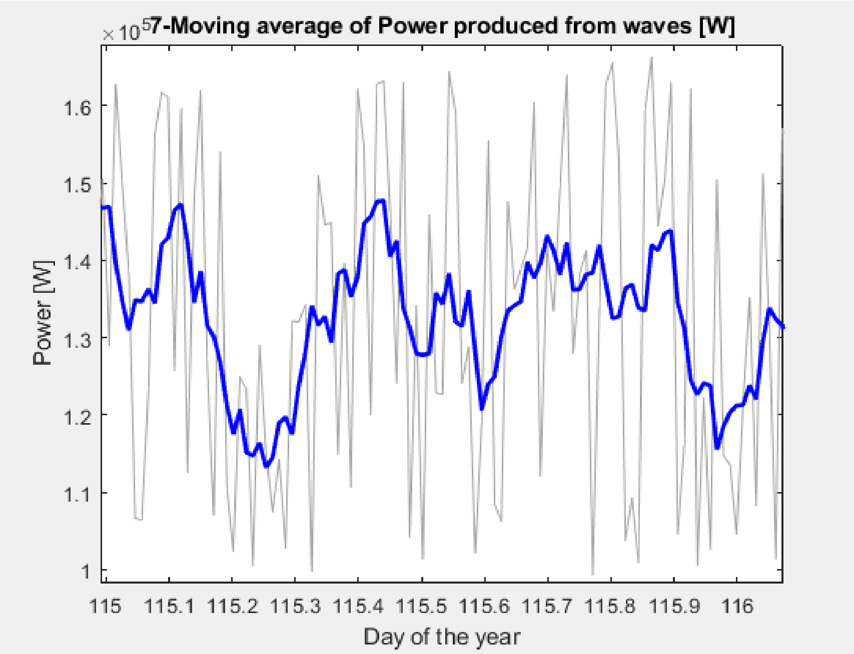


Figure A.12: Focus on day 115th for the wave power production yearly trend.

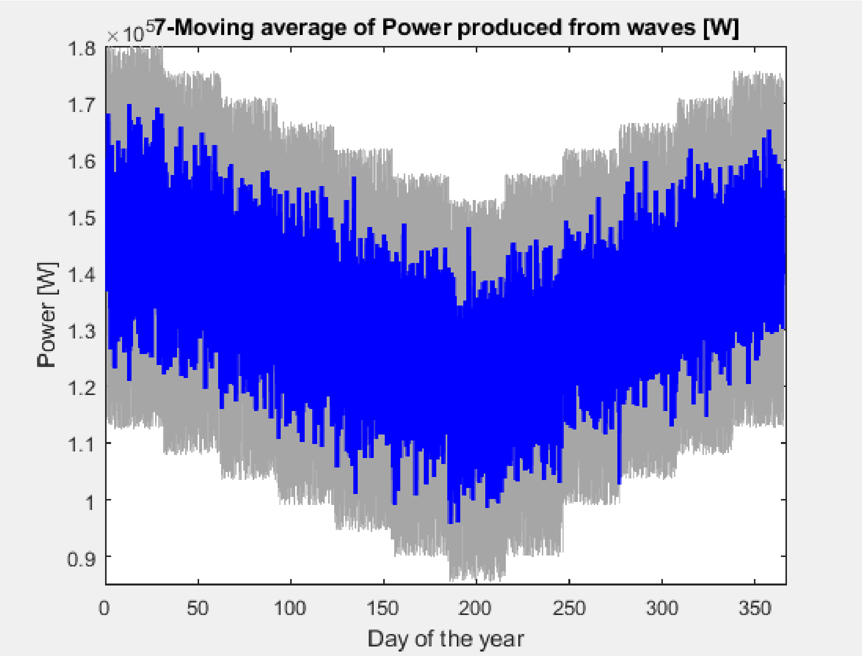


Figure A.13: Wave power production yearly trend.

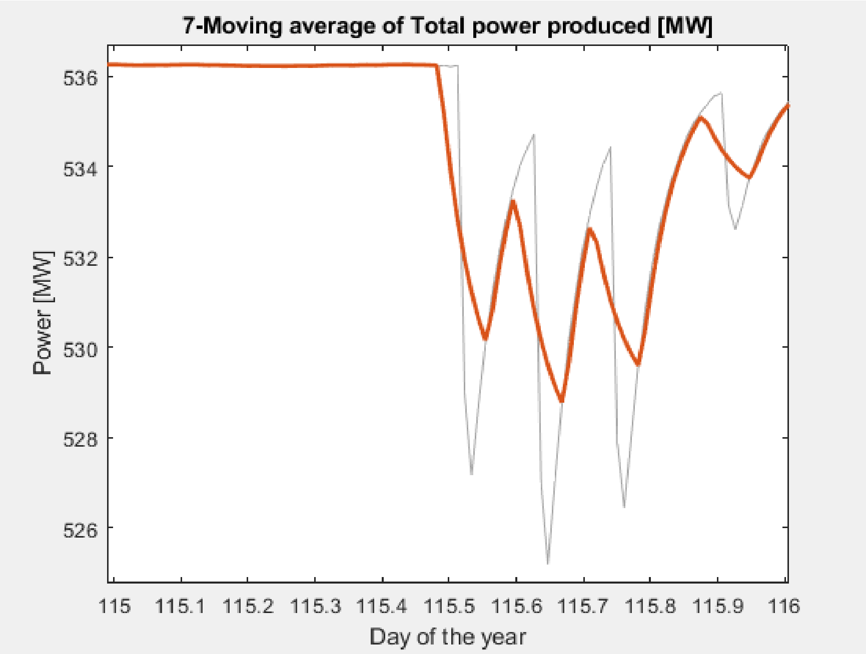


Figure A.14: Focus on day 115th for the total power production yearly trend, with the outputs of the three blocks combined.

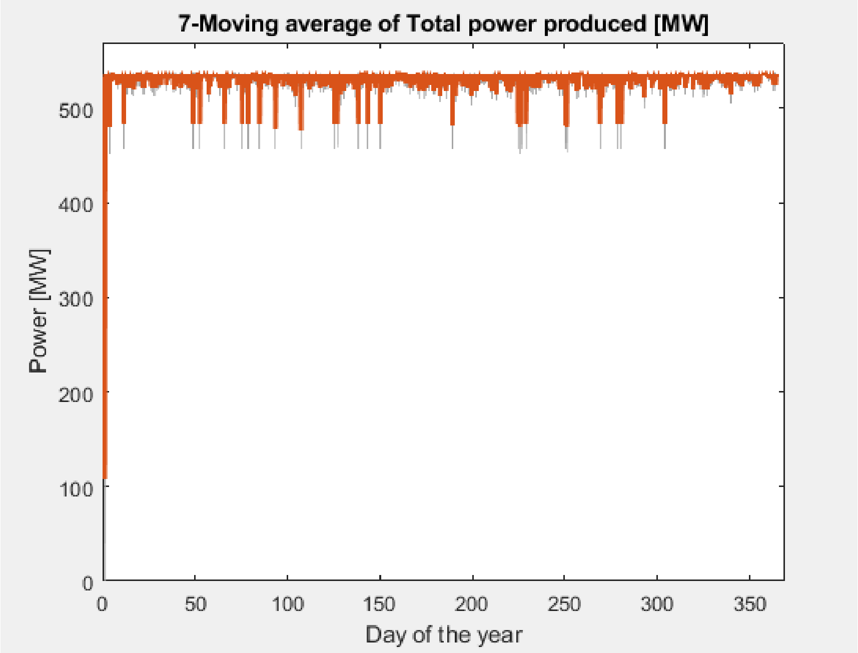


Figure A.15: Total power production yearly trend, with the outputs of the three blocks combined. The output is completely dominated by the wind production modules, which was therefore not shown before.

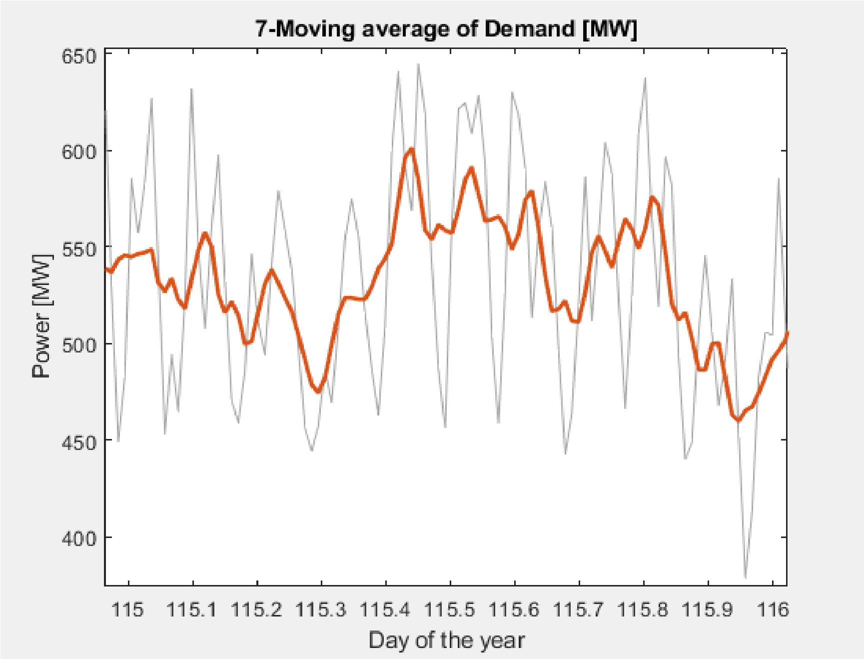


Figure A.16: Power demand trend during day 115th.

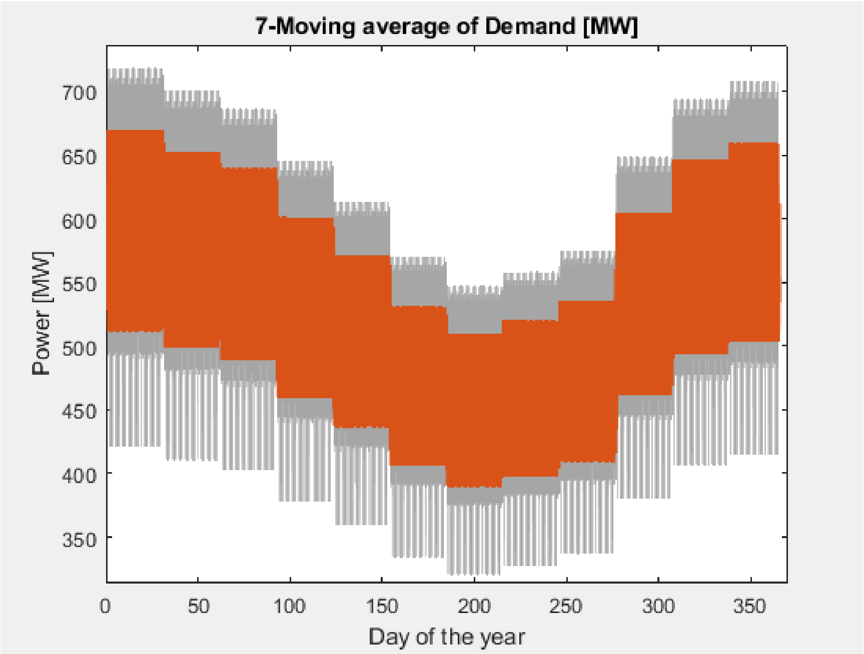


Figure A.17: Power demand yearly trend.

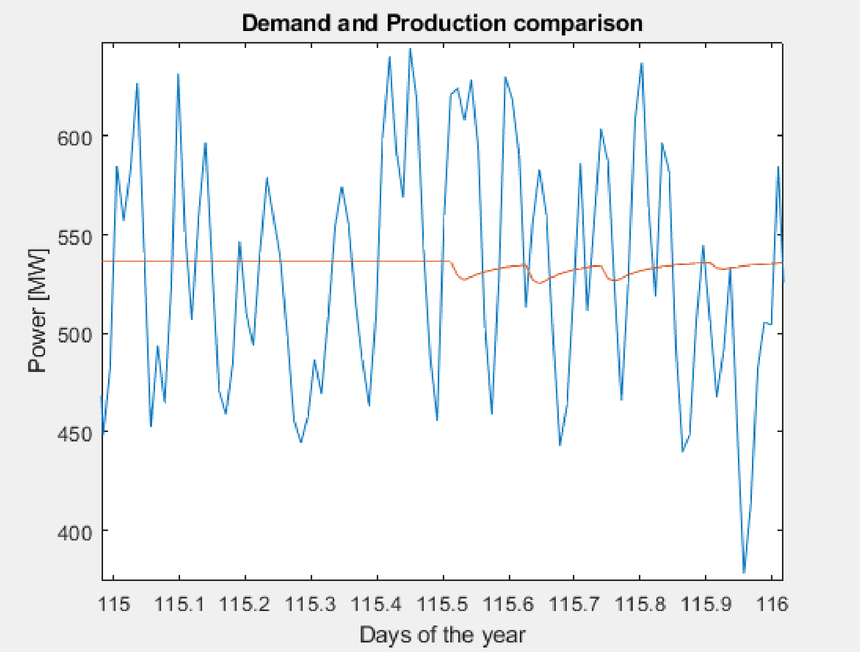


Figure A.18: Comparison amongst demand and power production during day 115th.

A.3.0.1 Results

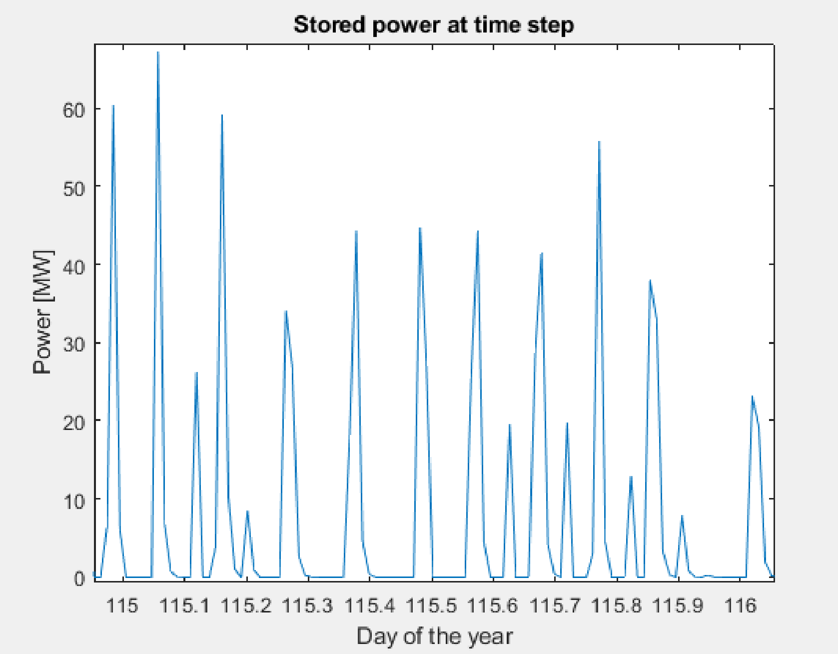


Figure A.19: MW stored power per iteration during the day 115th.

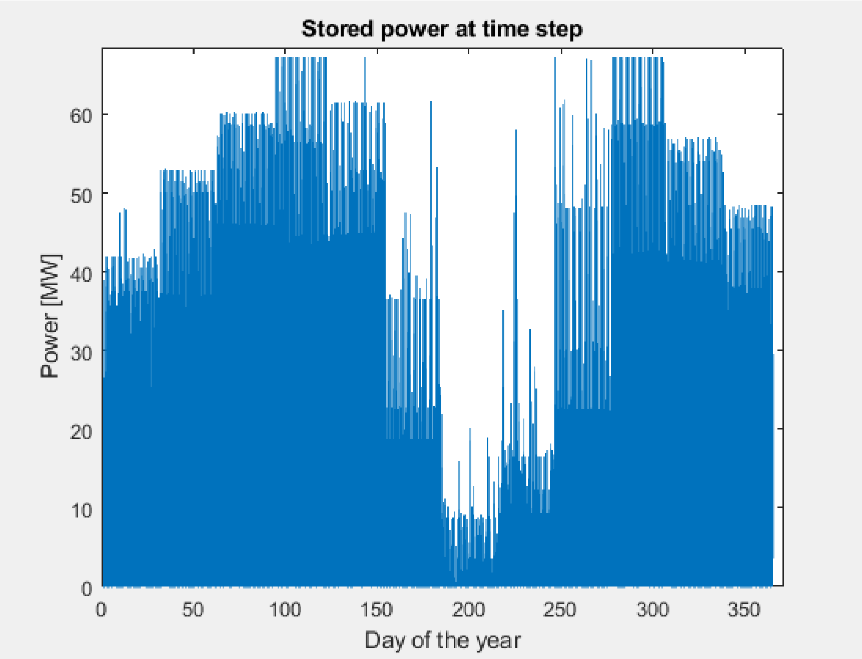


Figure A.20: MW stored power per iteration yearly trend.

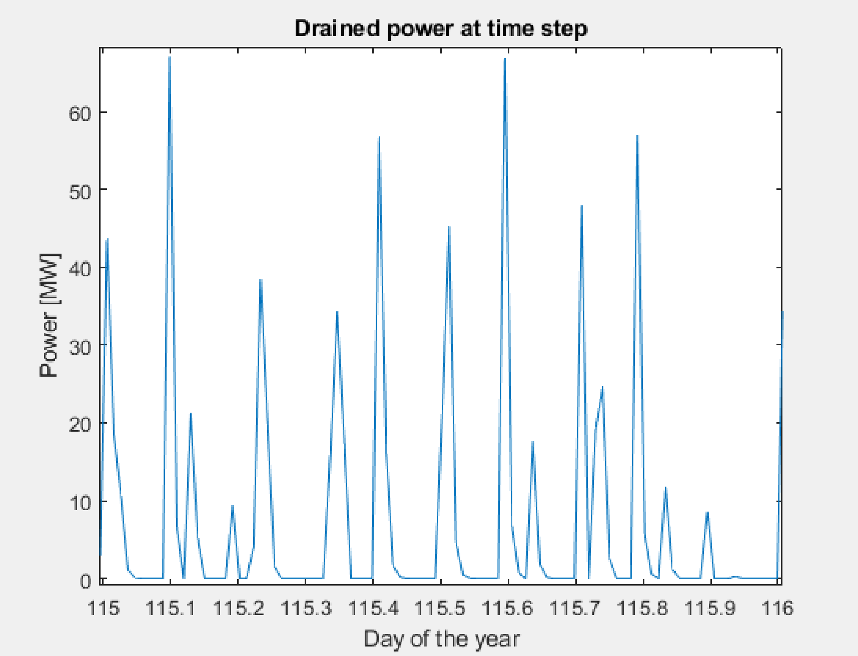


Figure A.21: MW drained power per iteration during the day 115th.

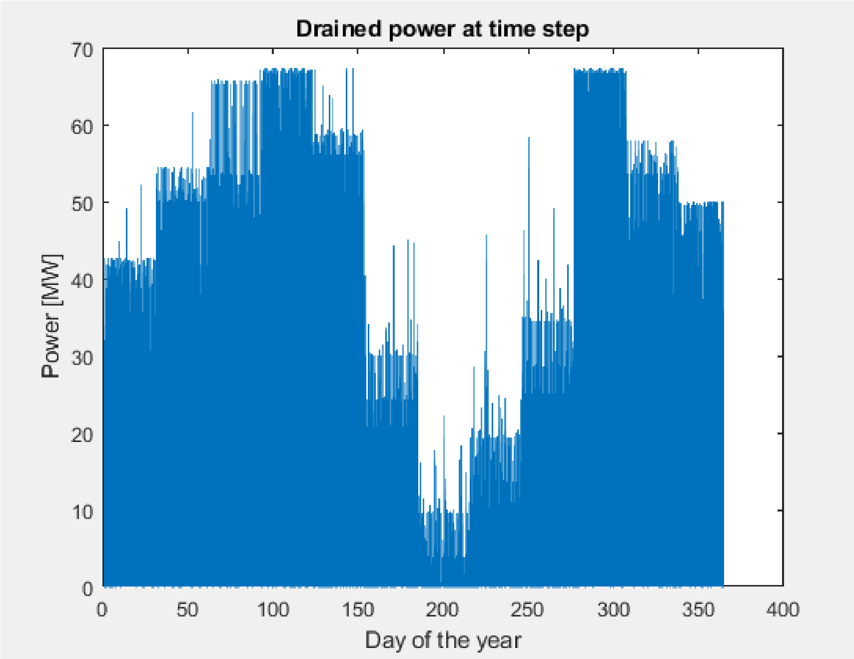


Figure A.22: MW power drained per iteration yearly trend.

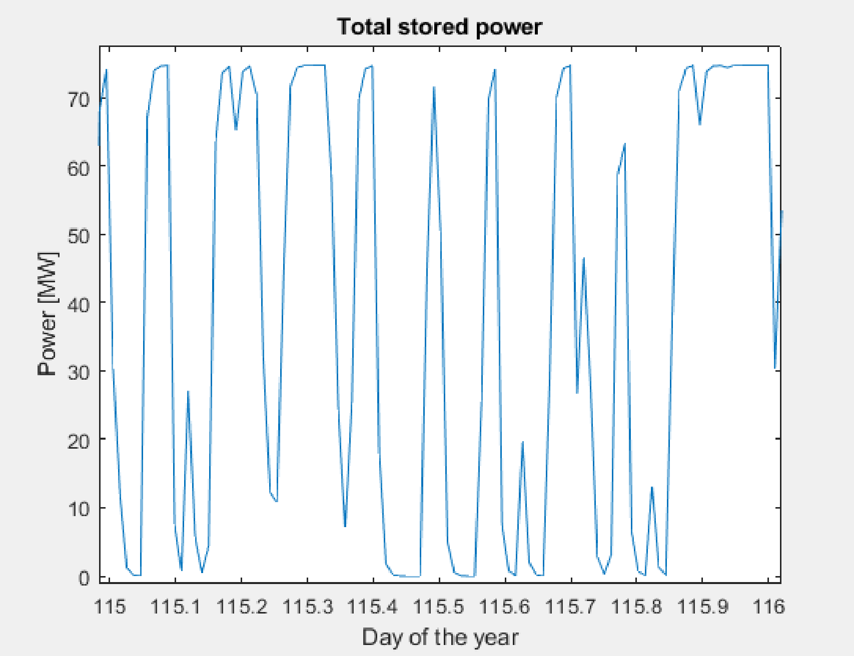


Figure A.23: Total MW power stored trend during the day 115th.

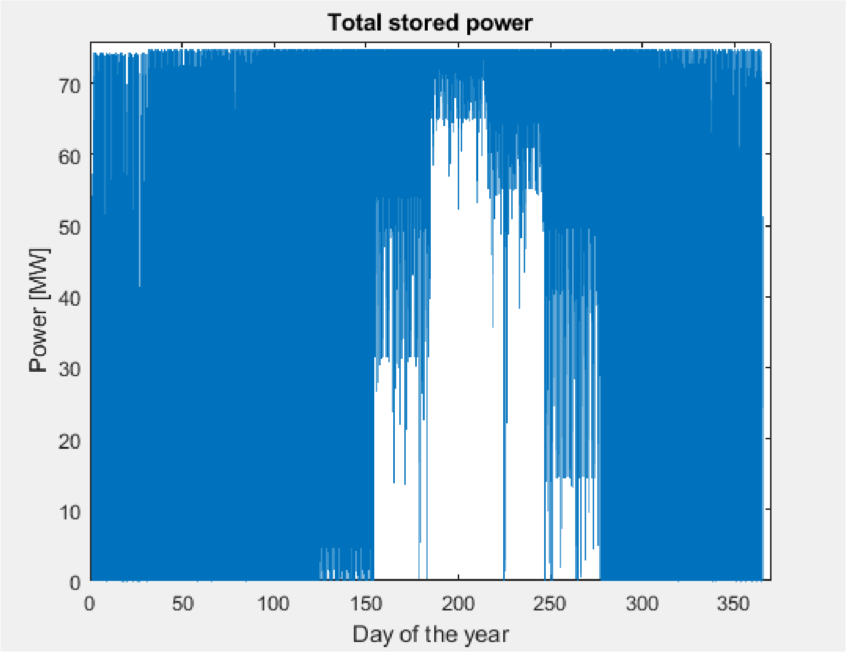


Figure A.24: Total MW power stored yearly trend.

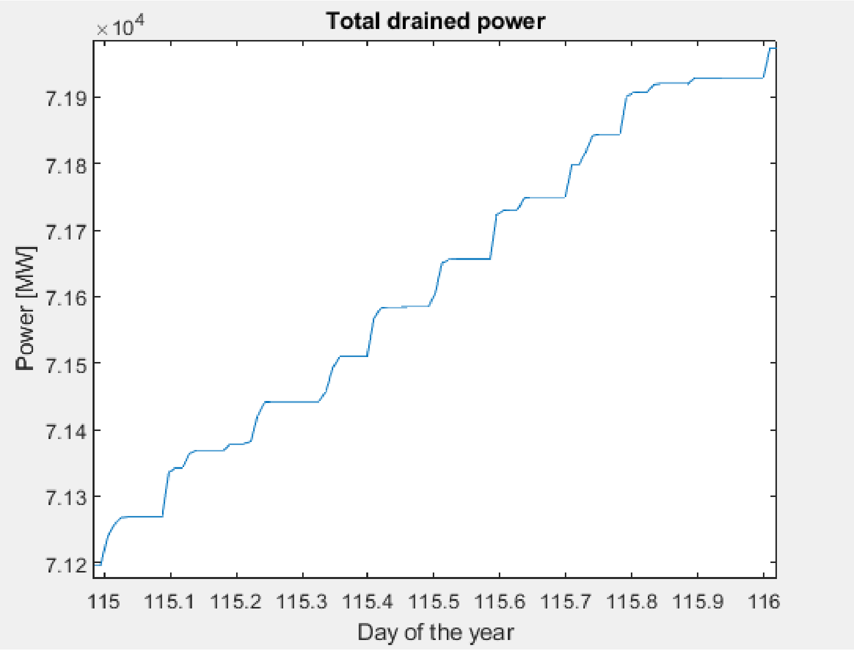


Figure A.25: Total MW drained power trend during the day 115th.

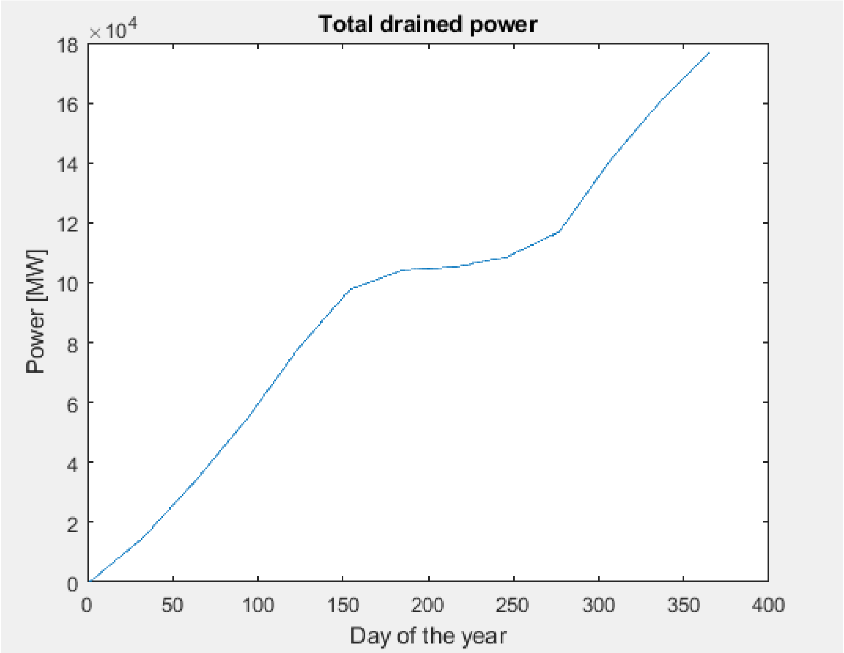


Figure A.26: Total MW power drained yearly trend.

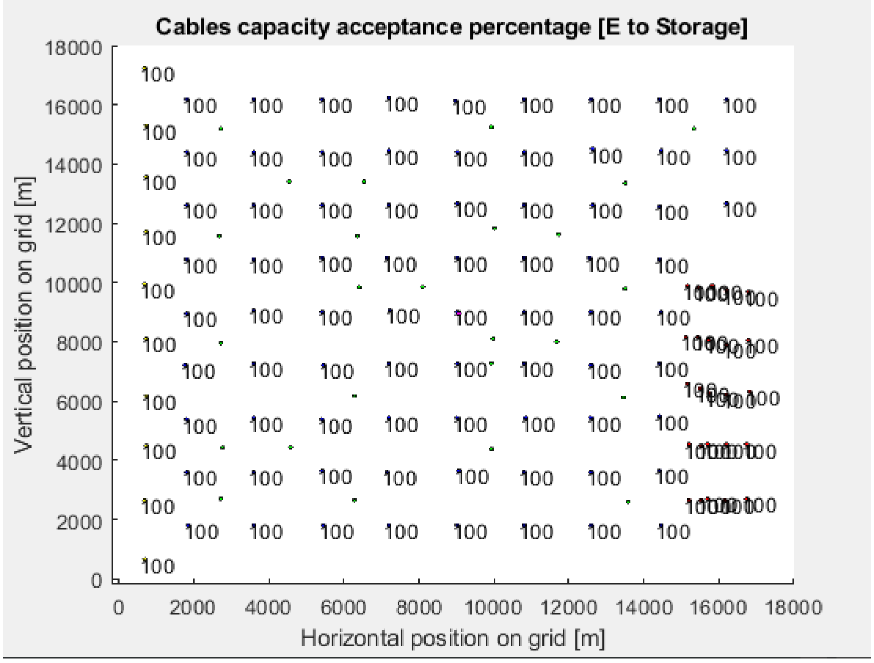


Figure A.27: Cables capacity acceptance in percentage for production elements to Ocean Battery(ies) connections.

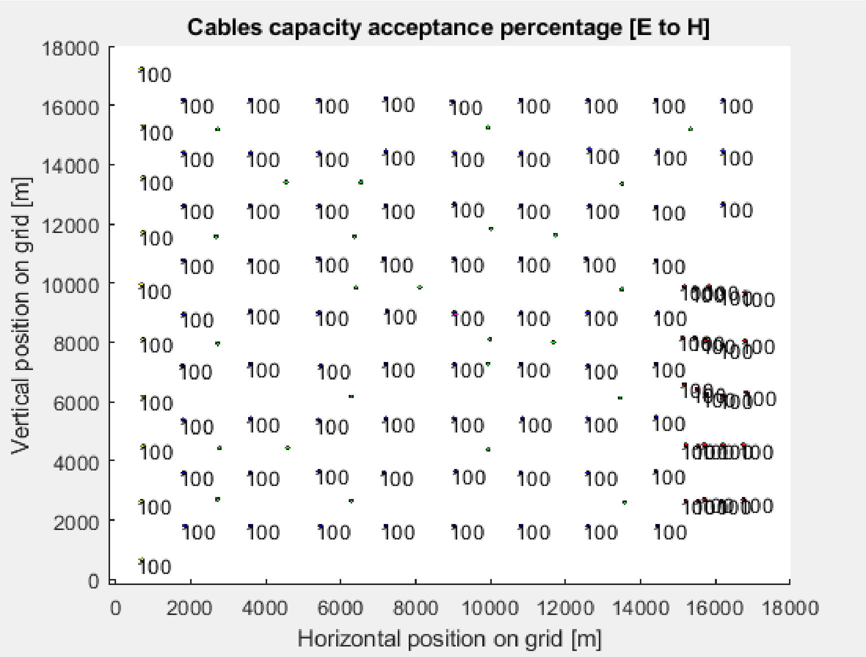


Figure A.28: Cables capacity acceptance in percentage for production elements to hub(s) connections.

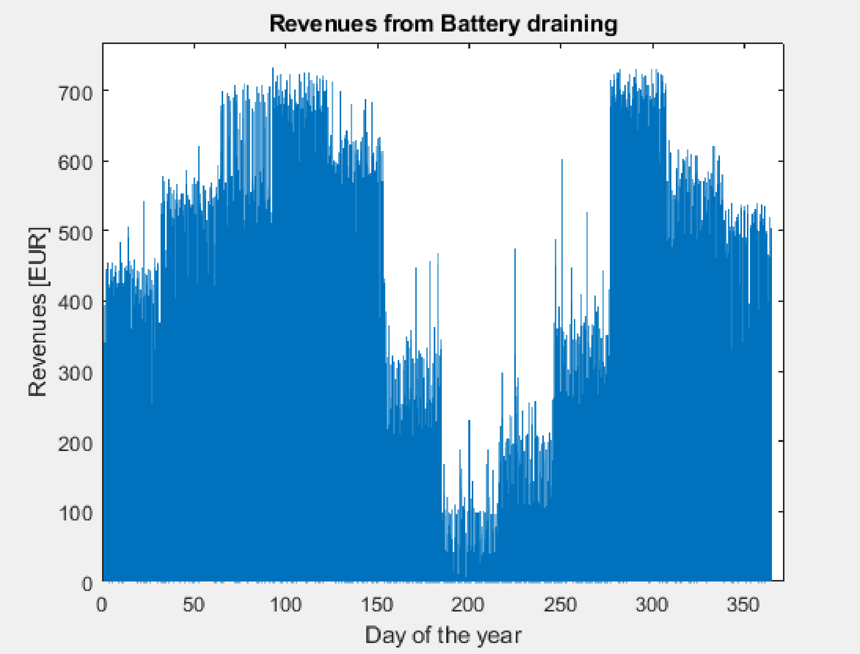


Figure A.29: Trend of revenues attained from Battery(ies) draining yearly.

A.3.1 Western France: Offshore Bayonne

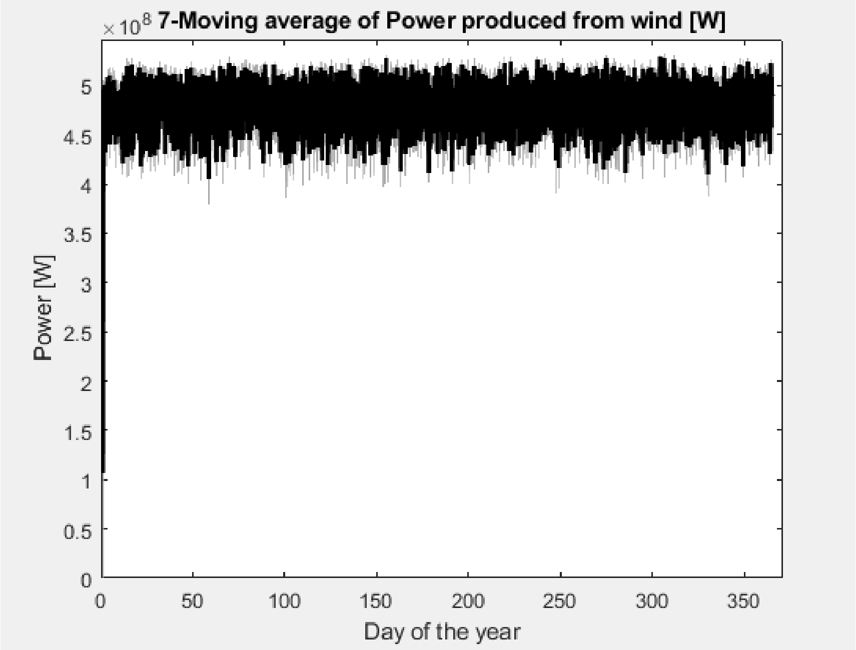


Figure A.30: Wind power production yearly trend.

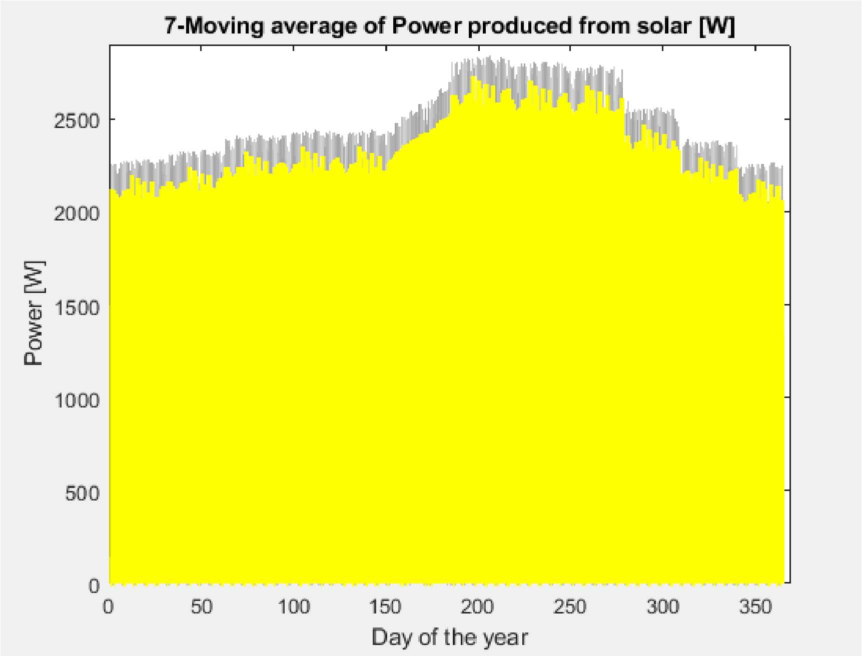


Figure A.31: Solar power production yearly trend.

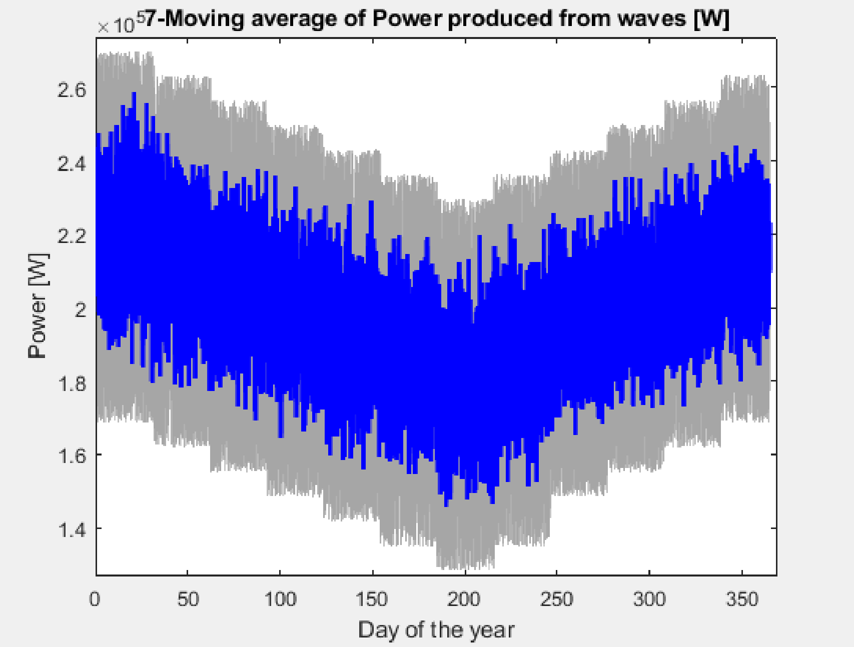


Figure A.32: Wave power production yearly trend.

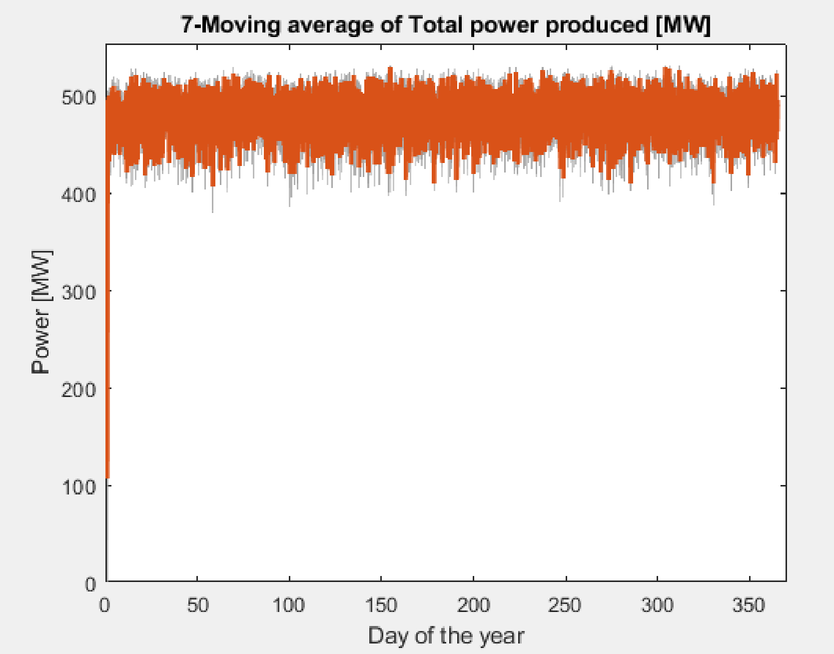


Figure A.33: Total power production yearly trend.

A.3.1.1 Results

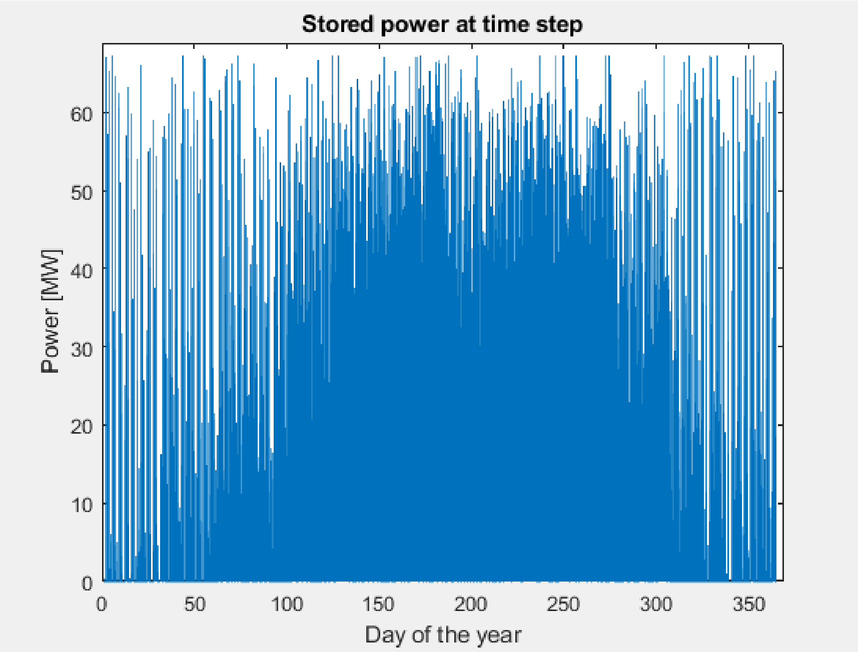


Figure A.34: MW stored power per iteration yearly trend.

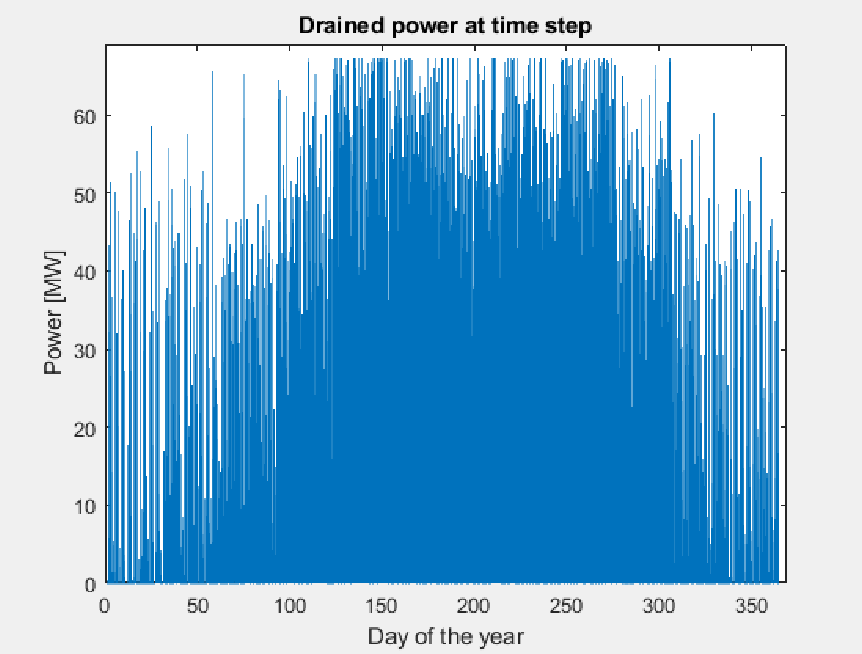


Figure A.35: MW drained power per iteration yearly trend.

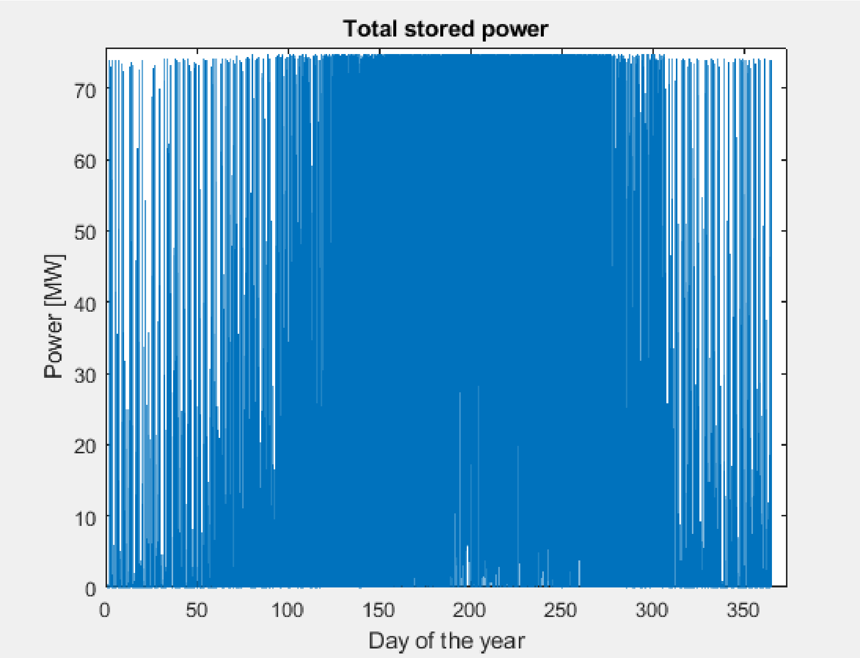


Figure A.36: MW total stored power yearly trend.

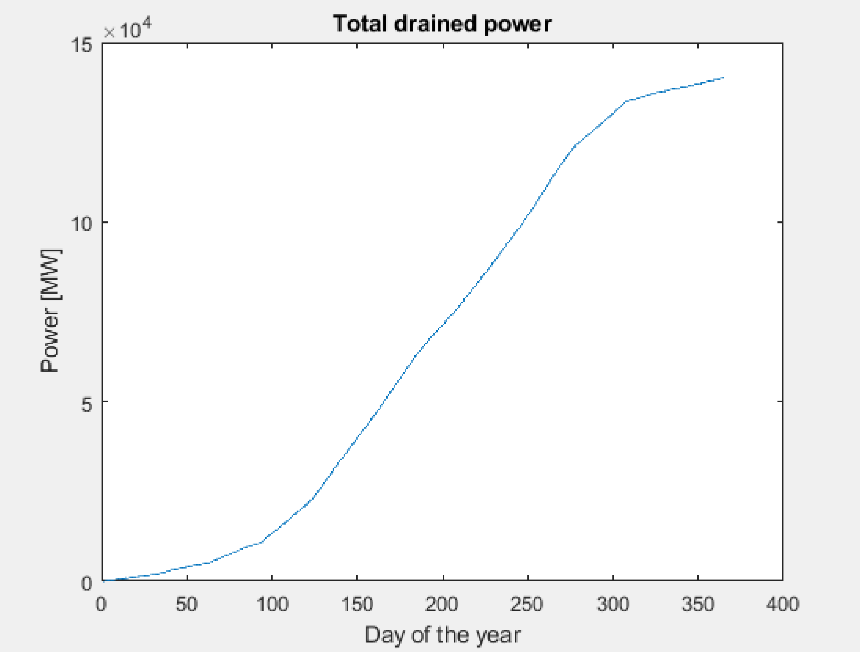


Figure A.37: MW total drained power yearly trend.

A.4 Wind Offshore Hybrid Integration

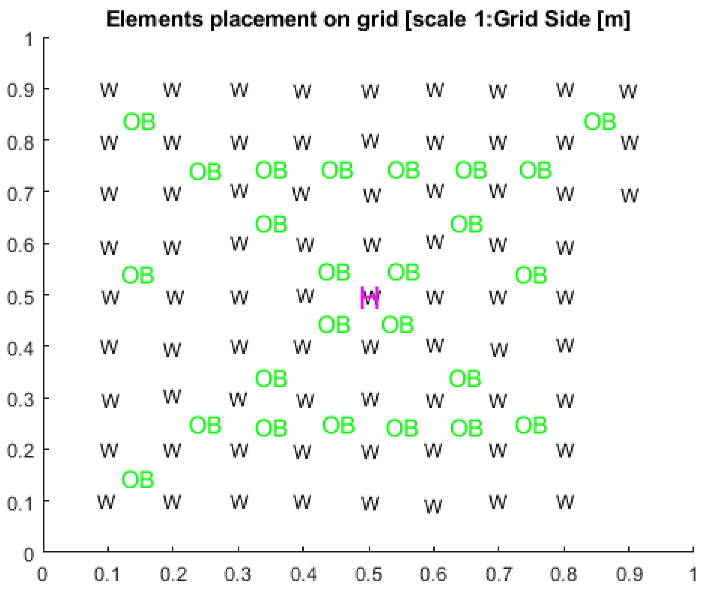


Figure A.38: Scrutinized grid composition for the scenario of exclusive wind power production.

A.4.1 Northern Netherlands: Offshore Eemshaven

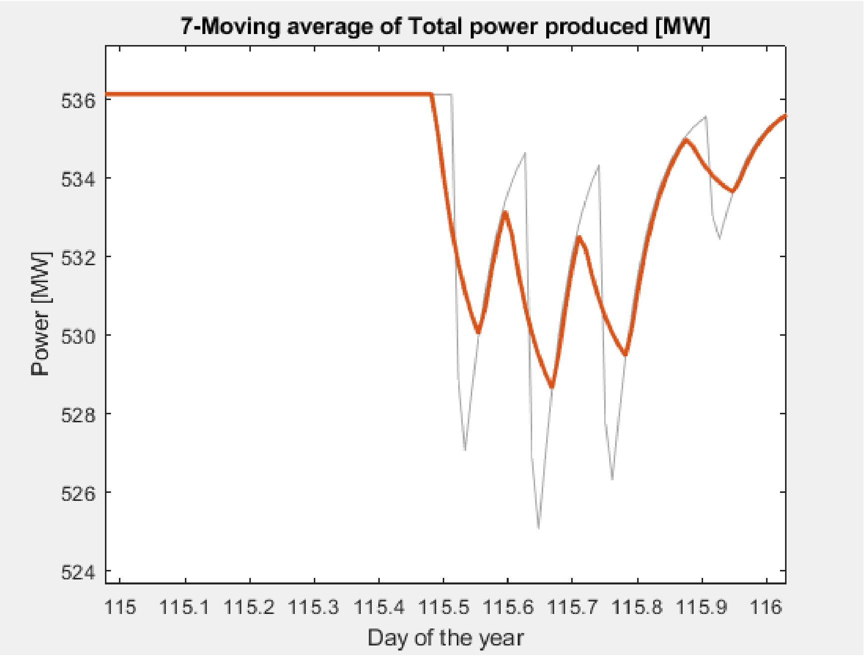


Figure A.39: Total power production during the day 115th.

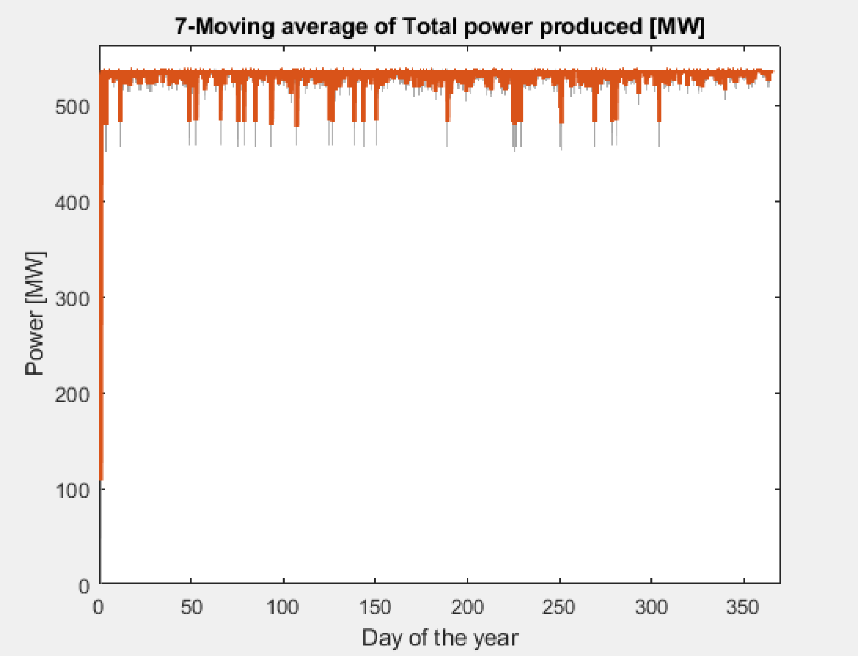


Figure A.40: Total power production yearly trend.

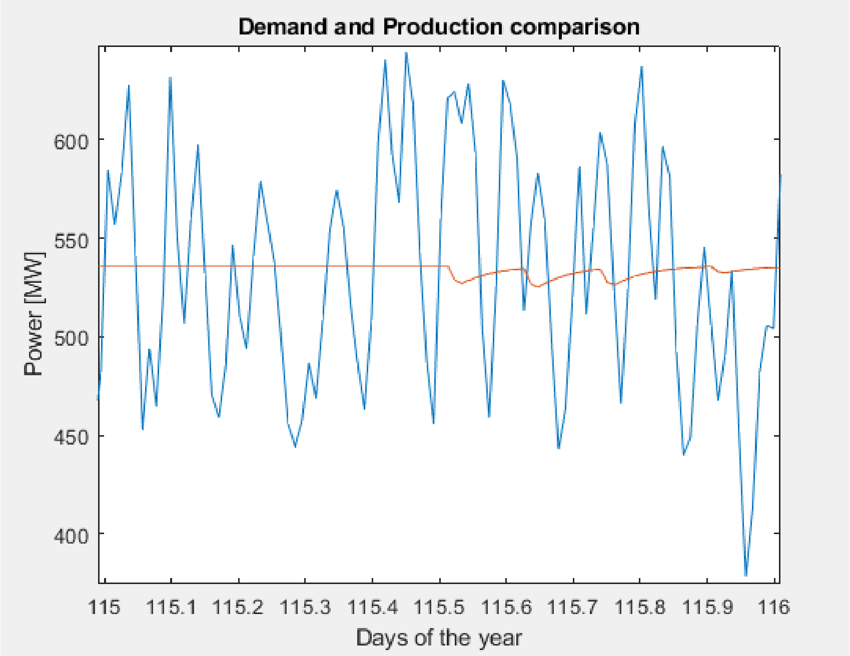


Figure A.41: Comparison amongst power production and power demand during the day 115th.

A.4.1.1 Results

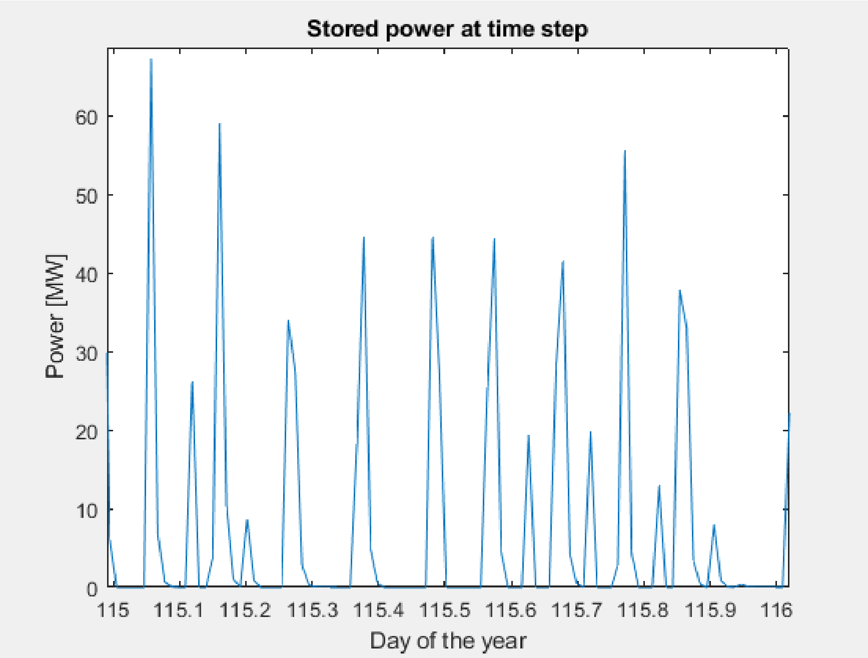


Figure A.42: Stored power per iteration trend during the day 115th.

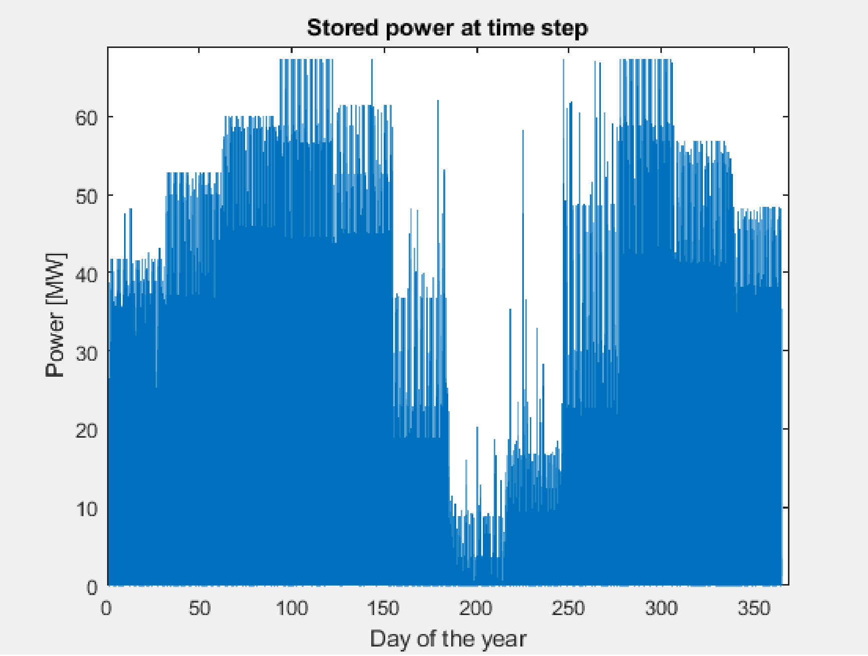


Figure A.43: Stored power per iteration yearly trend.

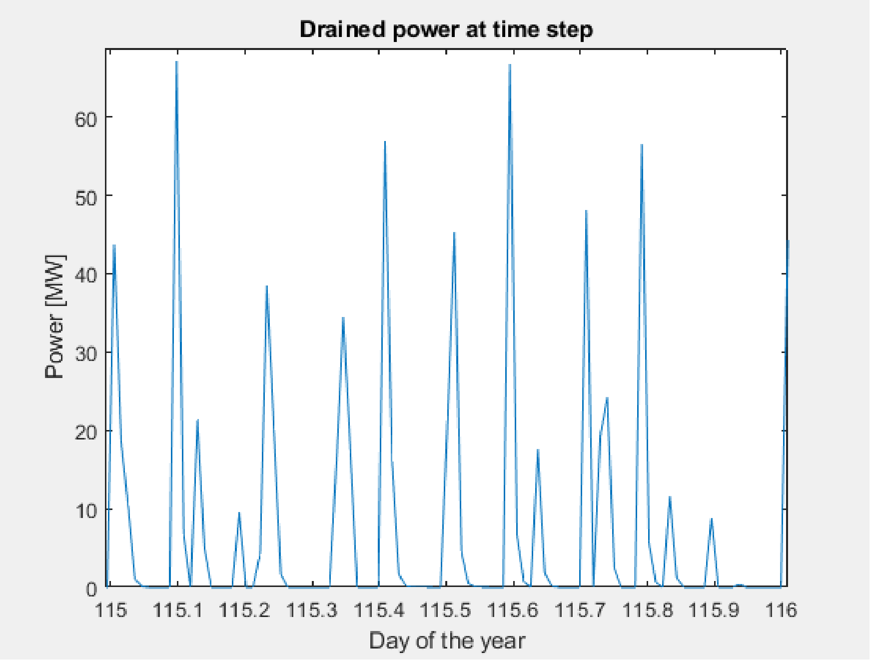


Figure A.44: Drained power per iteration trend during the day 115th.

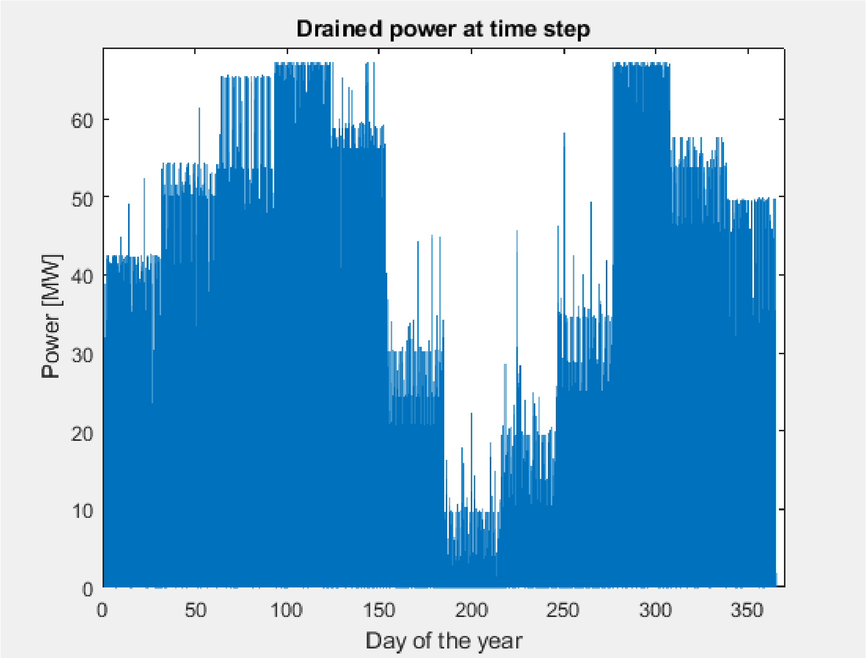


Figure A.45: Drained power per iteration yearly trend.

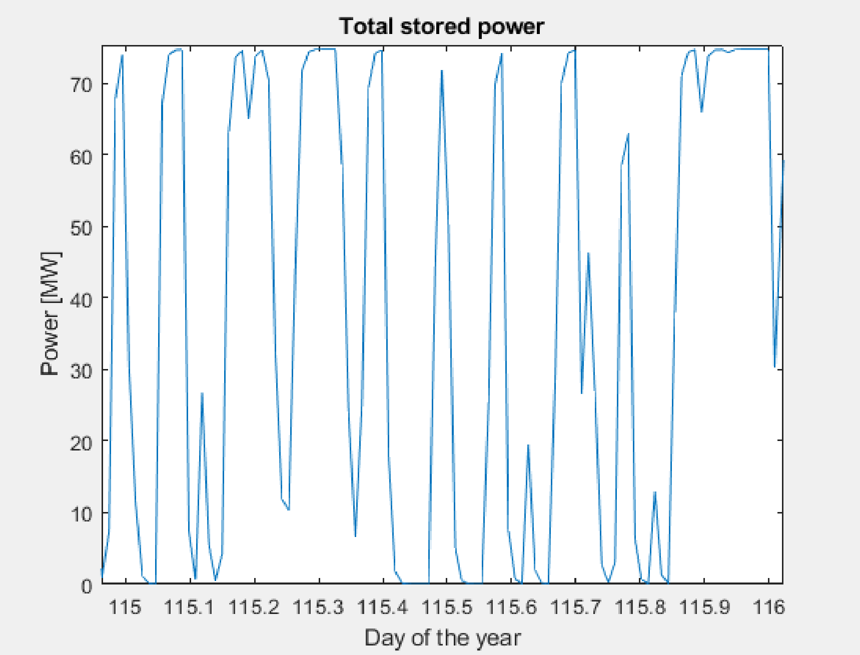


Figure A.46: Total MW stored power trend during the day 115th.

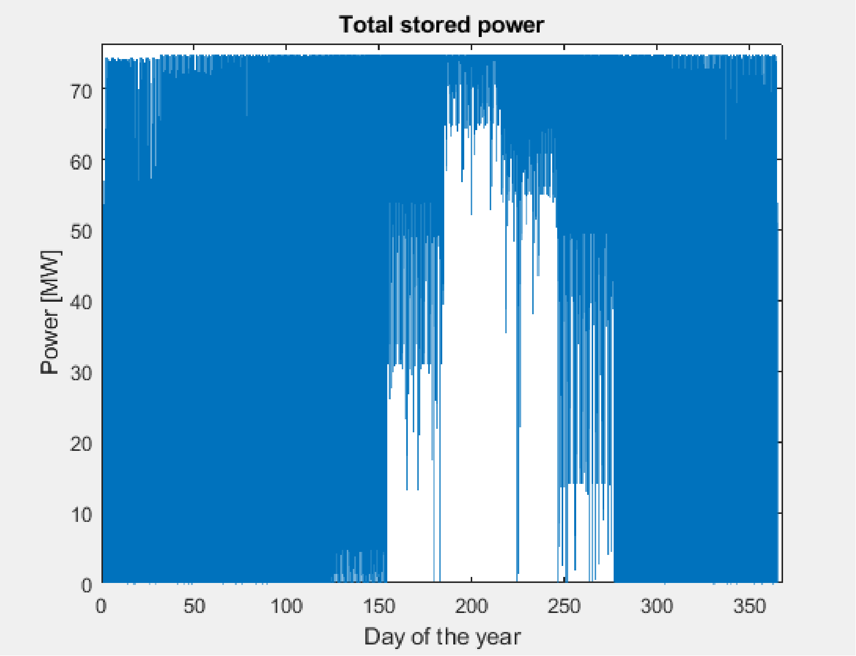


Figure A.47: Total MW stored power yearly trend.

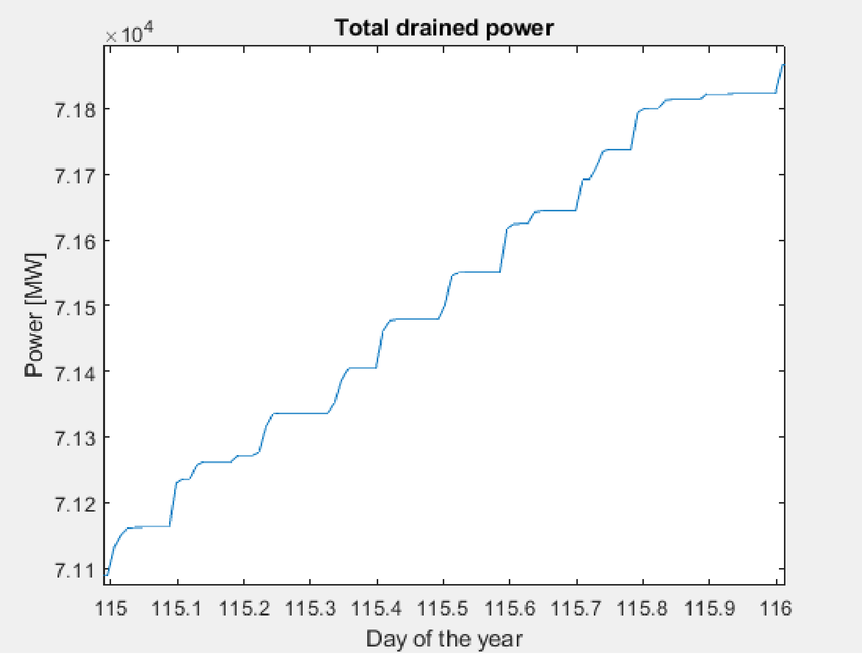


Figure A.48: Total MW drained power trend during the day 115th.

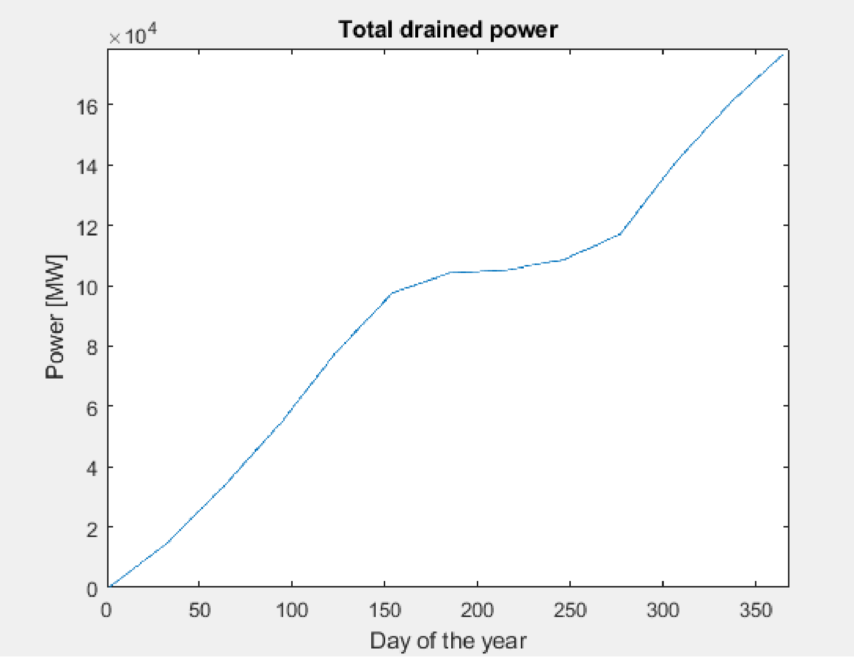


Figure A.49: Total MW drained power yearly trend.

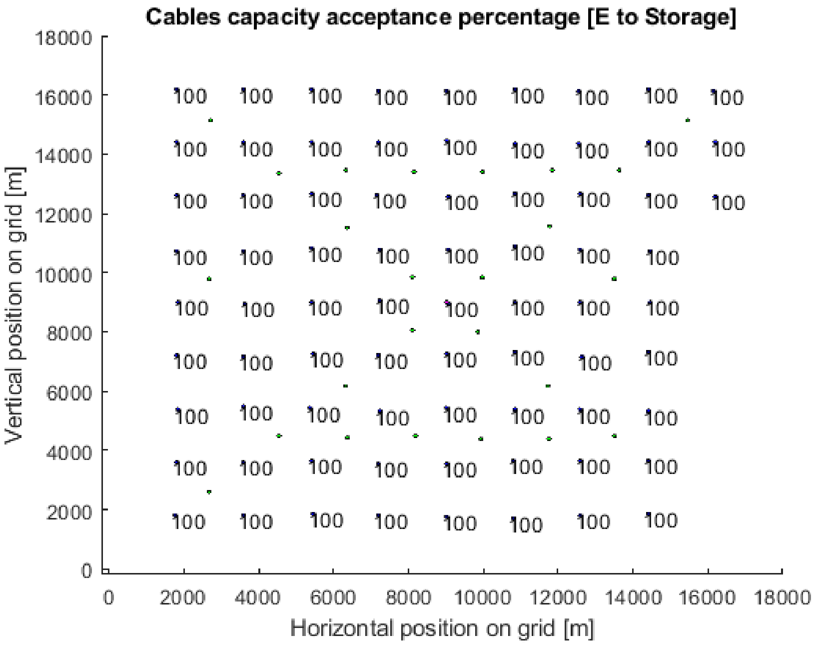


Figure A.50: Cables capacity acceptance in percentage for production elements to Ocean Battery(ies) connections.

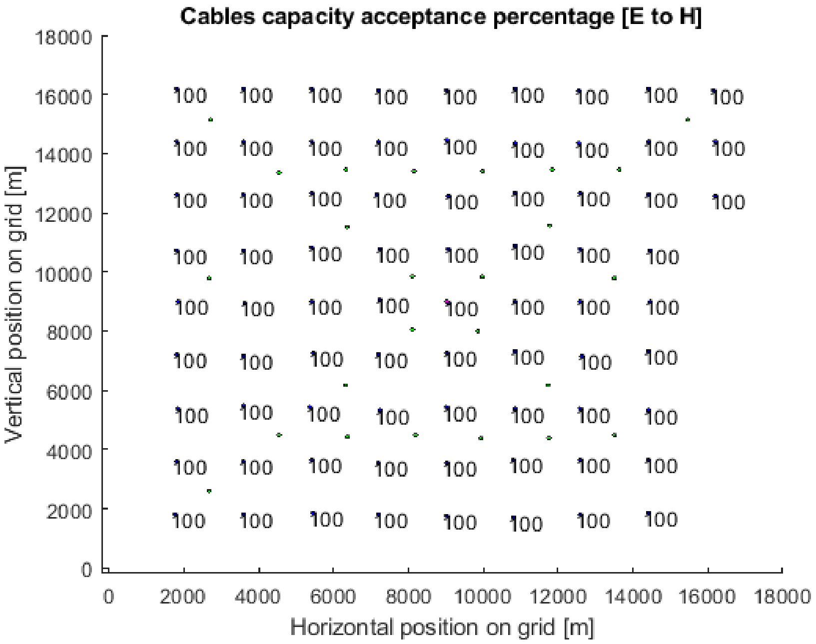
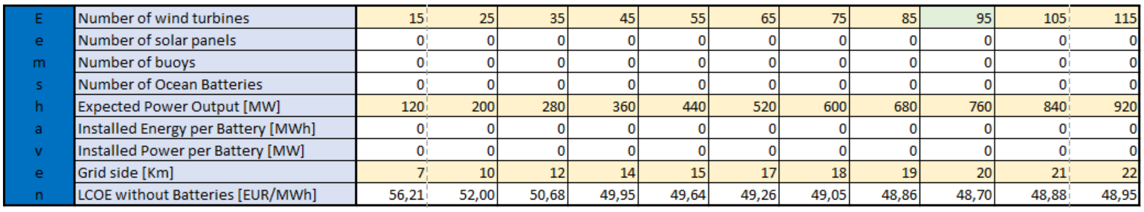


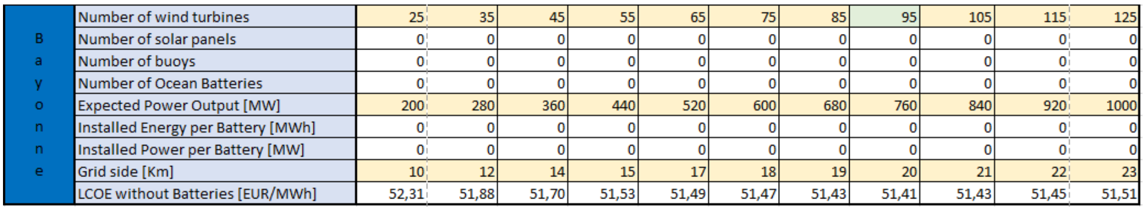
Figure A.51: Cables capacity acceptance in percentage for production elements to grid hubs connections.

A.5 Discussion



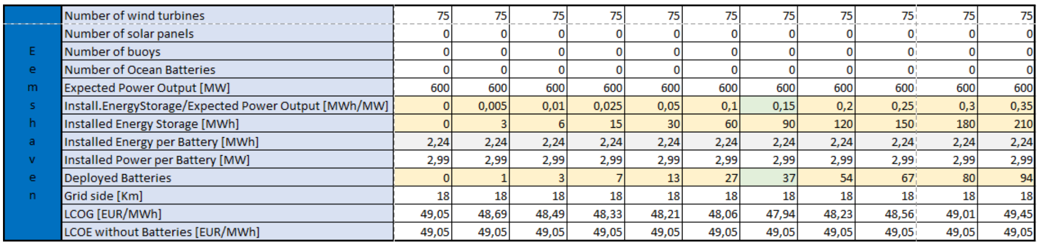
Eemshaven	Number of wind turbines	15	25	35	45	55	65	75	85	95	105	115
	Number of solar panels	0	0	0	0	0	0	0	0	0	0	0
	Number of buoys	0	0	0	0	0	0	0	0	0	0	0
	Number of Ocean Batteries	0	0	0	0	0	0	0	0	0	0	0
	Expected Power Output [MW]	120	200	280	360	440	520	600	680	760	840	920
	Installed Energy per Battery [MWh]	0	0	0	0	0	0	0	0	0	0	0
	Installed Power per Battery [MW]	0	0	0	0	0	0	0	0	0	0	0
	Grid side [Km]	7	10	12	14	15	17	18	19	20	21	22
	LCOE without Batteries [EUR/MWh]	56,21	52,00	50,68	49,95	49,64	49,26	49,05	48,86	48,70	48,88	48,95

Figure A.52: Table of the sensitivity analysis on the number of wind turbines with respect to the location of Eemshaven.



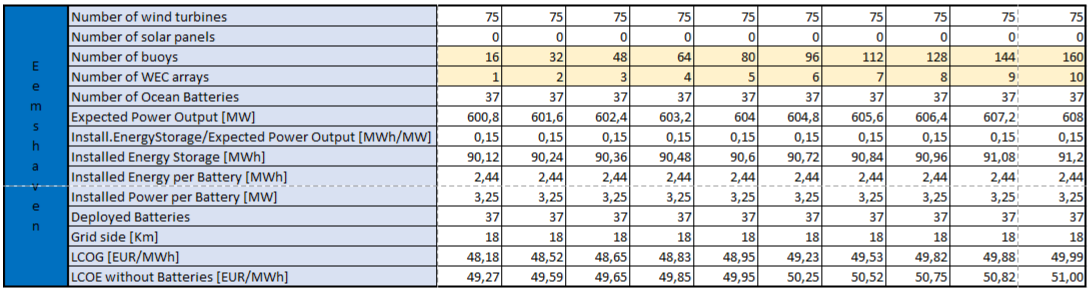
Bayonne	Number of wind turbines	25	35	45	55	65	75	85	95	105	115	125
	Number of solar panels	0	0	0	0	0	0	0	0	0	0	0
	Number of buoys	0	0	0	0	0	0	0	0	0	0	0
	Number of Ocean Batteries	0	0	0	0	0	0	0	0	0	0	0
	Expected Power Output [MW]	200	280	360	440	520	600	680	760	840	920	1000
	Installed Energy per Battery [MWh]	0	0	0	0	0	0	0	0	0	0	0
	Installed Power per Battery [MW]	0	0	0	0	0	0	0	0	0	0	0
	Grid side [Km]	10	12	14	15	17	18	19	20	21	22	23
	LCOE without Batteries [EUR/MWh]	52,31	51,88	51,70	51,53	51,49	51,47	51,43	51,41	51,43	51,45	51,51

Figure A.53: Table of the sensitivity analysis on the number of wind turbines with respect to the location of Bayonne.



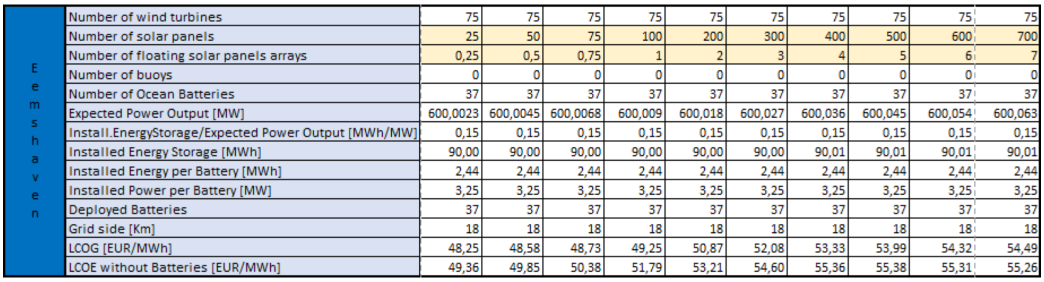
Eemshaven	Number of wind turbines	75	75	75	75	75	75	75	75	75	75	75
	Number of solar panels	0	0	0	0	0	0	0	0	0	0	0
	Number of buoys	0	0	0	0	0	0	0	0	0	0	0
	Number of Ocean Batteries	0	0	0	0	0	0	0	0	0	0	0
	Expected Power Output [MW]	600	600	600	600	600	600	600	600	600	600	600
	Install.EnergyStorage/Expected Power Output [MWh/MW]	0	0,005	0,01	0,025	0,05	0,1	0,15	0,2	0,25	0,3	0,35
	Installed Energy Storage [MWh]	0	3	6	15	30	60	90	120	150	180	210
	Installed Energy per Battery [MWh]	2,24	2,24	2,24	2,24	2,24	2,24	2,24	2,24	2,24	2,24	2,24
	Installed Power per Battery [MW]	2,99	2,99	2,99	2,99	2,99	2,99	2,99	2,99	2,99	2,99	2,99
	Deployed Batteries	0	1	3	7	13	27	37	54	67	80	94
	Grid side [Km]	18	18	18	18	18	18	18	18	18	18	18
	LCOG [EUR/MWh]	49,05	48,69	48,49	48,33	48,21	48,06	47,94	48,23	48,56	49,01	49,45
	LCOE without Batteries [EUR/MWh]	49,05	49,05	49,05	49,05	49,05	49,05	49,05	49,05	49,05	49,05	49,05

Figure A.54: Table of the sensitivity analysis on the optimal energy capacity of storage - expected power output ratio with respect to the location of Eemshaven.



Eemshaven	Number of wind turbines	75	75	75	75	75	75	75	75	75	75
	Number of solar panels	0	0	0	0	0	0	0	0	0	0
	Number of buoys	16	32	48	64	80	96	112	128	144	160
	Number of WEC arrays	1	2	3	4	5	6	7	8	9	10
	Number of Ocean Batteries	37	37	37	37	37	37	37	37	37	37
	Expected Power Output [MW]	600,8	601,6	602,4	603,2	604	604,8	605,6	606,4	607,2	608
	Install.EnergyStorage/Expected Power Output [MWh/MW]	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15
	Installed Energy Storage [MWh]	90,12	90,24	90,36	90,48	90,6	90,72	90,84	90,96	91,08	91,2
	Installed Energy per Battery [MWh]	2,44	2,44	2,44	2,44	2,44	2,44	2,44	2,44	2,44	2,44
	Installed Power per Battery [MW]	3,25	3,25	3,25	3,25	3,25	3,25	3,25	3,25	3,25	3,25
	Deployed Batteries	37	37	37	37	37	37	37	37	37	37
	Grid side [Km]	18	18	18	18	18	18	18	18	18	18
	LCOG [EUR/MWh]	48,18	48,52	48,65	48,83	48,95	49,23	49,53	49,82	49,88	49,99
	LCOE without Batteries [EUR/MWh]	49,27	49,59	49,65	49,85	49,95	50,25	50,52	50,75	50,82	51,00

Figure A.55: Table of the sensitivity analysis on the number of Ocean Grazer WEC arrays with respect to the location of Eemshaven.



Eemshaven	Number of wind turbines	75	75	75	75	75	75	75	75	75	75
	Number of solar panels	25	50	75	100	200	300	400	500	600	700
	Number of floating solar panels arrays	0,25	0,5	0,75	1	2	3	4	5	6	7
	Number of buoys	0	0	0	0	0	0	0	0	0	0
	Number of Ocean Batteries	37	37	37	37	37	37	37	37	37	37
	Expected Power Output [MW]	600,0023	600,0045	600,0068	600,009	600,018	600,027	600,036	600,045	600,054	600,063
	Install.EnergyStorage/Expected Power Output [MWh/MW]	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15
	Installed Energy Storage [MWh]	90,00	90,00	90,00	90,00	90,00	90,00	90,01	90,01	90,01	90,01
	Installed Energy per Battery [MWh]	2,44	2,44	2,44	2,44	2,44	2,44	2,44	2,44	2,44	2,44
	Installed Power per Battery [MW]	3,25	3,25	3,25	3,25	3,25	3,25	3,25	3,25	3,25	3,25
	Deployed Batteries	37	37	37	37	37	37	37	37	37	37
	Grid side [Km]	18	18	18	18	18	18	18	18	18	18
	LCOG [EUR/MWh]	48,25	48,58	48,73	49,25	50,87	52,08	53,33	53,99	54,32	54,49
	LCOE without Batteries [EUR/MWh]	49,36	49,85	50,38	51,79	53,21	54,60	55,36	55,38	55,31	55,26

Figure A.56: Table of the sensitivity analysis on the number of solar panels with respect to the location of Eemshaven.

B Appendix - Technical Manual for the User

The present appendix serves as technical manual for future users of the model. As explained in chapter 3, the designed Techno-financial Model is composed of two different blocks: the Power Model and the Cost Model. In order for the comprehensive model to properly function, the simulation of the former must be initially run, whereas the latter must follow. In fact, in order to produce results, the Cost Model requires data which are elaborated by the Power Model. In the following sections, the detailed sequence of actions to be performed by the user in order to allow the Model to accurately function is described.

B.1 List of Relevant Files

It is immediately required to enlist the files composing the Techno-Financial Model. As it is a complex tool, these will be distinguished amongst those belonging to the Power simulation and those to the Cost Model, as follows:

- Files for the Power Model: “HybridIntegrationEemshaven.slx”, “workspacestart.m”, “EemshavenWindspeedSheet6.xls”, “EemshavenWavePerBuoySheet5.xls”, “EemshavenVoltageSheet4.xls”, “EemshavenSunIrradSheet5.xls”, “HybridIntegrationBayonne.slx”, “BayonneSunIrradiation.xls”, “BayonneVoltageSheet4.xls”, “BayonneWaveperBuoySheet2.xls”, “BayonneWindSpeed.xls”, “Copy of DemandSheet5.xls”

- Files for the Cost Model: “GeneralModel.m”, ” inputs.m”, “caseYESbattery.m”, “caseNObattery.m”, “soldtoshore.m”, “physicalcapacityEtoH.m”, “physicalcapacityEtoS.m”, “physicalcablescapacitySTORtoHUB.m”, “physicalcapacityHtoShore.m”, “sustainedcapacityHtoShore.m”, “sustainedcapacityEtoS.m”, “sustainedcapacityEtoH.m”, “sustainedcapacityStoH.m”, “energypriceperW.m”, “sold.m”, “cablesmatrixStoH.m”, “cablesmatrix.m”, “cablesmatrixtohub.m”, “AFRRmarket.m”, “plotcircle.m”, “makecirclefigure.m”, “circles.m”

B.1.1 Power Simulation Files Explained

These files are either Simulink, or Excel files. Nonetheless, one “.m” file is present as well: “workspacestart.m” contains the workspace of the variable which are crucial for the model of the wind turbine. Furthermore, “HybridIntegrationEemshaven.slx” represents the Power Model of the hybrid integration for the investigation of offshore Eemshaven as a location. Therefore, the file refers to “EemshavenWindspeedSheet6.xls”, “EemshavenWavePerBuoySheet5.xls”, “EemshavenVoltageSheet4.xls”, “EemshavenSunIrradSheet5.xls”, “Copy of DemandSheet5.xls” as input datasheets. These Excel files are built, as explained in chapter 3, as 35515 x 2 arrays: the first column represents the time step, which is updated with a cadence of 0.05 s; the second column represents the value of the respective quantity. The same applies for “HybridIntegrationBayonne.slx” and its respective Excel spread sheets, which operate the power simulation for a location offshore Western France. For those datasheets containing multiple sheets, only the sheets indicated within the Excel files’ name must be consulted.

Chapter B.2 will discuss the procedure to run each component of the Techno-financial Model.

B.1.2 Cost Simulation Files Explained

All MATLAB files are properly commented, in order to allow the user a smooth understanding of the represented processes. Here, the key aspects of each of the enlisted file are reported. On the other hand, section B.2 will discuss the procedure to run each component of the Techno-financial Model. Firstly, the file “GeneralModel.m” represents the main file of the Cost Model. All the other files are functions, which are contained within, called from and executed during the run of “GeneralModel.m”. File “inputs.m” contains a wide set of inputs which influence the model’s behaviour, such as: Ocean Battery capacity, turbine power, time step, time window to be simulated, number of iterations, cables’ characterization, etc.. Files “caseYESbattery.m” and “caseNObattery.m” contain the functions which perform the analysis for the cases of Battery(ies) deployed and storage absent, respectively. Files “soldtoshore.m” and “sold.m” calculate respectively the power amounts transferred to the hub and the power amount transferred to the shore. Files from “cablesmatrixStoH.m”, “cablesmatrix.m”, “cablesmatrixtohub.m”, calculate the length of the grid cables based on the element placement operated during the initial stages of the “GeneralModel.m”’s simulations. Functions from “physicalcapacityEtoH.m”, “physicalcapacityEtoS.m”, “physicalcablescapacitySTORtoHUB.m” to “physicalcapacityHtoShore.m” store the information of cables capacities for each grid connection present within the farm. Subsequently, “sustainedcapacityHtoShore.m”, “sustainedcapacityEtoS.m”, “sustainedcapacityEtoH.m”, “sustainedcapacityStoH.m” assess whether the hypothesized transmitted power across cables could be effectively sustained by the respective cables. Files “AFRRmarket.m” and “energypriceperW.m” respectively model the demand and produced power forecasts (useful for establishing the actual energy price) and the price of the power per watt, based on the previously obtained forecasts. Files “plotcircle.m”, “makecirclefigure.m” and “circles.m” allow to draw the topology mapping tools within the “GeneralModel.m” simulation.

B.2 How to Run the Techno-Financial Simulation

The Techno-Financial Model shall be executed by accurately following a defined procedure. In particular, it is required to first run the Power Model and, only afterwards, to run the Cost Model. The detailed sequence of actions which allow the Techno-financial Model to assess hybrid integrations profitability is reported in the next sections.

B.2.1 Power Simulation

Firstly, it is required to open the software MATLAB, which hosts both the simulations. Since the Power Model is engineered within Simulink (which one of MATLAB’s environments), once MATLAB has opened, Simulink must be launched. Secondly, it is required to load in MATLAB the workspace "workspacestart.m", which contains key parameters for the power simulation initiation. This is necessary since the wind turbine model is a re-adaptation of the Three-Phase Asynchronous Wind Turbine Generator presented in the Mathworks literature [35]. Alternatively to loading this workspace, it is simply possible to launch $ee_asm_generator$ command from MATLAB's command window. Now, it is required to provide as input to the three production components of the Power Model the input spreadsheets on wind speed data, sun irradiation, voltage trend of the solar panels, wave power produced by each buoy and demand. These all depend on the location which the user decide to analyze, obviously. These spreadsheets shall be selected as inputs in the following *From Spreadsheet* blocks present in the Power Model, respectively: *Wave Power Input Data*, *Panels Input Data*, *Wind Power Production*, *Solar Power Production*, *Wave Power Production*, *Demand.* Finally, the simulation time shall be set up, and the simulation may begin. The run of the Power Model produces the three production power trends per production component based on the scrutinized area, and the load demand trend for the same location. These databases are immediately sent to MATLAB's workspace once produced, for the financial simulation to be performed by the Cost Model, as it will be discussed in section B.2.2. This allows to conclude the Techno-financial assessment of the given project, for the given location.

B.2.2 Financial Simulation

Once the Power Model simulation is concluded, the Cost simulation (namely the file "GeneralModel.m") shall be run. The setting of such stage is simpler than that for the previous: it is simply required to press MATALAB's run button. Before clocking it, the user shall modify the values given as input to the Cost Model from file "inputs.m", based on the physical requirements of the actual project to be analysed. As soon as the inputs have been inserted, it is possible to run the Cost Model. Immediately, the user is asked to insert the grid characterization parameters. Afterwards, the elements composing the grid (wind turbines, solar panels, Ocean battery(ies), etc.) can be located by the user across the grid. This is allowed by the function *ginput*, which grants precision of investigation. As the last element is located, the Cost Model runs autonomously by producing plots, databases, key performance index: the overall financial assessment is executed.

C Appendix - Model's Pseudocodes

The present appendix presents the pseudocodes implemented in MATLAB in order to heuristically model the hybrid integration behavior. In order to provide a clear distinction amongst components and processes, the chapter will be divided amongst multiple sections.

C.1 Cables Length

The designed Techno-Financial Model takes into account the length of cables in order to assess capital and operational costs. These are calculated by considering the location of each element, provided by the user through function *ginput* at the simulation incipit, as well as the grid dimension. Afterwards, the lengths are calculated based on the shortest reciprocal distance amongst two elements: namely, the Pitagora's theorem has been implemented. Therefore, the formula in order to calculate the cables' length based in Cartesian coordinates of each element recites as follow:

$$\begin{aligned}
fori &= 1 : NUMelements_e \\
forj &= 1 : NUMelements_d \\
cablelength_{e,d} &= sqrt(((x_e(i,1) - x_d(j,1))^2) + (y_e(i,1) - y_d(j,1))^2) \\
&end \\
&end
\end{aligned} \tag{C.1}$$

where e and d represent two generic elements of the grid: either Ocean Batteries, or production elements or hubs. Such code is implemented, and adapted to the specific circumstance, within functions "cablesmatrix.m", "cablesmatrixStoH.m" and "cablesmatrixtohub.m".

C.2 AFRR Energy Market

The heuristic model of the AFRR market calculates the forecasts on production and demand for the following day. Based on such predictions, the difference amongst the two trends is estimated and the price per W is decided, around the pivot value reported in the literature [13]. The AFRR market operates the following assessment: if the demand is higher than the Production, the price of the power per W is high; viceversa, if the demand is lower than the Production, the price of the power per W is low. Here the difference amongst the two trends is attained, which will be crucial for the price calculation in the next paragraph.

$$\begin{aligned}
&fori = 1 : NUMiterations \\
ProducedPwTodayPerIterat(1,i) &= TotPwWind(1,i) + TotPwSun(1,i) + TotPwWave(1,i); \\
ProdPwTomorrowPerIterat(1,i) &= ProdPwTodayPerIterat(1,i) * randecproduction(1,i); \\
DemandTomorrowPerIterat(1,i) &= row_demand(1,i) * randvecdemand(1,i); \\
&end \\
&fori = 1 : NUM_iterations \\
DemMinusProd(1,i) &= DemandTomorrowPerIterat(1,i) - ProdPwTodayPerIterat(1,i); \\
&end
\end{aligned} \tag{C.2}$$

C.2.1 Price of Power

In case the demand is higher than the power production, the pivotal price value gets increased by a percentage. Viceversa, in case the demand is lower than the production the pivotal price value gets decreased by a percentage, as follows:

```
$fori = 1 : NUM_iterations$
    $DemMinusProd(1, i) = DemandTomorrowPerIterat(1, i) - ProdPwTomorrowPerIterat(1, i);$
$end$
$fori = 1 : NUM_iterations$
    $if(DemMinusProd(1, i) > 0)$
        $priceperW(1, i) = 0.00001 + (0.00001 * normalizedDifferenceDminP(1, i));$
    $elseif(DemMinusProd(1, i) == 0)$
        $priceperW(1, i) = 0.00001;$
    $elseif(DemMinusProd(1, i) < 0)$
        $priceperW(1, i) = 0.00001 - (0.00001 * normalizedDifferenceDminP(1, i));$
    $end$
$end$
```

(C.3)

C.3 Case with no Batteries Deployed

For the case of storage capacity absent, the model simply operates an analysis of Production and Demand in order to calculate the required power to send to the grid. Afterwards the latter gets compared with the cables capacity, the revenues are calculated. Here is the pseudocode:

$$\begin{array}{r}
for i = 1 : NUMiterations \\
if(Demand(1, i) <= (ProducedPower(1, i))) \\
ProdMinusDem(1, i) = (ProducedPower(1, i)) - Demand(1, i); \\
for j = 1 : NUM_{p}roduction_{e}lements \\
if(sustained_{E}toH(i, j) == 1) \\
sold_{e}nergy(1, i) = Demand(1, i); \\
unsold_{e}nergy(1, i) = ProdMinusDem(1, i); \\
elseif(sustained_{E}toH(i, j) == 0) \\
sold_{e}nergy(1, i) = physicalcablescapacityEtoH(1, j); \\
unsold_{e}nergy(1, i) = ProdMinusDem(1, i); \\
end \\
end \\
elseif(Demand(1, i) > (ProducedPower(1, i))) \\
DemMinusProd(1, i) = Demand(1, i) - (ProducedPower(1, i)); \\
if(ProducedPower > 0) \\
for j = 1 : NUM_{h}ubs \\
if(soldtoShore(i, j) > physicalcablescapacityHtoShore(1, j)) \\
sold_{e}nergy(1, i) = physicalcablescapacityHtoShore(1, j); \\
elseif(soldmatrixtoShore(i, j) <= physicalcablescapacityHtoShore(1, j)) \\
sold_{e}nergy(1, i) = soldmatrixtoShore(i, 1); \\
end \\
end \\
end \\
elseif(ProducedPower <= 0) \\
sold_{e}nergy(1, i) = 0; \\
bought_{e}nergy(1, i) = DemMinusProd(1, i); \\
end
\end{array} \tag{C.4}$$

C.3.1 Revenues Assessment

The revenues are here distinguished amongst revenues deriving from sold power and revenues lost due to inability to transfer the power through the cables. Here, vectors incoming from functions "sold.m", "soldtoshore.m" and "energypriceperW" are used. These store the databases on whether the cable was able to sustain the produced power and on the heuristic model of the power price per W, respectively.

$$\begin{array}{r}
REVENUESpowersold(1, i) = soldpower(1, i) * price(1, i) * 0.1; \\
REVENUESnotraised(1, i) = unsoldpower(1, i) * price(1, i); \\
end
\end{array} \tag{C.5}$$

$$TOTRevNOBattery = sum(REVENUESpowersold) - sum(REVENUESnotraised);$$

C.4 Ocean Battery

The Ocean Batteries implementation required a set of heuristic models to be implemented in MATLAB. In fact, since it is a highly dynamical model inserted within a complex context, assumption on its behavior had to be heuristically implemented within the Techno-Financial Model.

C.4.1 Charging and Discharging

Firstly, the processes of charging and discharging are operated based on the comparison between power demand and power production. If the production is higher than the demand, then: in case the Batteries present available capacity and the difference amongst production and demand is higher than the available capacity in the Batteries, only the latter amount multiplied by the pump efficiency gets stored; in case the Batteries present available capacity and the difference amongst production and demand is lower than the available capacity in the Batteries, only the former amount multiplied by the pump efficiency gets stored; in case the Batteries do not present available capacity, then nothing gets stored. This decision is performed at every iteration. On the other hand, regarding the draining process: in case the Batteries present ready capacity and the difference amongst demand and production is higher than the ready capacity in the Batteries, only the latter amount multiplied by the turbine efficiency gets drained; in case the Batteries present ready capacity and the difference amongst demand and production is lower than the ready capacity in the Batteries, only the former amount multiplied by the turbine efficiency gets drained; in case the Batteries do not present ready capacity as from the total power stored at the previous iteration, then nothing gets drained. This decision is performed at every iteration. In case demand and production are equal, nothing get stored nor drained. The quantities of stored and drained power are constantly recorded within specific allocations. Here is the pseudocode of the heuristic charging and discharging model production-and-demand based:

$$\begin{aligned} TotalPowStored(1,1) &= 0; \\ TotalPowDrained(1,1) &= 0; \\ fori &= 2 : NUMiterations \end{aligned} \tag{C.6}$$

If the demand is lower than the power production at the given iteration:

$$
\begin{array}{r}
if(Demand(1,i) < (ProducedPower(1,i))) \\
ProdMinusDem(1,i) = (ProducedPower(1,i)) - Demand(1,i); \\
if(TotalPowStored(1,i) < AvailablePowerCapacity) \\
if(ProdMinusDem(1,i) <= (AvailablePowerCapacity - TotalPowStored(1,i-1))) \\
if(ProdMinusDem(1,i) <= AvailablePowerCapacity) \\
StoredPowerAtIterat(1,i) = PumpEff * ProdMinusDem(1,i); \\
TotalPowStored(1,i) = TotalPowStored(1,i-1) + (1/PumpEff) * StoredPowerAtIterat(1,i); \\
TotalPowDrained(1,i) = TotalPowDrained(1,i-1); \\
elseif(ProdMinusDem(1,i) > AvailablePowerCapacity) \\
StoredPowerAtIterat(1,i) = PumpEff * AvailablePowerCapacity; \\
TotalPowStored(1,i) = TotalPowStored(1,i-1) + (1/PumpEff) * StoredPowerAtIterat(1,i); \\
TotalPowDrained(1,i) = TotalPowDrained(1,i-1); \\
end \\
elseif(ProdMinusDem(1,i) > (AvailablePowerCapacity - TotalPowStored(1,i-1))) \\
StoredPowerAtIterat(1,i) = PumpEff * (AvailablePowerCapacity - TotalPowStored(1,i-1)); \\
TotalPowStored(1,i) = TotalPowStored(1,i-1) + (1/PumpEff) * StoredPowerAtIterat(1,i); \\
TotalPowDrained(1,i) = TotalPowDrained(1,i-1); \\
end \\
elseif(TotalPowStored(1,i) == AvailablePowerCapacity) \\
StoredPowerAtIterat(1,i) = 0; \\
TotalPowStored(1,i) = TotalPowStored(1,i-1); \\
TotalPowDrained(1,i) = TotalPowDrained(1,i-1); \\
DrainedPowerAtIterat(1,i) = 0; \\
end
\end{array}
\tag{C.7}
$$

If the demand is higher than the power production at the given iteration:

$$\begin{gathered}
elseif(Demand(1,i) > (ProducedPower(1,i))) \\
DemMinusProd(1,i) = Demand(1,i) - (ProducedPower(1,i)); \\
if(TotalPowStored(1,i-1) > DemMinusProd(1,i)) \\
DrainedPowerAtIterat(1,i) = TurbineEff * DemMinusProd(1,i); \\
TotalPowDrained(1,i) = TotalPowDrained(1,i-1) + (1/TurbineEff) * DrainedPowerAtIterat(1,i); \\
TotalPowStored(1,i) = TotalPowStored(1,i-1) - (1/TurbineEff) * DrainedPowerAtIterat(1,i); \\
elseif(TotalPowStored(1,i-1) < DemMinusProd(1,i)) \\
DrainedPowerAtIterat(1,i) = TurbineEff * TotalPowStored(1,i-1); \\
TotalPowDrained(1,i) = TotalPowDrained(1,i-1) + (1/TurbineEff) * DrainedPowerAtIterat(1,i); \\
TotalPowStored(1,i) = TotalPowStored(1,i-1) - (1/TurbineEff) * DrainedPowerAtIterat(1,i); \\
elseif(TotalPowStored(1,i-1) == DemMinusProd(1,i)) \\
DrainedPowerAtIterat(1,i) = DemMinusProd(1,i); \\
TotalPowDrained(1,i) = TotalPowDrained(1,i-1) + (1/TurbineEff) * DrainedPowerAtIterat(1,i); \\
TotalPowStored(1,i) = TotalPowStored(1,i-1) - (1/TurbineEff) * DrainedPowerAtIterat(1,i); \\
elseif(TotalPowStored(1,i) == 0) \\
DrainedPowerAtIterat(1,i) = 0; \\
StoredPowerAtIterat(1,i) = 0; \\
DemMinusProd(1,i) = Demand(1,i) - ProducedPower(1,i); \\
TotalPowDrained(1,i) = TotalPowDrained(1,i-1); \\
TotalPowStored(1,i) = TotalPowStored(1,i-1); \\
end
\end{gathered} \tag{C.8}$$

If the demand equals the power production at the given iteration:

$$\begin{gathered}
elseif(Demand(1,i) == (ProducedPower(1,i))) \\
DrainedPowerAtIterat(1,i) = 0; \\
StoredPowerAtIterat(1,i) = 0; \\
TotalPowDrained(1,i) = TotalPowDrained(1,i-1); \\
TotalPowStored(1,i) = TotalPowStored(1,i-1); \\
end \\
end
\end{gathered} \tag{C.9}$$

C.4.2 Revenues Assessment

Here, the information on the sold power and the sustained power capacity by the cables are used. In case the draining has taken place, energy was sold and revenues at the draining moment price may be calculated. By contrast, in case storing took place, revenues were not raised at the current price.

```
for i = 1 : NUMiterations
    if(DrainedPowerAtiterat(1, i)  = 0)
        selling(1, i) = 1;
    elseif(StoredPowerAtiterat(1, i)  = 0)
        notselling(1, i) = 1;
    end
    REVENUESfromDraining(1, i) = selling(1, i) * DrainedPowerAtiterat(1, i) * price(1, i);
    REVENUESnotraised(1, i) = notselling(1, i) * StoredPowerAtiterat(1, i) * price(1, i);
end
TOTrevenuesfromDraining = sum(REVENUESfromDraining);
for i = 1 : NUMiterations
    for j = 1 : NUMproductionelements
        if(sustainedEtoH(i, j) == 1)
            if(sold(i, j) > 0)
                REVENUESfromGenerating(1, i) = sold(i, j) * price(1, i);
            end
        end
    end
end
TOTrevenuesfromGenerating = sum(REVENUESfromGenerating);
TOTrevenuesYESBattery = TOTrevenuesfromGenerating + TOTrevenuesfromDraining;
```

(C.10)

C.5 LCOE Assessment

The LCOE [27] is calculated by first condensing the costs at the numerator through the sum of Capex and Opex and by then dividing such value by the sum of the produced power. Obviously, two distinct calculations are operated for the two cases, since whilst the Batteries are deployed, both capital and operational expenditures are higher. Nonetheless, the revenues attained from Battery draining may be used to cover few operational cost shares.

$$
\begin{gathered}
OPEXNumeratWITH = zeros(1, lifetimefarm); \\
CAPEXNumeratWITH = CapexProd + CapexStor - TOTrevenuesfromDraining * lifetimefarm; \\
fori = 1 : lifetimefarm \\
OPEXNumeratWITH(1, i) = (OpexProd + OpexStor)/((1 + WACC)^{i}); \\
end \\
LCOEnumeratWITH = CAPEXNumeratWITH + sum(OPEXNumeratWITH); \\
if(NUM_{b}atteries == 0) \\
sum_{t}otal_{s}tored_{p}ower = 0; \\
end \\
fori = 1 : lifetimefarm \\
LCOEdenominatWITHpw(1, i) = (TotPwProduced)/((1 + WACC)^{i}); \\
end \\
LCOEdenominatWITH = sum(LCOEdenominatWITHpw); \\
LCOEwith = (LCOEnumeratWITH/LCOEdenominatWITH); \\
OPEXNumeratWITHOUT = zeros(1, lifetimefarm); \\
CAPEXNumeratWITHOUT = CapexProd; \\
fori = 1 : lifetimefarm \\
OPEXNumeratWITHOUT(1, i) = (OpexProd)/((1 + WACC)^{i}); \\
end \\
LCOEnumeratWITHOUT = CAPEXNumeratWITHOUT + sum(OPEXNumeratWITHOUT); \\
fori = 1 : lifetimefarm \\
LCOEdenominatWITHOUTpw(1, i) = (TotPwProduced)/((1 + WACC)^{i}); \\
end \\
LCOEdenominatWITHOUT = sum(LCOEdenominatWITHOUTpw); \\
LCOEwithout = (LCOEnumeratWITHOUT/LCOEdenominatWITHOUT);
\end{gathered}
\tag{C.11}
$$