KTH ROYAL INSTITUTE
OF TECHNOLOGY

DEGREE PROJECT IN ENERGY AND ENVIRONMENT,
SECOND CYCLE, 30 CREDITS STOCKHOLM, SWEDEN 2022

Energy management for 24/7 CFE supply with wave energy technology

A techno-economic assessment of an energy system in Portugal

INGEBORG MYHRUM SLETMOEN
MARTINA SEKKENES

Stockholm, Sweden 2022

Master of Science Thesis

Department of Energy Technology

KTH 2022

Energy management for 24/7 CFE supply with wave energy technology

TRITA-ITM-EX 2022:187

Ingeborg Myhrum Sletmoen

Martina Sekkenes

Approved	Examiner	Supervisors
	Björn Laumert	Silvia Trevisan & Rafael Eduardo Guedez Mata

Abstract

The ocean has tremendous potential in terms of energy generation, and wave energy is especially promising. However, wave energy technology is still non-commercial. Along with ambitious renewable energy targets and investments, much is happening within the field and the wave energy converter developers CorPower Ocean intend to have their technology proven in the upcoming years. This study aims at investigating the value of commercial wave energy in an energy system. This is fulfilled by the possibilities of achieving 24/7 Carbon-free Energy with the wave energy technology from CorPower Ocean at the stage of commercialization. An energy system is modeled with wave energy, floating offshore wind energy, lithium-ion battery storage and the Portuguese national grid, supplying Northvolt's and Galp's future lithium conversion facility in Portugal. Different system configurations are compared based on three Key Performance Indicators: 24/7 Carbon-free Energy performance, system emission, and cost for the electricity consumer. In addition, a review of available financial support mechanisms for renewable energy technologies and especially wave energy is done to understand how such mechanisms can affect the economic feasibility of the energy system modeled. The wave energy technology from CorPower Ocean shows to have a high power output and 24/7 carbon-free Energy performance in this study. Although a combination of wave and floating offshore wind energy better ensure energy security with generation profiles that peak at different times, the modeling shows that a system with wave energy alone is preferred for supplying the facility with electricity both from an environmental and economic perspective. The economic feasibility of Lithium-ion battery storage in the system is uncertain and to achieve 24/7 Carbon-free Energy supply of the facility a longer duration storage solution is needed. The price for wave energy in this study is higher than for other commercial renewable energy technologies such as solar PV. However, based on the available financial support structures from governments and other stakeholders, wave energy technology has the potential to be competitive as soon as the technology is proven.

Keywords: Wave Energy, CorPower Ocean, Floating Offshore Wind Energy, Lithium-ion Battery Storage, Energy System Modeling

Sammanfattning

Energigenerering från våra hav har stor potential, inte minst från vågkraft. Trots att vågkraftstekniken ännu inte har nått ett kommersiellt stadie händer det mycket inom området i takt med fler ambitiösa miljökrav och investeringar. CorPower Ocean utvecklar vågkraftsteknik och planerar att ha sin teknik bevisad inom några år. Den här studien syftar till att undersöka värdet av kommersiell vågkraft, vilket uppfylls genom möjligheterna till förnybar el 24 timmar om dygnet med CorPower Ocean's vågenergiomvandlare. Ett energisystem modelleras med vågkraft, flytande vindkraft, litium-jon batterier och det portugisiska elnätet för att försörja Northvolts och Galps planerade anläggning för litiumkonvertering i Portugal. Olika systemkonfigurationer är jämförda utifrån tre parametrar: 24/7 förnybar el prestation, systemutsläpp och elkostnad för konsumenten. I tillägg utförs en studie om vilka finansiella supportmekanismer som finns för hållbar energiteknik och speciellt för utvecklingen av vågkraft. Detta för att få insikt i om vågkraft kan få finansiellt stöd och konkurrera med andra förnybara energitekniker. Studien visar att vågkraftstekniken presenterar bra utifrån de tre parametrarna. Trots att en kombination av våg och flytande vindkraft ger bättre elsäkerhet med alternerande produktionskurvor visar modelleringen att ett system med endast vågkraft är att föredra både från ett ekonomiskt och ett miljöperspektiv. En investering av litium-jon batterier i energisystemet är tveksam och för att uppnå förnybar elförsörjning av anläggningen 24 timmar om dygnet krävs en energilagringsteknik som möjliggör lagring över längre perioder. Priset för vågkraft i studien är högre än för andra kommersiella förnybara energitekniker så som solpaneler. Baserat på det finansiella stöd som finns från myndigheter och andra intressenter så är det möjligt för vågkraften att bli konkurrenskraftig så fort tekniken är bevisad.

Nyckelord: Vågkraft, CorPower Ocean, Flytande Vindkraft, Litium-jon Batterilagring, Energisystem-modellering

Acknowledgements

Much praise is directed to our supervisor Silvia Trevisan, who has been a significant supporter throughout this project period. Your continuous feedback and inputs have been fundamental for the fulfillment of this project. Thank you.

This project has been done in collaboration with CorPower Ocean and gratitude is directed to the whole team. Further, much praise is directed to Anders Jansson, our industrial supervisor. He has been an important contact and this project would not be the same without his influence and engagement. Thank you.

Huge gratitude is directed to the WavEC Offshore Renewables team in Lisbon, Portugal. We are more than thankful for your welcome at the WavEC office and for sharing your expertise during our stay in Lisbon. Thank you.

We are grateful for the data and inputs Aurora provided for this study; it would not have been the same without your help. Thank you.

Lastly, we are grateful for family, friends, and others that in some way helped us fulfill this study. Thank you.

Table of Contents

List of Figures

List of Tables

List of Acronyms and Abbreviations

BESS	Battery Solutions
BEUR	Billion Euro
BTM	Behind-the-meter
CapEx	Capital Expenditures
CFE	Carbon-Free Energy
CO_2-eq	Carbon dioxide equivalents
CP	CorPower Ocean
EIC	European Innovation Council
ESS	Energy Storage System
EU	European Union
FiT	Feed-in Tariffs
FLOW	Floating Offshore Wind
FTM	In-front-of-the-meter
GHG	Greenhouse Gas
GWh	Gigawatt-hour
HOMER	Hybrid Optimization of Multiple Energy Resources
HRP	Hourly Renewable Penetration
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
KPI	Key Performance Indicator
km	Kilometer
kW	Kilowatt
kWh	Kilowatt-hour
LCOE	Levelized Cost of Energy
Li-ion	Lithium-ion
m	Meter
MEUR	Million Euros
MW	Megawatt
MWh	Megawatt-hour
NPC	Net Present Cost
NPV	Net Present Value
OEE	Ocean Energy Europe
OpEx	Operating Expenditures
PPA	Power Purchase Agreement
PPPA	Physical Power Purchase Agreement
PTO	Power Take Off
PV	Photovoltaic
REC	Renewable Energy Certificates
RET	Renewable Energy Technology
RF	Renewable Fraction
RP	Renewable Penetration
TWh	Terawatt-hour
UN	United Nations
VPPA	Virtual Physical Power Purchase Agreement
WACC	Weighted Average Cost of Capital
WEC	Wave Energy Converter
YRP	Yearly Renewable Penetration

1. Introduction

Global greenhouse gas (GHG) emissions are leading to severe consequences for the climate and the concentration of carbon dioxide equivalents (CO_2-eq) are increasing in the atmosphere. The concentration of GHG reached 460 ppm of CO_2-eq in 2019 which equals an increase of more than 180 ppm compared to pre-industrial levels. The concentration of CO_2-eq is interlinked with the global temperature increase through the greenhouse effect and needs to be decreased to slow down global warming (EEA 2022). The European Commission published the REPowerEU Plan in March 2022, addressing how the European Union (EU) can be independent of Russian fossil fuels, this as a response to the Russian invasion of Ukraine. The plan emphasizes how the instability in Europe and the climate crisis together increase the urgency of the renewable energy system transition (Kulovic 2022).

As targets and legislations for climate change are being implemented in countries all over the world, mitigation and adaptation measures are increasing globally. The Paris Agreement, adopted in Paris December 12th, 2015, stands as an important legally binding international treaty with a combining ambition on climate change. The Agreement was signed with the main target of keeping the global temperature decrease under 1.5°C compared to pre-industrial levels (IPCC 2021). In addition to the Paris Agreement the United Nations (UN) Sustainable Development Goals are covering 17 focus areas for targets related to climate change. The seventh goal focuses on energy and addresses how access to modern, reliable, and sustainable energy must be ensured for all. One of the targets is to reach a global energy mix with a substantially larger share of renewable energy technologies (RET) by 2030 (UNDP n.d.). Energy diversification is one of the main strategies for avoiding dependence on one source and ensuring energy security. An energy secure system is built to meet uncertainties by ensuring adaptiveness (Akrofi 2021).

Furthermore, the UN published the "24/7 Carbon-Free Energy Compact" late 2021. The compact addresses the concept of 24/7 Carbon-free Energy (CFE), and how the electricity consumption for every kilowatt-hour (kWh) for all hours of the day can be met by carbon-free sources of electricity (UN 2021). In line with more ambitious renewable targets, the interest in 24/7 CFE has increased. To enable 24/7 CFE supply the energy mix must include sources of energy that have different production profiles and fill in the renewable gap of the hourly generation (Roberts 2021).

According to the International Renewable Energy Agency (IRENA) the ocean has tremendous potential in terms of energy generation. Theoretically, twice the world's electricity demand could be covered with ocean energy technology. Together with other offshore renewables such as floating offshore wind (FLOW) and solar PV, the ocean energy technologies; wave, tidal, salinity gradient and ocean thermal energy conversion represent an important part of the growing blue economy (IRENA 2020a). In 2020, the electricity generation from marine technologies was 1.6 terawatt-hour (TWh), which equals an increase of 400 gigawatt-hour (GWh) compared to 2019. Despite the significant potential and the benefits of offshore renewables and ocean energy, the commercial state of marine energy is yet ahead of us. International Energy Agency (IEA) states that the status of the marine energy sources is off track and for the EU to be climate neutral by 2050 a significantly higher pace of the deployment is required. Policies giving research and development a push is essential for marine energy technologies to become economically feasible and to further make large-scale deployment possible (IEA n.d.).

Wave energy has a large generation potential of approximately 29,500 TWh/year and is estimated to be able to cover 10% of the European electricity demand by 2050 (Onea & Rusu 2018). Although, today wave energy technology is not yet proven. The leading wave energy technology developers are currently testing their wave energy converters (WECs) at sea, both single- and multi-device pilot farms (OEE n.d.a). CorPower Ocean is one of them, testing their full-scale WEC in Portugal this summer (2022) (CPO n.d.a). Further, Portugal is one of the countries who have high ambitions and noticeable progress in the wave energy field. The country intends to be a global key player in marine energy technology. However, if the country wants to be on the frontline for wave energy, the national energy sector needs to consider the current state of the technology and introduce necessary policy instruments. Research and development support is needed to push this not yet mature power technology towards becoming competitive (Cunha-e-Sá, Lopes & Saldanha 2017).

With an electricity mix using RETs, the importance of securing a stable and reliable grid arises. Renewables such as solar and wind are variable and intermittent sources of energy that bring challenges in balancing the energy demand-supply mismatch. Therefore, strategies and technologies solving these problems are significant. Power curtailment is stated to be strongly correlated with grid penetration of various renewables (Chen, Hu & Yang 2021). The interest in hybrid renewable energy sources is emerging to meet this challenge. Hybrid energy generation with wind and wave energy has shown to be promising. This is as the production profiles for offshore wind and waves reach their peak at different times during a day and year (Albert 2020). Further, energy storage is a promising solution, where battery energy storage systems (BESS) are the most flexible. Lithium-ion (Li-ion) batteries have in recent years been the technology with the highest phase of development amongst the BESS solutions (Chen, Hu & Yang 2021) (Blaabjerg et. al. 2018). To sum up, a variated energy mix and energy storage are significant to achieve 24/7 CFE and mitigate climate change. Offshore renewable energy technologies are on the rise and are expected to fill an important role in the renewable energy transition.

1.1. Aim and Objectives

The study aims to investigate the value of commercial wave energy technology in an energy system. This is fulfilled by analyzing the performance of the wave energy technology from CorPower Ocean in an energy system at the stage of commercialization. The possibilities of achieving 24/7 Carbon-free Energy are investigated in combination with wave energy, FLOW energy, Li-ion battery storage and the Portuguese national grid, supplying Northvolt's and Galp's future lithium conversion facility.

The specific research questions to be answered are as follows.

1. How does the wave energy technology perform in the system alone and in combination with FLOW energy? Further, what is the better option for the electricity consumer in terms of cost and emission for supplying the facility load: buying all electricity from the Portuguese grid or having Power Purchase Agreements with the wave and wind energy plants?

2. Is Li-ion battery storage an economically feasible option to complement wave and FLOW energy towards achieving a 24/7 Carbon-free Energy supply of the facility?

3. How much financial support is required for wave energy to reach market price and compete with already commercial renewable energy technologies? Further, what financial support is available in Europe and specifically in Portugal for wave energy?

1.3. Research Methodology

This study was carried out via an energy system modeling and was further complemented with a review of financial support for wave energy. The energy system modeling was done to see how wave, floating offshore wind energy and energy storage can meet the approach of 24/7 CFE. More specifically, with the CorPower Ocean wave energy converter, Vestas V164 8000 wind turbine and Li-ion batteries. This was done in the optimization tool HOMER Pro (Hybrid Optimization of Multiple Energy Resources) (HOMER Energy n.d.). In addition, a complementary model for the energy storage was made in Excel and used for the Li-ion battery storage investigation. Both environmental and economic metrics were used for the system evaluation and analysis. More details of the modeling part can be seen in *Section 3.2.*

A review of financial support for wave energy was done to get a better knowledge of how financial support mechanisms affect the emerge and deployment of renewable energy technologies and especially wave energy. Additionally, it was done to understand how such mechanisms affect the energy system modeled in this study. More details of how the review was executed is found in *Section 3.3.*

Figure 1. presents the research process of this study. During the project this flowchart was used as guidance to structure the methodology of the report. However, it does not reflect the timeline of the study. The different main steps followed were, relevance and context setting, structure of the study, system set-up, modeling and research, results, analysis, and discussion.

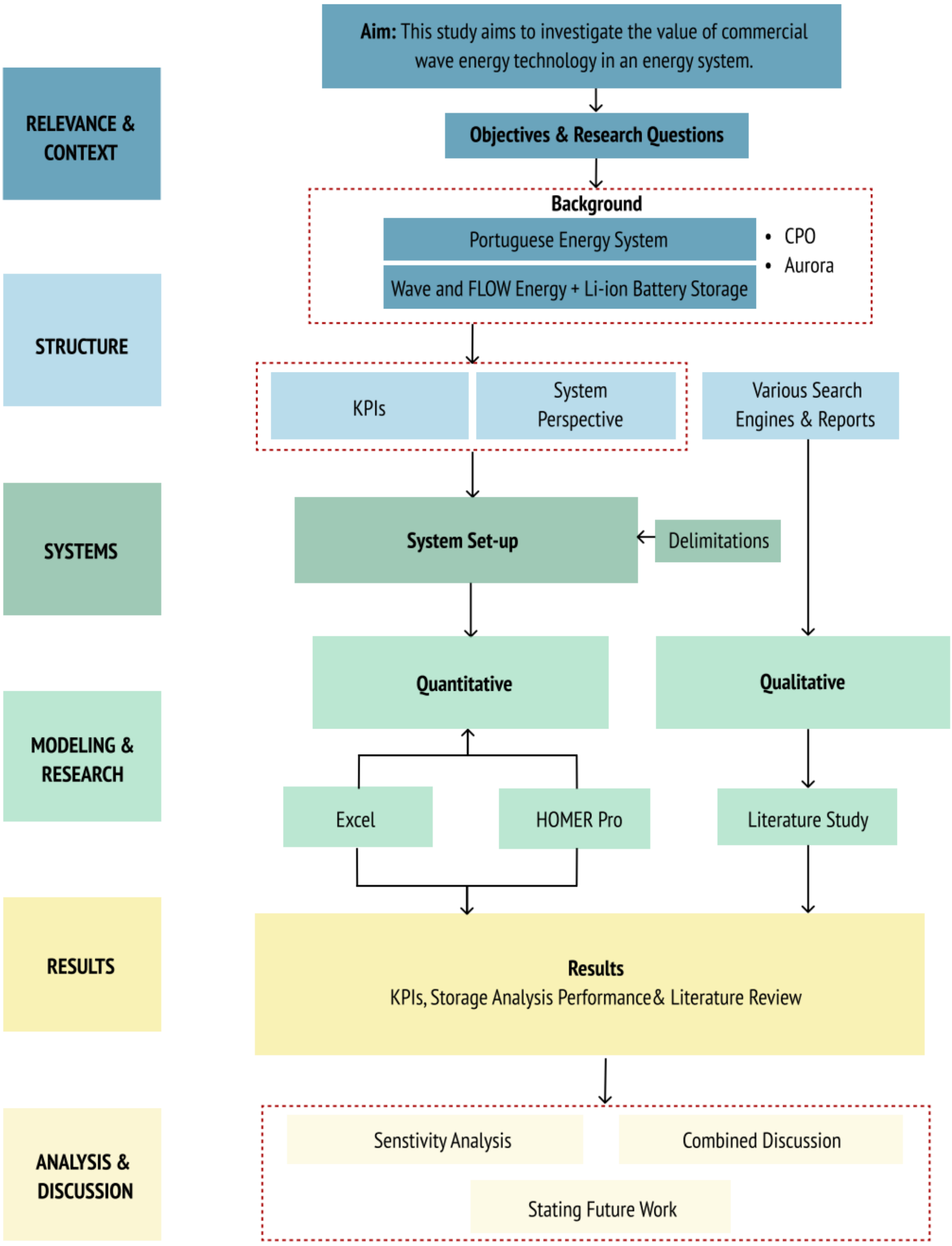


Figure 1.The Project Procedure.

1.3.1. Work Specifications

Ingeborg Myhrum Sletmoen and Martina Sekkenes are the authors of this report. The study was executed as a team. Although, to ensure an efficient process the main responsibility of some parts was divided between the two authors. This was done mainly in the starting process of a new investigation in the study. Most of the work was done together and for the divided responsibility areas constant communication and discussions were held. The individual work specifications are listed below.

Ingeborg	Martina
HOMER Pro Modeling	Energy Storage Model and Modeling
Emissions Calculation	Energy Price Calculations
CorPower Ocean Technology	Wave Energy Output
Cross-Project Tasks	

1.4. Delimitations

The delimitations of the study are listed below:

- The renewable energy sources investigated were wave energy and FLOW energy and for the energy storage, Li-ion batteries were chosen.
- The load of the conversion facility was limited to the electricity demand of the equipment of the facility.
- The system model was built as an on-site “behind-the-meter” Power Purchase Agreement with a buy-all, sell-all approach of the electricity.

1.5. Structure of the Thesis

Chapter 3 presents a background of the main components and concepts of this study. Firstly, the wave and floating offshore wind energy and energy storage technologies, with special focus on the CorPower Ocean wave energy converter, FLOW energy and Li-ion batteries. Further, the project of Northvolt and Galp, the Portuguese grid mix and national renewable energy targets are introduced. Followed by current trends and concepts within the renewable energy market such as 24/7 CFE, renewable energy auctions and Power Purchase Agreements. And finally, related, and similar work to this study is stated.

Chapter 4 covers the method of the study. Initially, Key Performance Indicators and the system set-up are explained. Further, the steps of the energy system modeling part are covered, including how the system inputs and settings were obtained and chosen and how the battery storage model was made. Followed by a description of how the review was done.

Chapter 5 is the results and analysis of the study, starting with a wave and floating offshore wind energy performance comparison outside Viana do Castelo, Portugal. Followed by the results from the modeling in HOMER Pro and the Key Performance Indicators. The results and analysis from the battery storage part of the study are then presented. Finally, a sensitivity analysis is performed leading into the review addressing relevant financial support mechanisms for wave energy in Europe and in Portugal.

Chapter 6 covers a discussion of the work done in the study where the system set-up, results and limitations are discussed. Further, considerable improvements of the study are addressed.

Chapter 7 is the final chapter presenting the conclusion that answers the research questions of the study. Relevant, and interesting future work for the study is also suggested here.

2. Background

Information addressing the main components and concepts of this study are presented in the following chapter.

2.1. Marine Energy Technology

Marine energy technology includes all the available techniques that convert energy from the oceans and/or perform energy production out at sea (Cunha-e-Sá, Lopes & Saldanha 2017). They are considered to have an important role in the renewable energy transition where the key technologies today are offshore wind, wave, and tidal energy (SEAI n.d.).

The offshore energy technologies have several advantages in common. Firstly, the most vital advantage, applied to any renewable energy source, is the low climate impact. An increased share of marine energy technologies in the energy mix is a way to reduce the GHG emissions from the energy sector. In addition, marine energy technologies, as well as other new energy sources, enable a more constant electricity supply to the grid. A more diverse energy system ensures a firm capacity, especially for RET energy generation. Further, a socio-economic benefit of marine energy technology is that it creates jobs. The power technologies exploiting the energy in waves and tides come with some additional advantages to the above mentioned. Compared to solar and wind, ocean energy is considered more predictable. Both waves and tides depend heavily on the location and therefore provide a resource pattern that is less intermittent and easier to forecast. Worth emphasizing is also the promising social acceptance towards ocean energy. This is because the energy converters are either submerged or relatively small bodies floating on the water surface. They are less visible than for example wind turbines (IRENA 2020a).

As already mentioned, wave power has a great potential to enable constant supply together with offshore wind power. Waves are created when the wind blows over the oceans and they continue to have significant size after wind speeds decrease. Thus, wave energy and offshore wind energy alternate well (IRENA 2020a). This study investigates wave and offshore wind energy specifically, as well as the combination of the two. The following sections go into further detail regarding the potential and current state of each of the technologies.

2.2. Offshore Wind Energy

Offshore wind energy has the potential to access wind resources that are stronger, compared to onshore. Offshore wind energy can be divided into two subcategories after their foundation being either: bottom-fixed or floating, where floating technologies allow for larger water depths and a longer distance to shore. The largest share today is bottom-fixed. However, the commercial interest of floating offshore wind (FLOW) has increased in recent years and more installed capacity is to be seen (U.S. Department of Energy 2021).

The FLOW technology is opening for a new market within marine technologies. An amount of 18,866 megawatt (MW) of offshore wind energy capacity was installed between 2019-2020. In Europe, the United Kingdom and Portugal are the two countries with the highest amount of operating capacity of the global FLOW energy pipeline with 30, respectively, 25 MW (U.S. Department of Energy 2021).

2.2.1. Offshore Wind Energy in Portugal

The installed capacity of FLOW in Portugal is from the WindFloat Atlantic project which is in the north outside the coast of Viana do Castelo. The Park consists of three turbines with 8.4 MW of capacity each and supplies enough electricity for 60,000 households yearly. The last of these turbines was implemented in 2020, and the project became operational later the same year. The three turbines are connected to shore with a 20 kilometer (km) long subsea cable (EDP n.d.).

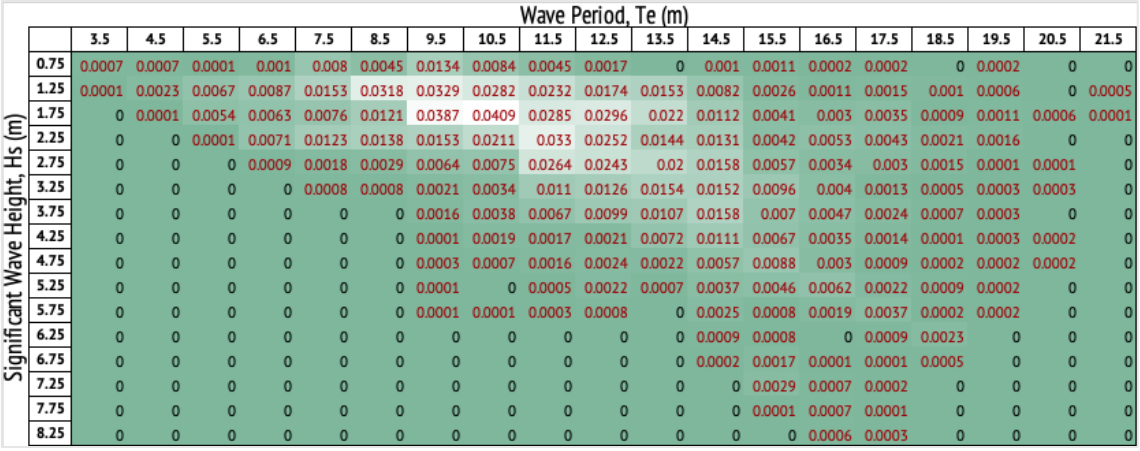
In addition to the already operating capacity, more implementation of FLOW is planned in Portugal. The Portuguese government has approved six more sites, in total 125 MW of installed capacity, for FLOW deployment (U.S. Department of Energy 2021) (IEA 2021).

2.3. Wave Energy

This section explains how energy extraction from waves work in theory and the working principles of different types of WECs. Further, the current state of wave energy technology is presented, both from a global perspective and in Portugal, looking into the latest development. CorPower Ocean and the HiWave-5 project are also introduced.

2.3.1. Wave Energy Conversion

Waves are generated either locally or from a distance. Locally generated waves are called wind seas and when distant wind generates the waves it is called swell. The energy density of the swell waves is known to be higher and is therefore more of interest for the WEC developers (Onea & Rusu 2018). The wave height, length, and period tell how much energy that could potentially be extracted by a WEC (OEE n.d.a). Normally, a scatter diagram is used to show the annual energy distribution of a specific location, with the wave height on one axis and the wave period on the other. *Figure 2* shows the wave scatter diagram outside the coast of Viana do Castelo in 2020. More specifically, it is a histogram obtained from Copernicus that shows the appearance of different sea-states for a chosen location and year (Copernicus n.d.). The energy distribution also varies over the seasons. During the winter months the wave energy potential is higher than during the summer months (CPO, pers. comm., spring 2022).



Wave Period, Te (m)

Significant Wave Height, Hs (m)

	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5	21.5
0.75	0.0007	0.0007	0.0001	0.001	0.008	0.0045	0.0134	0.0084	0.0045	0.0017	0	0.001	0.0011	0.0002	0.0002	0	0.0002	0	0
1.25	0.0001	0.0023	0.0067	0.0087	0.0153	0.0318	0.0329	0.0282	0.0232	0.0174	0.0153	0.0082	0.0026	0.0011	0.0015	0.001	0.0006	0	0.0005
1.75	0	0.0001	0.0054	0.0063	0.0076	0.0121	0.0387	0.0409	0.0285	0.0296	0.022	0.0112	0.0041	0.003	0.0035	0.0009	0.0011	0.0006	0.0001
2.25	0	0	0.0001	0.0071	0.0123	0.0138	0.0153	0.0211	0.033	0.0252	0.0144	0.0131	0.0042	0.0053	0.0043	0.0021	0.0016	0	0
2.75	0	0	0	0.0009	0.0018	0.0029	0.0064	0.0075	0.0264	0.0243	0.02	0.0158	0.0057	0.0034	0.003	0.0015	0.0001	0.0001	0
3.25	0	0	0	0	0.0008	0.0008	0.0021	0.0034	0.011	0.0126	0.0154	0.0152	0.0096	0.004	0.0013	0.0005	0.0003	0.0003	0
3.75	0	0	0	0	0	0	0.0016	0.0038	0.0067	0.0099	0.0107	0.0158	0.007	0.0047	0.0024	0.0007	0.0003	0	0
4.25	0	0	0	0	0	0	0.0001	0.0019	0.0017	0.0021	0.0072	0.0111	0.0067	0.0035	0.0014	0.0001	0.0003	0.0002	0
4.75	0	0	0	0	0	0	0.0003	0.0007	0.0016	0.0024	0.0022	0.0057	0.0088	0.003	0.0009	0.0002	0.0002	0.0002	0
5.25	0	0	0	0	0	0	0.0001	0	0.0005	0.0022	0.0007	0.0037	0.0046	0.0062	0.0022	0.0009	0.0002	0	0
5.75	0	0	0	0	0	0	0.0001	0.0001	0.0003	0.0008	0	0.0025	0.0008	0.0019	0.0037	0.0002	0.0002	0	0
6.25	0	0	0	0	0	0	0	0	0	0	0	0.0009	0.0008	0	0.0009	0.0023	0	0	0
6.75	0	0	0	0	0	0	0	0	0	0	0	0.0002	0.0017	0.0001	0.0001	0.0005	0	0	0
7.25	0	0	0	0	0	0	0	0	0	0	0	0	0.0029	0.0007	0.0002	0	0	0	0
7.75	0	0	0	0	0	0	0	0	0	0	0	0	0.0001	0.0007	0.0001	0	0	0	0
8.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0006	0.0003	0	0	0	0

Figure 2. Wave Scatter Diagram Viana do Castelo 2020.

The WEC technology can be explained as a body that absorbs the energy of a wave and converts it into electricity. To achieve optimal wave energy absorption, the design and controlling system of the WEC plays a significant role. For maximum power output, an optimal interaction between the WEC and each wave is aimed for. It is challenging to develop a device that is optimized over the entire bandwidth of motion periods that occurs in the sea. Ideally the device always allows maximum motion and excitation, until the point when the wave size can destroy the WEC, then it should not absorb the wave (CPO, pers. comm., spring 2022).

There are three main types of WEC designs: point absorber, attenuator, and terminator. A point absorber is a WEC that can capture energy from several directions of the floating buoy. Point absorbers are small compared to the wavelength and move mainly in heave at the water surface. An attenuator is a line absorber aligned parallel with the direction of the wave. It has the same length as the wavelength or longer. And lastly the terminator is a line absorber like the attenuator and has at least the length of the wave. However, the terminator is aligned parallel to the wave crest (CPO, pers. comm., spring 2022).

2.3.2. Wave Energy State of the Art

Wave energy has the potential to be a large source of energy from our seas, with an estimated global generation of 29,500 TWh/year (OEE n.d.a) (Onea & Rusu 2018). Despite this promising potential, and the fact that the WEC technology development took off already in the 70s, only 2.31 MW of wave energy was installed by 2020 and the technology is still in a non-commercial state (IRENA 2020a) (Esteban 2017).

As mentioned, the leading WEC developers are currently testing their devices at sea, both single- and multi-device pilot farms. Further, the planning of future commercialization and implementation of large-scale projects is ongoing (OEE n.d.a). Different types of WECs are relevant and moving towards becoming mature technologies. Some developers aim for large-scale generation with wave energy farms and others for smaller, more specific offshore cases (IRENA 2020a). Pipeline activity indicates that closer to 500 MW of wave energy will be deployed in the upcoming years (IRENA 2020a).

2.3.3. Wave Energy in Portugal

Wave energy in Portugal is of significant relevance. Looking at the wave power resource, the continental coast of Portugal is one of the most promising areas for wave energy generation in Europe. The potential of wave energy generation is estimated to be approximately 15 GW along the coast of the country (Gunn & Stock-Williams 2012). Several studies have concluded that the northeast of Portugal is the best option for wave power deployment. Bento et. al. (2015) investigated the wave energy resource differences along the Portuguese coast using more than thirty years of historical wave data. The conclusion was that the energy that can be extracted from waves is the highest in the northwest of Portugal. Further south in Portugal the waves are smaller, and the impact of season variability is higher. Cunha-e-Sá et al. (2017) performed a site-selection study for marine energy technology in Portugal, including the parameters of water depth and distance to grid. Again, the north coast of Portugal was found to be better for wave power deployment. However, Bento et. al. (2018) developed a method for evaluating wave energy farms in Portugal that includes economical metrics. The conclusion was that areas around Lisbon would be the most suitable for wave energy generation once the technology is economically feasible. HiWave-5 is a project developed by CorPower Ocean (CPO) and he following section describes this project further.

2.3.4. CorPower Ocean - The HiWave-5 Project and Technology

After decades of research and WEC technology development, HiWave-5 is CorPower Ocean's (CPO) flagship project where the product will finally be tested at full-scale in the sea. It is the final phase before the realization of commercializing their developed WEC. A target with the project is to make the product certified and warrantied, thus ready for the market by 2024, and this to eventually become a bankable technology that can compete with other renewable power technologies (CPO n.d.a). The Hiwave-5 project is in the north of Portugal, on the coast of Aguçadoura. The project consists of several different stages. First, demonstration and prototype certification of a full-scale single device will take place during the summer of 2022. Moving on to the next stage, installing a larger system with 3 WECs coupled in one array will be installed. This will be one of the first wave farms in the world to deliver electricity to the grid (CPO, pers. comm., spring 2022).

The CPO WEC is a point absorber WEC shaped as a buoy, which in an array can achieve the same wave absorption as a line absorber. The technology generates energy from waves by using the stored pressure from a pre-tension system to keep the force of the buoy downwards. This is one of the key components of the device (Bould et. al. 2016). See *Figure 3 and 4* for the CPO buoy and in detail device specifications.

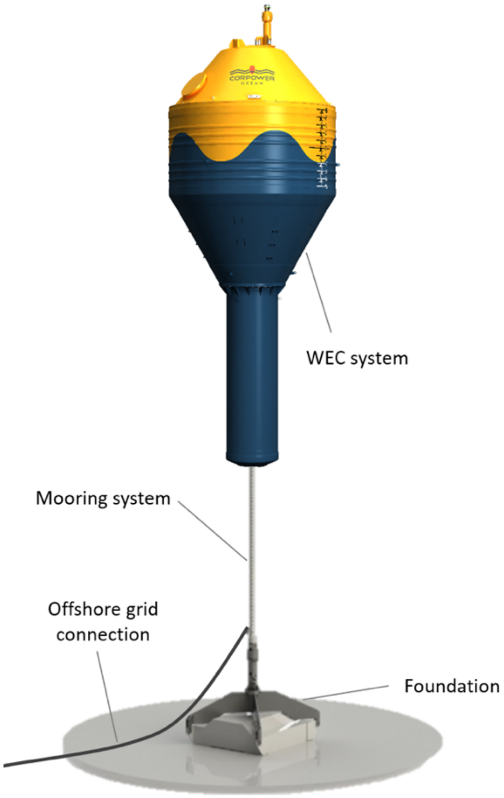


Figure 3. CorPower Ocean's Wave Energy Converter. (CPO n.d.b).

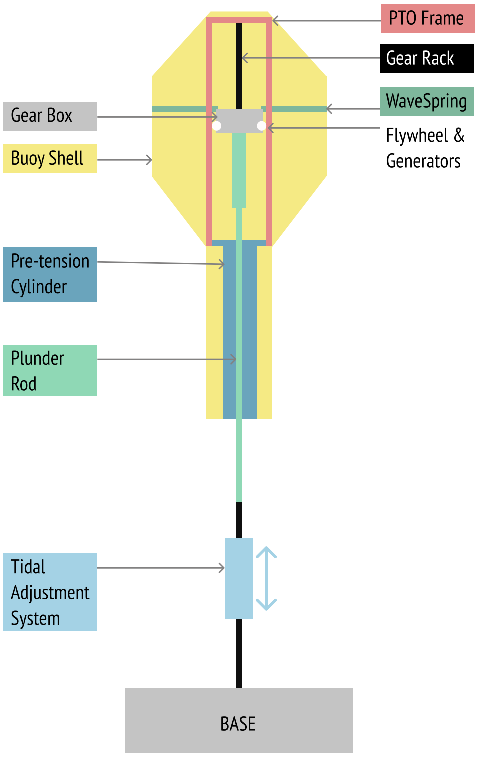


Figure 4. Device Specifications. (Bould et. al. 2016).

The CPO WEC absorbs waves in two directions from the water surface while being fastened to the seabed through a tension leg mooring system. In this way, waves are converted into electricity, both by the back and forth, and up and down motion of the buoy. When the waves hit the buoy, it pushes it upwards while the pre-tensions system drives it downwards. Hence, the energy generated is equal in both directions. The technology is inspired by the human heart pumping principle where a stored hydraulic pressure is used to contribute to a force for the return stroke of the heart. Further, it is through the Power Take Off (PTO) that the motions of the waves can be converted from mechanical energy to electricity. The CPO buoy is built with a novel phase control technology, known as the WaveSpring, controlled after the wave climate to match the waves. This is another key component and increase the power captured from the waves. The phase control system makes the bandwidth of the buoy widened. In this way the WEC can better follow the wave motion, and be in tuned or detuned state, through oscillation. The detuned state is to protect the buoy from storms and extreme wave conditions and makes the buoy transparent for the waves (CPO n.d.b.). A third significant component is the Cascade gear box, which is dividing the load into smaller gears and is together with the gear rack allowing energy to be converted from linear motion to rotational (Bould et. al. 2016). Today's version of the CPO device has a rated capacity of approximately 300 kilowatt (kW) and with further development it is expected to reach a rated preliminary capacity of 350-500 kW (CPO, pers. comm., spring 2022).

2.4 Li-ion Batteries

Energy storage solutions (ESS), especially large-scale can assist the increased penetration of renewables in the grid by balancing and stabilizing the system (Blaabjerg et. al. 2018). For instance, it can help mitigate the intermittent energy output of wind energy (Das & Khaki 2019).

There are different storage solutions available whereas the most conventional is pumped hydro storage. However, BESS have emerged due to its potential to increase system flexibility as it can quickly store electricity and reinject whenever needed. This is especially important with an increased share of renewables, as they are intermittent sources of energy. Battery storage is also more flexible in terms of geographical location and sizing. Depending on the purpose of the storage, batteries can be installed in different parts of the electrical power system and range between a few and hundreds of megawatt-hours in energy capacity (IRENA 2019a). Large-scale batteries placed along the transmission/distribution system or at the generation site, also called in-front-of-the-meter (FTM) batteries, aim to balance, and secure the grid from a system operator perspective. Further, there are behind-the-meter (BTM) batteries which instead are located after the utility meter of the electricity consumer. This type of battery is mainly installed to reduce the electricity bill (ESA 2018).

Amongst battery energy storage solutions, Li-ion batteries are most mature at this stage. This is mainly due to reduced costs in recent years (IRENA 2019a). Additionally, the high efficiency of over 90% is a significant incentive for investing in such batteries. Moreover, Li-ion batteries can store energy at megawatt scale and are known for high reliability (Blaabjerg et. al. 2018).

2.5. The Aurora Project

Portugal is the 6th largest producer of lithium in the world and was responsible for 1.8% of the global lithium production in 2015 (Pereira 2018). The IEA states (2021) the potential for Portugal to utilize the lithium resources for the value chain of battery production and emphasizes how a sustainable development of this industry is required (IEA 2021). The value of lithium has increased much in recent years due to the importance of lithium as a component in one of the electrodes and the electrolyte in batteries (Pereira 2018).

Aurora is a joint venture between Swedish battery company Northvolt and Portuguese gas company Galp in the implementation of a lithium conversion facility in Portugal. It is a collaboration established to follow the trends in the value chain of batteries and fast increase of lithium hydroxide utilized in batteries. Aurora emphasizes that the facility will be the largest and most sustainable in Europe with a yearly production capacity of 35,000 tons of lithium hydroxide. This will further enable 50 GWh of battery production every year, sufficient for around 700,000 electric vehicles. The facility will start operating in 2025 and is predicted to be commercial in 2026 (Galp & Northvolt 2021). Galp and Northvolt recently presented (April 2022) that the location of the facility will be in Setúbal, Portugal (Northvolt 2022). In this study, preliminary electricity load data of the Aurora lithium conversion facility has been provided.

2.6. The Portuguese Energy System

In the following section a description of the Portuguese energy system will be presented.

2.6.1. Current Power Capacity and Grid Composition

In February 2022 mainland Portugal generated 7090 GWh of electricity in total, with a peak generation of 8,482 MW. Out of the total electricity generated, 56.5% was generated with renewable energy sources and 38.84% was generated with fossil fuels. *Figure 5 s*hows this current Portuguese energy composition. The renewable capacity consists mostly of onshore wind power and hydro power (REN n.d.a.).

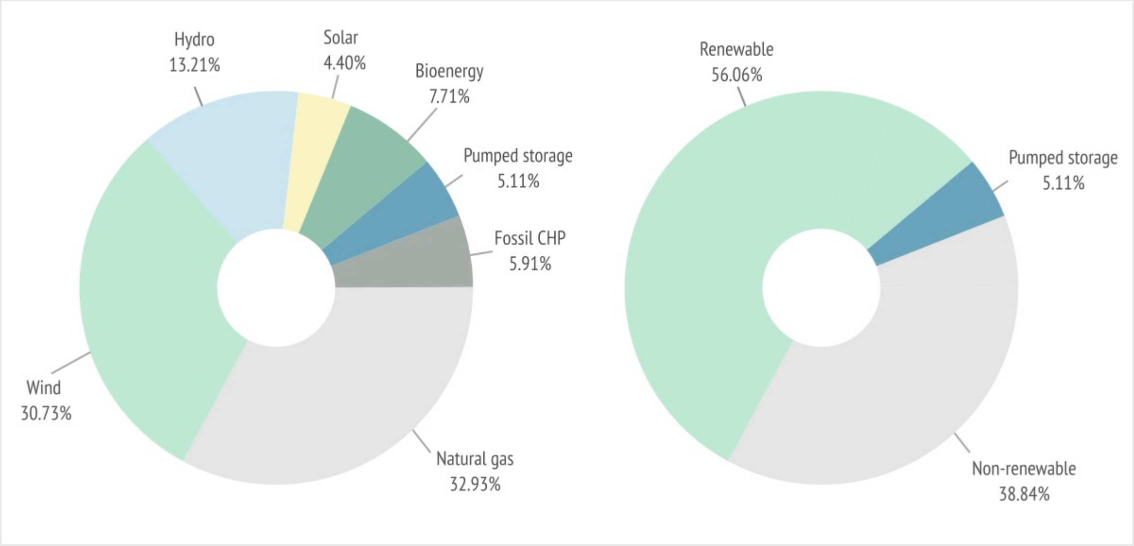


Figure 5. The Portuguese Energy Mix

(REN n.d.a.).

The renewable energy generation in Portugal varies due to the seasonal variability of renewable energy sources. In the energy system, the main contributor to the non-consistent RET generation is hydropower as it covers a big share of the total production (IEA 2021). *Figure 6* shows the fluctuations in electricity generation by source between March 2020 and March 2022.

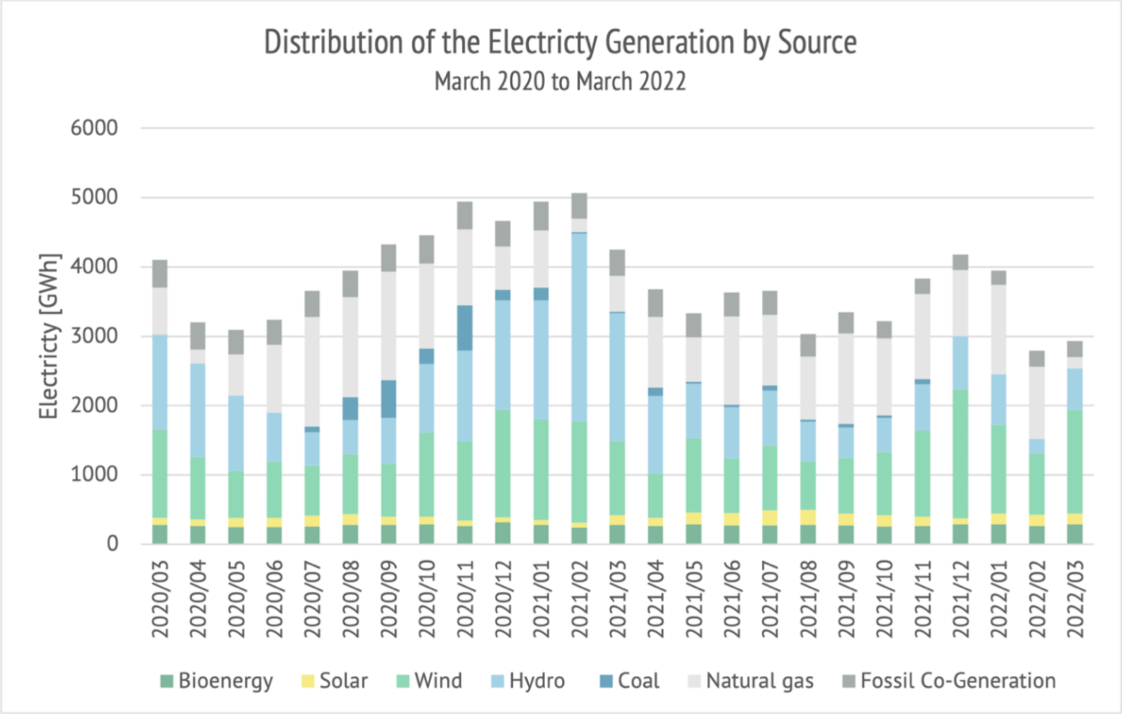


Figure 6. Distribution of the Electricity Generation by Source.

(REN. n.d.a.).

2.6.2. National Energy Targets

Portugal was early to set ambitious goals of becoming climate neutral. The national energy and climate plan includes targets towards achieving carbon neutrality by 2050. In 2030, the total GHG emissions in the country are planned to be reduced by 45-55% and to eventually reach 85-90% by 2050. The reduction percentages are compared to the levels in 2005 (IEA 2021). To reach the targets on time Portugal work towards making the nationwide energy demand completely electrified and supplied with renewable energy sources. The share of electrification in the energy sector is targeted to increase to 32-33% by 2030 and 66-68% by 2050, compared to 2019 when the level of energy load covered by electricity was 25%. In addition, the share of renewables for electricity generation is targeted to increase. The share was 54% in 2019 and is targeted to increase to 80% by 2030 and 100% by 2050. With this, the renewable energy capacity is therefore targeted to increase much in Portugal by 2050. Specific targets are also set for wave and FLOW energy implementation. For wave energy, an installed capacity of 30 MW is targeted by 2025 and 70 MW by 2030. Further, for FLOW the targets are 100 MW in 2025 and 300 MW in 2030 (IEA 2021). However, the first FLOW auction of 3-4 GW is planned in the summer 2022, exceeding the national targets for the technology (Reuters 2022).

2.7 Trends in the Renewable Energy Market

Much is happening in the energy sector along with global targets and legislations. New concepts are therefore emerging between stakeholders within the sector. The concepts relevant for the modeling in this study are presented below.

2.7.1. 24/7 Carbon-free Energy

The UN (2021) emphasizes the concept of 24/7 Carbon-free Energy (CFE) in the “24/7 Carbon Free Energy Compact ". 24/7 CFE is when electricity consumption for every hour of the day can be met by carbon-free sources of electricity. However, challenges follow with this approach; to manage to reach an end-stage where the electricity system is fully decarbonized and policy design that will accelerate this process. To reach 24/7 CFE everywhere at any time, all stakeholders need to be involved, the political environment should be scaled after the CFE requirements, and the energy ecosystem should include solutions accordingly. The UN states in the compact that certain actions and principles should be committed to by stakeholders across the energy ecosystem. Nonetheless, with the current innovation and clean energy transition the goal is possible (UN 2021).

Renewable energy certificates (RECs) are used with the intention to make the interest in renewable investment higher as an extra income with the REC purchases would follow. It functions such that every generated MWh from a RET plant is awarded with a REC, that further can be sold. However, today's RECs are not stating when the energy is generated, which is significant to know for the approach of 24/7 CFE, as there is a difference between 100% CFE and 24/7 CFE. A demand can be covered by 100% CFE if purchases are done from renewable plants. However, how much of the energy that covers the demand every hour of the day is not certain. Therefore, for stakeholders to be able to follow the requirements of 24/7, time stamped CFE will be crucial. Lately a shift in the marked have started, and the interest in more long-term contracts through Power Purchase Agreements have emerged. Where a buyer instead is pledged to buy RECs and energy from a RET project for 10 to 25 years (Roberts 2021).

2.7.2. Power Purchase Agreements

A Power Purchase Agreement (PPA) is a legal contract between the project developer (electricity generator) and a consumer (power purchaser). The contract will in long-term meet the requirements of quantity and price for the electricity generator and the power purchaser. Renewable PPAs are beneficial as they provide solutions that are economically feasible and secure that the supply of energy comes from clean sources. Signing renewable PPAs can lead to longer guaranteed price stability between the involved parties. This is due to that unknown fuel price fluctuations will not affect this agreed long-term price (Tang & Zhang 2019). The energy price is usually fixed and lower than the grid retail price. In addition, the project developer owns and maintains the energy plant, which reduces the risk for the costumer (SEIA 2018).

A traditional PPA functions such that the generation side provides electricity within a certain range per year and the buyer must pay for all the electricity generated. However, along with decreased energy storage costs, PPA approaches delivering real-time, on-demand electricity are emerging. This is then a power contract that enables 24/7 electricity supply from renewable energy sources. Nonetheless, such set-ups are complex and come with several challenges for both parties of the contracts. Financial risks increase for the investors due to the weather dependent energy technologies. In addition, such set-ups require an optimal mix of RETs, followed with a higher precision on the sizing of the RETs and storage to meet the power requirements of the buyer. Buyers will have to accept some level of generation fluctuations when using RET. For instance, ensuring hourly load supply might not be possible, but rather daily/monthly requirements can be assured. Such limitations must be accounted for to make it fair for both sides of an on-demand real-time PPA contract (Jain 2021).

PPAs can be classified in different ways; virtual (VPPA), physical (PPPA) or on-site “behind-the-meter” (BTM) PPA. A VPPA is a financial contract between an electricity consumer and a renewable energy project developer. This set-up makes it possible for the electricity consumer to meet their sustainability goals with assured renewable energy certificates, and the grid is decarbonized. However, the electricity consumer does not physically receive the electricity. The producer instead sells the electricity to the local grid through the wholesale market. If the price at the wholesale market differs from the fixed price set in the contract, a price exchange will happen between the parties in monthly or quarterly financial settlements. Thus, the consumer and the renewable energy project do not have to be located on the same electricity market. In a PPPA the electricity is instead physically transferred from the plant/plants to the consumer through the grid and an electricity distributor. A management fee is then added for maintenance and execution done by an intermediary distributor. A PPPA is limited to deregulated markets where you can choose your electricity supplier. Furthermore, the producer and consumer must be in the same wholesale market for the physical electricity transfer to be possible (Xie 2020).

Lastly, in an on-site BTM PPA structure the power plant is directly connected to the electricity costumer. For instance, this set-up is relevant with rooftop solar photovoltaic (PV) or on-site solar and wind installations. A contract between the project developer and the consumer is signed and all the electricity is bought by the electricity consumer. Eventual surplus can, if permitted, be sold to the grid. Off-grid systems are in general not possible for this structure. However, an energy storage solution could be included to store the surplus. Connection charges are a large cost contributor to the energy price in this type of system (Mendicino et. al. 2019).

2.7.3. Renewable Energy Market Prices

The Levelized Cost of Energy (LCOE) expresses the average net present cost of electricity generation over the lifetime of a plant and can be used to compare different energy technologies. It is calculated after how much it costs to build and operate a plant over its lifetime over the total power output of the plant over its lifetime, see *Equation 1*.

$$LCOE = \frac{Total\ Lifetime\ Cost}{Total\ Lifetime\ Output} \tag{1}$$

Figure 7 shows both historical changes and future predictions of the LCOE for solar PV, offshore wind, and wave energy. The costs for FLOW and wave energy are currently higher than other renewables. Based on the ongoing wave projects in 2020, the LCOE for wave power is between 0.28 and 0.51 EUR/kWh (IRENA 2020a). Further, European Strategic Energy Technology Plan targets for wave power to reach an LCOE of 0.20 EUR/kWh by 2025 and 0.153 EUR/kWh by 2030 is set (EC n.d.a.). However, CPO have made estimations based on their technology resulting in a more rapid decrease for the LCOE of wave energy (CPO, pers. comm., spring 2022). For offshore wind, The U.S. Department of Energy states (2021) that the LCOE of bottom-fixed turbines is 0.088 EUR/kWh. In comparison, the LCOE for floating foundations is 0.148 EUR/kWh. Predictions show that the costs for FLOW is declining and will decrease to a level between 0.056-0.097 EUR/kWh by 2030. Additional reduction of costs has a large potential and for now predictions are based on early estimations out of the early stage of the technology. Overall, including both types of foundations the declined rate of LCOE for offshore wind has been 28-51% between 2014-2020 (U.S. Department of Energy

2021). The LCOEs of bottom-fixed offshore wind and especially solar PV have decreased fast over the past years due to the cumulative increase of installed capacity for both technologies. The costs of both wave and FLOW energy are expected to do the same and investments could be feasible in the future (Cunha-e-Sá, Lopes & Saldanha 2017).

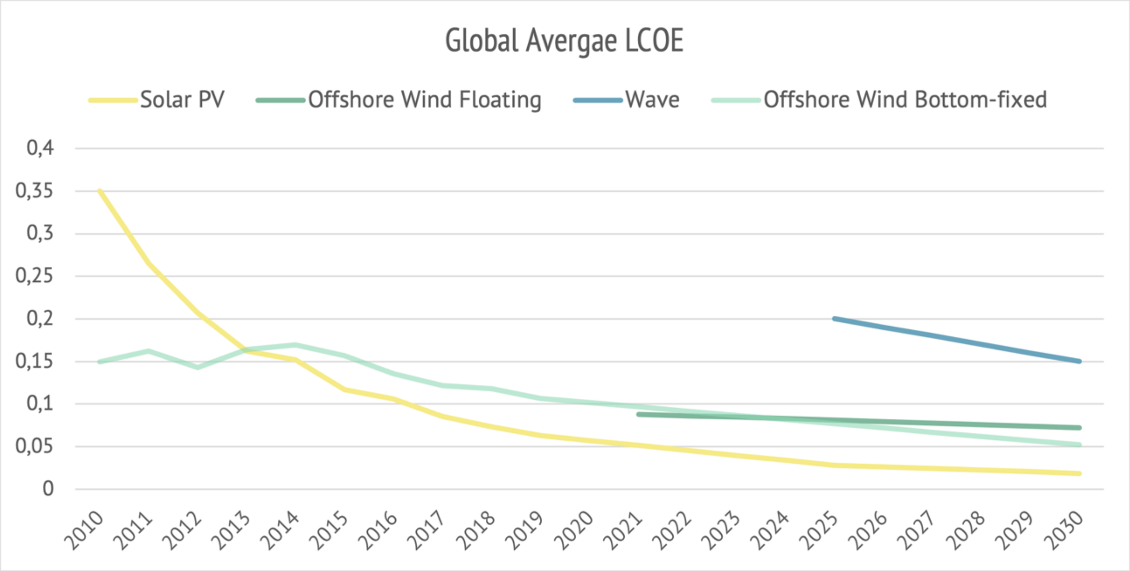


Figure 7. Market price for solar PV, offshore wind, and wave energy.

(IRENA 2020a)(Chozau & Têtu 2021)(U.S. Department of Energy 2021) (DNV n.d.).

2.8. Related Work

There are many techno-economic studies where different energy systems are modeled to meet specific demands, especially using HOMER Pro. On-grid as well as off-grid energy systems have been done with mono-, hybrid- and poly-generation of different energy sources and storage solutions. However, the studies modeling energy systems with wave energy technology are limited, especially in combination with both wind energy and storage. McTiernan & Thiagarajan Sharman (2020) made a review of a hybrid offshore wind and wave energy systems where research and development in the field is discussed, addressing the future potential of hybrid wind wave energy systems. Deng et. al (2022) made a simulation of novel wave and wind hybrid power generation system with hydraulic transmission. The study investigates the technical performance of the energy sources alone and in combination and concluded that wave and wind energy alternates well. Petracca et. al. (2022) conducted a design and techno-economic analysis of a novel hybrid offshore wind and wave energy system by creating a numerical model to investigate the performance of such a system, again showing the promising potential of combined wave and offshore wind energy in the marine energy sector. Keiner et al., (2022) performed a case study of the Maldives investigating how floating offshore technologies such as offshore solar, wind and wave energy can replace fossil fuels at locations with difficult topographical conditions. With the conclusion that offshore solar PV and wave energy will fill an important role in the future for places with restricted land area. Further, there is research investigating battery storage with wind energy generation. For instance, Das & Khaki (2019) investigated sizing and placement of battery energy storage systems and wind turbines with the aim to minimize costs and the losses of the system.

This study was dedicated to being a techno-economic investigation of a grid-connected energy system with wave energy technology from CPO, FLOW energy and Li-ion battery storage. This was done to supply a specific load with 24/7 renewable electricity.

3. Method

This study was done through energy system modeling and a complementary review of financial support for wave energy. In this chapter the Key Performance Indicators and the system set-up are introduced. Further, a detailed description of the method used is presented.

3.1. Key Performance Indicators

Three Key Performance Indicators (KPIs) were selected for the purpose of this study: 24/7 CFE performance, system emissions and system Net Present Value (NPV). This was done to measure the performance of the different system configurations in the energy system modeling. The KPIs covered both environmental and economic aspects and are presented below.

1. **24/7 CFE Performance**

   To achieve a 24/7 Carbon-free Energy (CFE) supply the load should be met completely with renewable sources at every hour. To represent the 24/7 CFE performance of the systems several metrics were considered.

   Renewable Fraction (RF) [%] – the yearly fraction of the total electricity delivered in the system that comes from RET, see *Equation 2*.

$$RF = \frac{RET_{Gen}}{RET_{Gen} + P_{Grid}} \qquad (2)$$

   Where,
   RET_{gen} = total renewable power generation [kWh/year]
   P_{grid} = Electricity purchased from the grid [kWh/year]

   The RF metric does not represent the 24/7 CFE performance of the systems, but rather the total RET generation over the total power served in the system. Thus, the yearly and hourly renewable penetration were also investigated, representing how much of the facility load that is covered with RET electricity both over the year and per hour.

   Yearly Renewable Penetration (YRP) [%] – the share of the facility load that is covered with RET over a year, see *Equation 3*.

$$YRP = \frac{RET_{Gen} - RET_{Surplus}}{Load} \qquad (3)$$

Where,
RET_{Gen} *= total renewable power generation [kW/year]*
$RET_{Surplus}$ *= surplus of renewable power generation [kW/year]*
Load = electricity demand of the facility [kW/year]

Hourly Renewable Penetration (HRP) [%] - the share of the facility load that is covered with RET every hour, see *Equation 4*.

$$HRP = \frac{RET_{Gen} - RET_{Surplus}}{Load} \tag{4}$$

Where,
RET_{Gen} *= total renewable electric power generation [kW/hour]*
$RET_{Surplus}$ *= surplus of renewable power generation [kW/hour]*
Load = electricity demand of the facility [kW/hour]

2. System Emissions

The system emissions are the total emissions caused from the electricity consumption over the project lifetime with the different energy systems. See S*ection 3.3.9.* for the method used for the Portuguese grid emission calculation.

3. Net Present Value

The Net Present Value (NPV) is a metric that represents the financial value for the facility to sign PPAs, invest in the renewable energy technologies and storage instead of buying the electricity from the grid, see *Equation 5.* The Net Present Cost (NPC) is the total cost of each system throughout the modeling period accounting for the electricity costs (PPA prices, grid electricity price and the wholesale price). Additional costs/revenues such as grid connection charges and carbon credits are not included. The system is seen as economically feasible to implement compared to the Base Case if NPV>0.

$$NPV_{System} = NPC_{Base\ Case} - NPC_{System} \tag{5}$$

Where,
NPV_{system} *= Net Present Value of a RET system configuration.*
$NPC_{Base\ Case}$ *= Net Present Cost of the Base Case.*
NPC_{System} *= Net Present Cost of a RET system configuration*

3.2. Energy System Modeling

In this section the method of the different estimations, set-ups and inputs for the energy system modeling are presented and explained.

3.2.1 Main Assumptions

- The exchange rate from USD to EUR was set to be 0.9268 (DNB 2022) and was assumed to be the same during the whole modeling period.
- The exchange rate from GBP to EUR was set to be 1.1679 (ECB 2022) and was assumed to be the same during the whole modeling period.
- Inflation was not considered in the modeling.
- Transmission and distribution costs and losses in the national grid were neglected.
- Grid electricity prices were based on values from 2019.
- The emissions from renewable energy technologies were neglected.
- The hourly wind and wave data used was from 2019.

3.2.2. System Set-up

The energy system was set-up to investigate the combination of wave energy, FLOW energy, energy battery storage and the Portuguese national grid from the electricity consumers perspective.

The different stakeholders of the energy system are referred to as following:

- The project developers – The parties that owns and runs the RET plants, and further have PPAs with the lithium conversion facility.
- The electricity retailer/distributor – Responsible for distributing electricity between the generation and the distribution side of the Portuguese grid. They buy the electricity for the wholesale price from the transmission side and sells electricity for a retail (grid electricity) price to electricity consumers.
- The electricity consumer – The owner of the lithium conversion facility who buys all the electricity from the plants for the agreed PPA prices and sells the surplus to the grid for the wholesale price. Further, when the RET generation is deficit, electricity is bought for the grid electricity price from the grid retailer.

The system logistics behind the PPAs and the batteries located at facility site are not the focus area of this study. If the plants were located outside Viana do Castelo and the facility in Setubal, the PPAs would be either physical or virtual. However, due to the available PPA approach in modeling tool used, HOMER Pro, the modeling was done according to a 'behind-the-meter PPA' structure where the RET generation occurs on the facility site. For the battery storage a "behind-the-meter" on-site solution was chosen as well, with the purpose to meet the load with 24/7 CFE. However, batteries also enable less grid purchase and potentially reduce the cost of the system. See *Figure 8. The Energy System*.

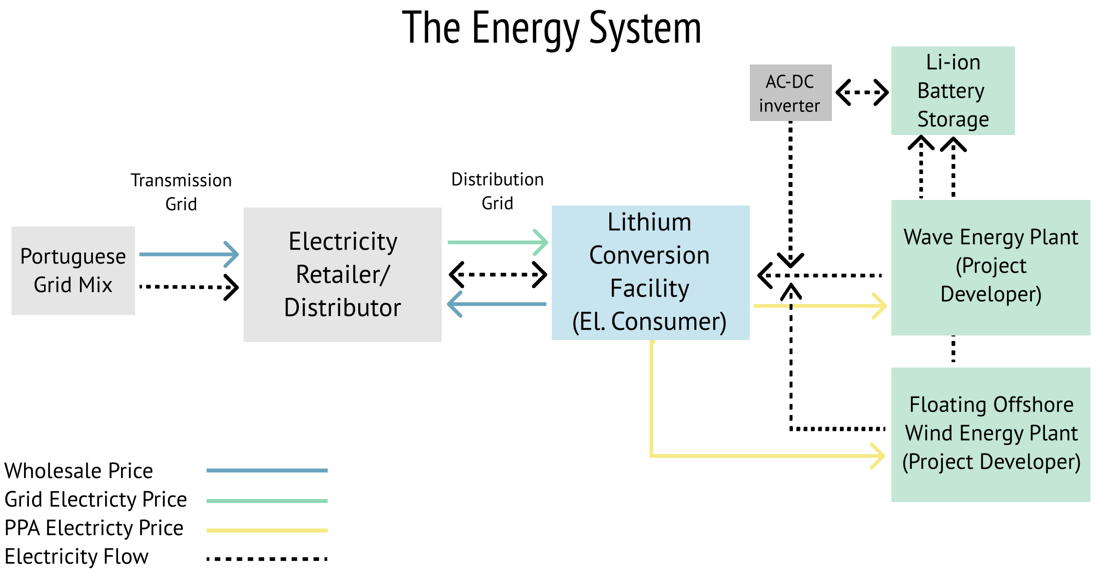


Figure 8. The Energy System.

The wave and FLOW energy plants were inspired by real plants with specific technologies and plant sites and were modeled as Power Purchase Agreement components. For the wave plant a 400 kW Wave energy converter from CPO was used and for the FLOW energy plant an 8 MW wind turbine from Vestas was chosen. Li-ion batteries were used for the energy storage modeling. However, brand and specific size was not considered in this study. The battery investigation focused solely on a sufficient rated energy capacity.

Five different system configurations were included in this study. These systems were referred to as Base Case, S2, S3, S4 and SB throughout the study. S2 and S3 were set for analyzing how wave and FLOW energy could supply the facility with electricity by themselves and S4 after how they could supply the facility in combination. SB was chosen to investigate how high renewable fraction that could be achieved with wave, wind, and storage all together, see *Table 1*.

Table 1. Set-up of Energy Systems for Modeling.

	Components of Energy System			
System	Grid	Wave Energy	Wind Energy	Storage
Base Case	X			
S2	X	X		
S3	X		X	
S4	X	X	X	
SB	X	X	X	X

The choice of systems from the modeling was based on the NPC and the RF. More specifically, for each HOMER Pro system (S2, S3 and S4) two subsystem categories were further analyzed. One subsystem was chosen after the lowest NPC (or highest NPV) and one after the highest RF. For each of the chosen subsystems the 24/7 CFE performance was analyzed. The subsystems are referred to as in *Table 2,* where X is the specific number of the system. Example: S2.1 is the system with only wave energy and lowest NPC.

Table 2. Choice of Systems Modeled in HOMER Pro.

Subsystem	Choice of System
SX.1	The lowest NPC
SX.2	The highest RF

Further, as explained the buy-all, sell-all system set-up of the study differs from the arrangement that would take place if the facility was supplied with wave and offshore wind energy through the grid. If a physical PPA arrangement would be set-up the concept of selling the surplus from facility site to the grid would not be present and the reduced cost for over generation would be removed. Therefore, the different systems (S2, S3 and S4) were modeled with a sell-back price set to zero to see how this impacts the optimal capacities of the systems as well as the system costs.

For the battery storage analysis, S4.1 including both wave and wind energy (with and without the possibility to sell RET generation surplus to the grid) was chosen and further analyzed according to the KPIs.

3.3. Inputs for Energy System Modeling

In this section the different settings and inputs that were used in HOMER Pro are described.

3.3.1. Aurora Conversion Facility Load

The energy system modeling was done to meet the preliminary load of the Aurora facility. Therefore, the hourly, daily, weekly, and seasonal load of the lithium conversion facility was calculated and then imported to HOMER Pro as hourly load data. It was based on preliminary values of the peak and average load of the facility equipment considering both availability and equipment utilization. In addition, relevant assumptions for the daily, weekly, and seasonal changes were used to shape the curves of the load. The daily load curve was based on a common load shape of a facility, peaking load in the afternoon and low load during the night, see *Figure 9*. The daily load curve was set to have three essential load hours during the night, ramping up to normal load between 4:00 and 13:00 o'clock to eventually peak for a couple of hours during the afternoon, followed with a normal load again and later down to essential load. The used load data (accounting for maintenance, stoppages, and utilization) of facility were preliminary and therefore not explicitly mentioned in the study.

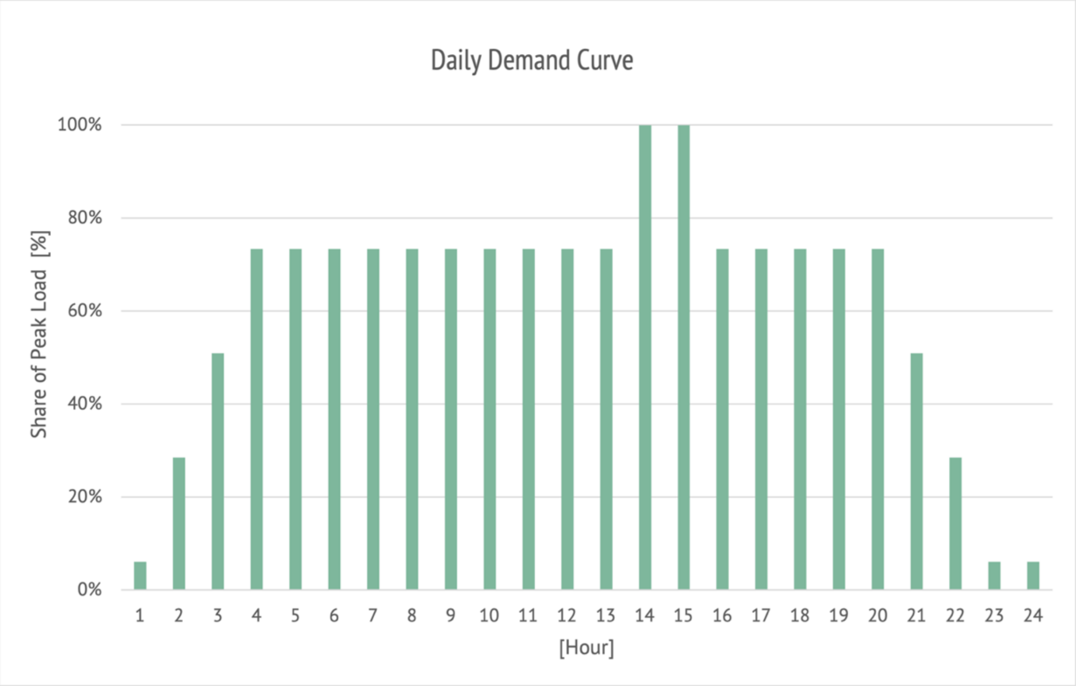


Figure 9. Daily Load Curve.

Over the week, it was assumed that every normal day of operation had the same curve, meaning that both weekdays and weekends had the same load shape. However, over the seasons the average load was assumed to change due to higher temperatures during summer, leading to cooling requirements of the equipment (U.S. Department of Energy

2022). Therefore, the load was set to vary slightly between the different seasons, with the highest average load during the summer months and the lowest average load during the winter months. Heating was neglected. Spring and fall were shaped to have the same daily demand. The consumption per season (spring, summer, fall and winter) was then set to add up to the total yearly consumption all together. The total yearly consumption was calculated based on the daily average. Two weeks of maintenance scheduled in July brought the share of the summer season load down slightly, even though the average hourly load was on a normal summer day closer to the peak load. For the yearly load curve see *Appendix I.*

3.3.2. General HOMER Pro Inputs

For the modeling in HOMER Pro some general inputs were used for all the system configurations. Parameters that were neglected or assumed to be a certain number were kept the same for the different systems modeled to keep consistency throughout the modeling. The modeling period was set to be 25 years between 2026-2051. This was because the Aurora lithium conversion facility is planned to be commercial in 2026 and 25 years equals the lifetime of the renewable technologies used. Further, both the discount rate and the inflation rate were neglected. The model in HOMER Pro was as earlier stated built from an electricity consumer perspective to represent the electricity costs of the facility, where no revenue is present. Yet, the choice of system can lower total NPC and a discount rate was instead accounted for in the PPA calculation as the plants are an investment of the project developers where revenue is expected, see *Section 3.3.7.* The inflation rate and degradation rate of the technologies have been neglected both in HOMER Pro and the PPA calculation.

3.3.3. Electricity Price Calculation

In HOMER Pro, a scheduled rate model was chosen for the daily, weekly, and yearly fluctuations of grid and sell-back (wholesale) prices. Daily wholesale electricity price curves in Portugal were obtained from (REN n.d.b.) and a scheduled rate model was chosen with three timeslots with different electricity prices (off-peak, shoulder and on-peak). The three timeslots were based on average price curves for the first Monday and Saturday, representing a weekday respectively a weekend, from January to December. The daily average off-peak, shoulder and on-peak hours throughout the week were set to vary slightly between weekdays and weekends but set to be constant over the year, see *Figure 10.*

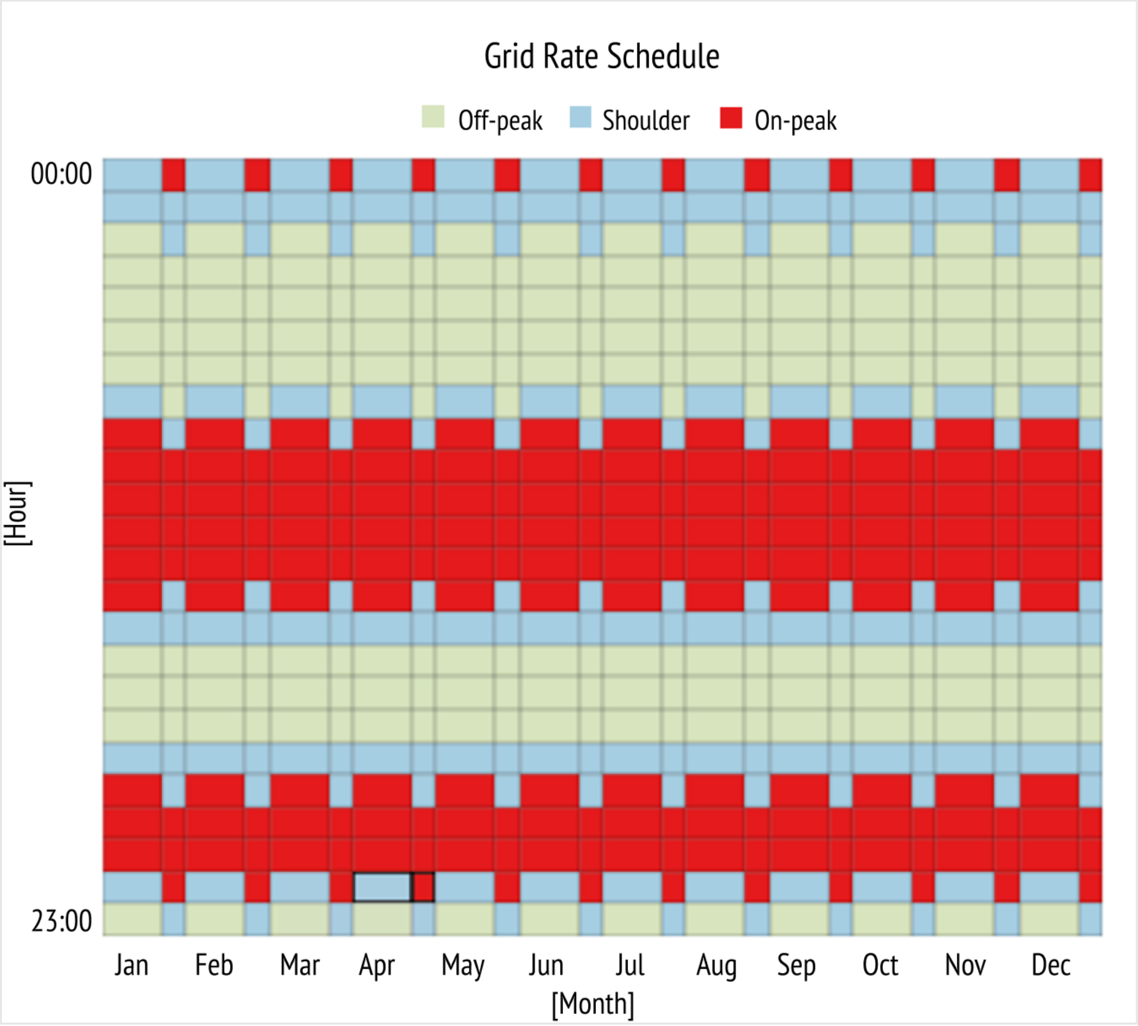


Figure 10. Grid Rate Schedule Input in HOMER Pro.

The sell-back (wholesale) electricity prices were based on the same historical data as the daily curves from 2019. Average off-peak, shoulder and on-peak values were calculated using data from the first Monday every month. The difference between weekdays and weekend was not considered for the specific electricity prices, only for the timeslots of off-peak, shoulder and on-peak.

The year 2019 was chosen due to the unstable electricity prices in the past years, see *Figure 11*. In fact, the increased electricity prices in the recent years are global and can be explained by higher gas prices, extreme weathers, and high carbon prices (Chestney 2022). However, to make sure that prices have not changed significantly over the past years (before 2019), the average wholesale prices found from 2019 were compared to wholesale prices from 2007 to 2017.

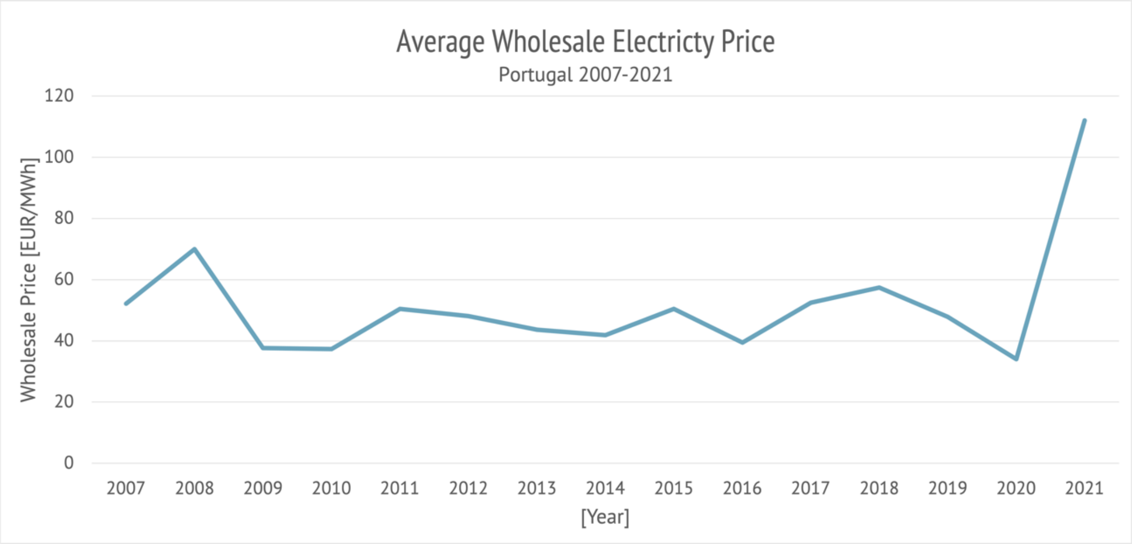


Figure 11. Average Wholesale Electricty Price in Portugal 2007-2021.
(OMIE n.d.).

The retail electricity prices were based on commercial/industrial retail electricity prices in Portugal. An average price from 2017-2019 for users consuming between 70,000 and 150,000 MWh/year was obtained from Eurostat (2022) and the shoulder price was chosen. Further, the on-peak and off-peak prices were assumed to differ with the same percentage from the shoulder price as the wholesale on- and off-peak prices. See *Table 3* for both the sell-back and the grid electricity prices used for the modeling in HOMER Pro.

Table 3. Electricity Price Input to HOMER Pro.
(Eurostat 2022) (OMIE n.d.)

	Grid Electricity Price	**Wholesale Price**
	[EUR/kWh]	[EUR/kWh]
Off-peak	0.0930	0.0461
Shoulder	0.1009	0.0500
On-peak	0.1057	0.0524

The prices were assumed to be constant throughout the project and demand charges were not considered. In addition, the Portuguese grid was assumed to be reliable and power outages were not accounted for in the HOMER Pro model. Further, also grid-related, HOMER Pro assumes that the grid is non-renewable. Thus, to get a complete analysis of the emissions from the systems, the emissions from the grid were neglected in HOMER Pro and investigated in detail in a separate Excel model, see *Section 3.3.9.*

3.3.4. Energy Plants in HOMER Pro

For the wave and the wind plants the outputs were obtained per device and then imported into HOMER Pro as costumed PPA plants. This was done because the specific RETs used in this study are not available options in the modeling tool. How the outputs were calculated is described below in the *Section 3.3.5* and *3.3.6.*

The capital expenditures (CapEx) and operating expenditures (OpEx) of the custom plants were not included in HOMER Pro as the project developer are responsible for these costs. The derating factor and required operation reserve were set to be the default values in HOMER Pro, which were 100% and 0%, respectively. To narrow down the number of possible system combinations a range between 0 and 120 WECs was enabled with steps of 5. For wind energy, 0 to 6 turbines were set as options. The maximal number of devices for each technology represents the same capacity, 48 MW. Further, to obtain relevant energy prices for the costumed wave and wind energy plants in HOMER Pro a calculation model was set up in Excel.

3.3.5. Wave Energy Output

A location 20 km offshore from Viana do Castelo in 2019 was chosen. The gross capacity factors for this location and the CPO WEC in 2030 were provided by CPO and cannot be shown in the report due to commercial sensitivity. The hourly capacity factors are the product of the technology performance (power matrix) and the wave data (wave scatter diagram). The power matrix of the CPO WEC has been obtained through simulations for all sea-states. Further as explained, the wave scatter diagram shows the appearance of different sea-states throughout a year for a specific location (CPO, pers. comm., spring 2022).

The hourly net capacity factors, accounting for the losses of the farm, from a CPO WEC farm were then calculated in Excel with *Equation 6.* The different losses considered were electrical farm losses that occur between the farm and the shore, auxiliary consumption which is the WECs own electricity use and can be viewed as a loss and lastly the array interconnection losses occurring between the devices in an array. The availability factor represents the actual time that the plant can produce electricity, mainly based on requirements of maintenance and reliability of the technology and plant (EnergyMag n.d.). Both the losses and the availability considered were based on future predictions done by CPO. Again, these are not explicitly shown in the report (CPO, pers. comm., spring 2022).

$$NCF = GCF * (1 - EFL) * (1 - AC) * (1 - AIL) * AF \quad (6)$$

Where,
GCF = Gross Capacity Factor [%],
NCF = Net Capacity Factor [%],
EFL = Electrical Farm Losses [%],
AC = Auxiliary Consumption [%],
AIL = Array Interconnection Losses [%],
AF = Availability Factor [%].

The hourly net output from one CPO WEC of 400 kW in Viana do Castelo in 2019 was then imported to HOMER Pro. The array interconnection losses were included as HOMER Pro optimized a WEC array and not a single device in the energy system.

3.3.6. Wind Energy Output

As Pfenninger et. al (2016), the tool Renewables.ninja was used to get site specific and hourly power output in 2019 for the chosen wind turbine. The tool allows for site search and input of specific latitude and longitude. Google Earth was used for measuring a point 20 km offshore from the harbor of Viana do Castelo. This resulted in a latitude of 41.671 and longitude of -9.2826. Further, the capacity, hub height and turbine type were chosen. Since the modeling is inspired by the already implemented WindFloat Atlantic wind plant outside Viana do Castelo the V164 8000 turbine with a capacity of 8 MW and hub height of 100 m was chosen (Principle Power n.d.)(EDP n.d.)(Renewables.ninja 2022).

3.3.7. Wave and Wind Energy Price

Fixed energy prices were set in HOMER Pro for the RET plants, representing the prices agreed on in the PPA contracts between the electricity consumer and the project developers. According to Carriveau. et. al. (2017) the LCOE is used to calculate the PPA price. However, for a project to have a payback time before decommissioning and be profitable the nominal PPA price must be higher than the nominal LCOE. This is done by accounting for a discount rate in the calculation. Moreover, Mendicino et. al. (2019) states that a PPA price typically is calculated considering several factors and costs such as length of the contract, price, min/max energy delivery, renewable energy credits, curtailment, reliability and insurance, interconnection and grid, metering, credit, taxes, billing, and decommissioning.

*Equation 7 w*as used to determine the energy prices of the wave and wind plant in this study (Callaba et al. 2016). By setting the NPV equal to zero over the lifetime of the plants, the energy price does in mathematical terms end up as the LCOE. A weighted average cost of capital (WACC), with a discount rate, was added to ensure profitability of the plants.

$$NPV = -\sum_{t=0}^{n_{com}-1} \frac{CapEx}{n_{con}(1+WACC)^t} + \sum_{t=n_{con}}^{n_{con}+n_{op}-1} \frac{\sum_{h=1}^{8760} PPA_{price} \cdot E_{net,h} - OpEx}{(1+WACC)^t} - \sum_{t=n_{con}+n_{op}}^{n_{con}+n_{op}+n_{dec}-1} \frac{C_{Decomission}}{n_{dec}(1+WACC)^t} \tag{7}$$

The calculation included CapEx, OpEx, decommissioning costs and the yearly electricity output for both plants (same as calculated in Section *3.3.5. Wave Energy Output* and Section *3.3.6. Wind Energy Output*). For the wave plant, predicted costs for a CPO WEC farm were used. For the wave plant, predicted costs for a CPO WEC farm were used. Where the CapEx includes material and production of the WECs, mooring and foundation, project development, services for infrastructure and contingencies, assembly, installation and commissioning, offshore electrical equipment, and onshore electrical equipment. The OpEx covers on-land facilities, vessel, staff, spare parts and consumables, insurance and seabed lease and swap units. The numbers are not explicitly shown in the study (CPO, pers. comm., spring 2022). Furthermore, the FLOW plant costs were interpolated for 2026 out of cost decline predictions for the turbine and a WACC of 5.4% was used, see *Table 4* (Duffy et. al. 2021). The decommissioning costs were set to be 5% of the CapEx costs for both plants (CPO, pers. comm., spring 2022). One year of both construction and decommissioning was assumed.

Table 4. Inputs for the Offshore Floating Wind Energy Plant.

CapEx [EUR/kW]	3976
OpEx [EUR/kW/year]	49
Decommissoning Cost [EUR/kW]	199
WACC [%]	5.4

Finally, the energy prices were found using the problem solver in Excel. The energy prices used for the wave and the FLOW plant in this study are 0.0598 EUR/kWh and 0.0895 EUR/kWh respectively, see *Table 5*.

Table 5. PPA Price Calculation.

	Wave Energy Plant	**Wind Energy Plant**
Energy Price [EUR/kWh]	0.0598	0.0895

Figure 12 displays the yearly cash flows and NPV of the wind energy plant project with the calculated energy price. An inflation rate of 1.77% was considered here to view the difference in payback time (Statista 2022a). The payback time is 15 years with the energy price of 0.0895 EUR/kWh. However, if considering an inflation rate the payback time would be 17 years. The NPV for the wave plant was not included due to commercial sensitivity of the data.

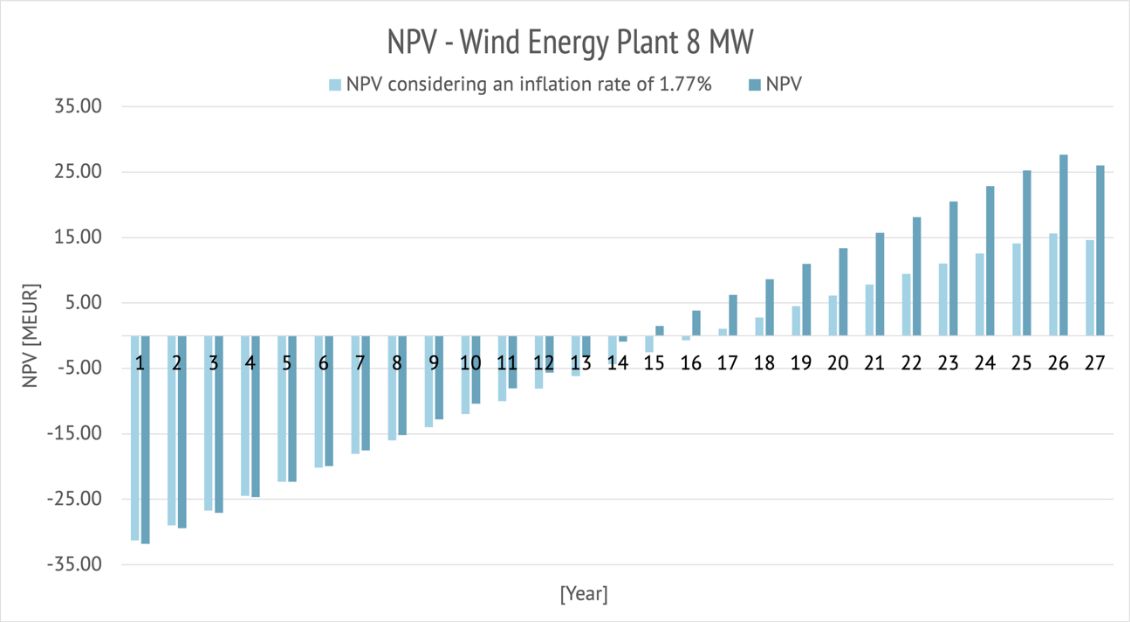


Figure 12. NPV of the Wind Energy Plant (8 MW).

In addition, the energy price for the wave plant was calculated considering funding and subsidies. This to analyze what is required to meet market prices for RET. Both the CapEx and OpEx costs were changed as different financial support would change the two differently. Further, a sensitivity analysis, with higher energy prices was performed in the HOMER Pro model. This as several factors, such as grid tariffs, distribution fees, inflation, and degradation were not considered in the calculation.

3.3.8. Battery Storage model

For the energy storage modeling a separate tool was built in Excel as the intended outcome was not possible in HOMER Pro. The model was made to complement the modeling in HOMER Pro to see how battery storage impacted S4 both in terms of 24/7 CFE and NPC. The model was built such that different rated energy capacities of batteries could be tested. The hourly outputs from HOMER Pro were used as inputs in the storage model: the hourly renewable generation, the sales due to renewable surplus and purchase from the grid when deficit generation from the plants. Thus, the model was set up on an hourly basis. Charge and discharge do not occur during the same hour.

As the facility buys all the electricity produced by the plants the electricity purchase from the wave and wind plants does not change with storage. What change with storage is the amount of grid purchase and the renewable energy sold to the grid due to renewable surplus. Therefore, the model was built such that when it is a renewable surplus the battery is charged and instead of purchasing electricity from the grid, the battery is discharged. Storage in the system enables higher supply from RET electricity as the energy can be used at a later stage when the generation is deficit. Thus, storage reduces the required grid purchase, which has a higher price and unknown source. *Figure 13* explains the logic behind the model. RET_Surplus in the figure means over-production from the wave and wind plant, and the battery is charged if there is space the battery. RET_deficit means that the wave and wind generation is not enough to cover the load and the battery is discharged. If the battery is full/empty the surplus/deficit electricity is still sold to the grid/purchased from the grid.

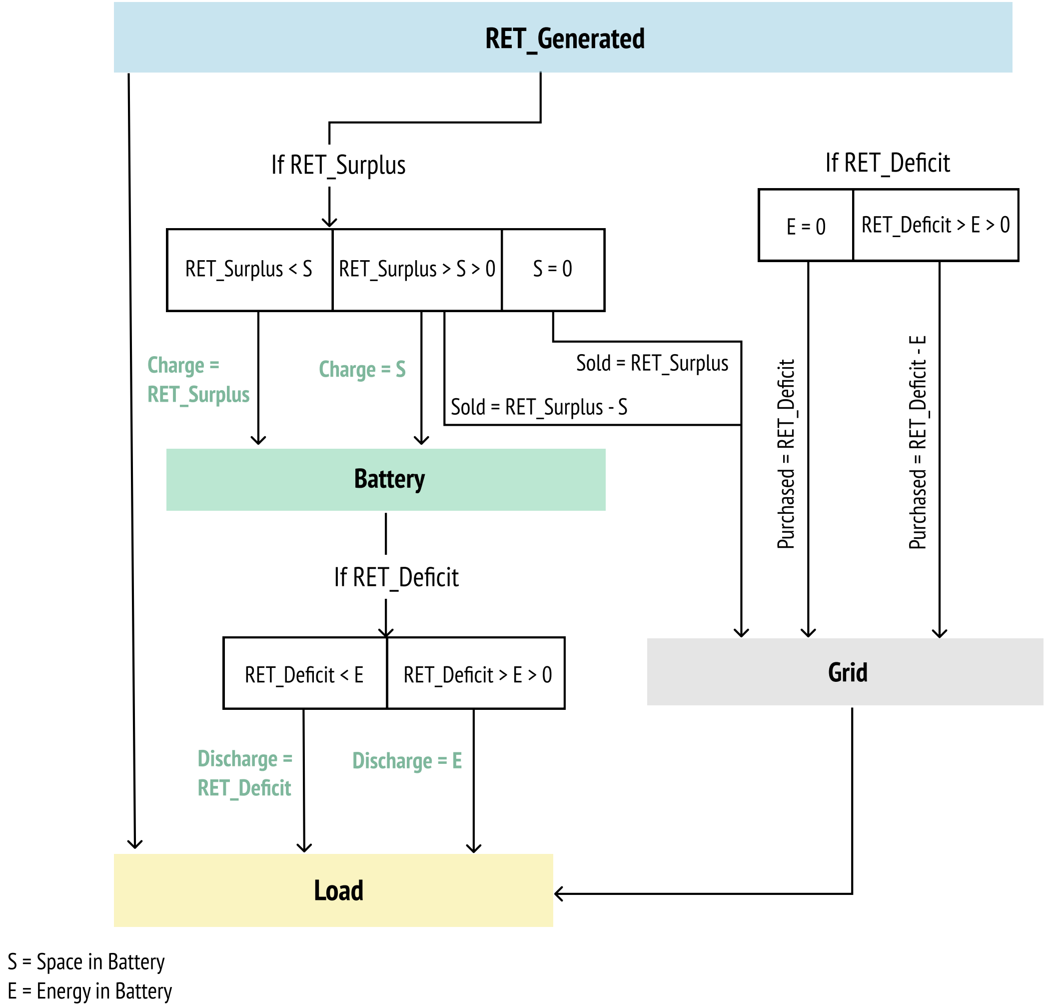


Figure 13. Logic of Battery Storage Model.

A technical parameter considered in the storage model was a discharge/charge percentage range of 20/80. This is recommended as a safe battery operating range to prolong the lifetime of a battery (Faisal et.al. 2020). Furthermore, as in the industrial and commercial peak lopping Li-ion storage system case study by BEIS (2018), this storage model was built to fully charge/discharge the batteries in 4 hours. This means that the power of the battery is 25% of the rated energy capacity. A Li-ion battery solution was chosen as it is known for being suitable for storage of renewable energy technologies and because there are several manufactures and types of such batteries (Nurunnabi & Roy 2015). The efficiency, accounting for losses within the charging/discharging cycles of the battery, was discarded and so was the degradation. The performance of the battery was considered to stay at 100% throughout the lifetime of each battery. However, the Li-ion batteries were considered to ware out after 15 years and then in need to be replaced (BEIS 2018).

The costs and cost predictions from BEIS (2018) for the same industrial and commercial peak lopping Li-ion storage were used. The CapEx consider the costs for design, capital, and installation, and the OpEx consider costs for operation, maintenance, replenishment/refurbishment of consumables, inspection, insurance, and security. Grid connection charges are not represented in the costs (BEIS 2018). Further, the costs in 2026 and 15 years later, in 2041, were interpolated, see *Table 6*. When the battery was replaced in 2041 both CapEx and OpEx were changed in the model according to *Table 6*. The OpEx costs were constant throughout the lifetime of each battery.

Table 6. Li-ion Storage Costs Used 2026-2041.

(BEIS 2018).

Year	**2026**	**2041**
CapEx [EUR/kW]	678	293
OpEx [EUR/kW]	28	12

As the load profile curve is one of the most important factors when choosing a suitable type and size of battery, the energy capacities investigated were chosen to suit the surplus/deficit of the wave and wind energy plants and then avoid grid purchase (Nurunnabi & Roy 2015). The purpose with the storage in this study is to reach 24/7 CFE. Thus, the max energy capacity investigated allowed the battery to discharge the max hourly grid purchase in S4.1. In addition, the amount of storage needed to reach 100% RF was investigated.

3.3.9. Portuguese National Grid Emission Calculation

Emissions for the different system configurations were calculated during the modeling period where the renewables installed were assumed to be emissions free. When the share of renewables increases in the systems the emission decreased accordingly. The modeling period goes one year beyond the targeted year of 100% renewable electricity generation in Portugal. Thus, the share remains the same for 2051. *Figure 14* show how the carbon intensity of the Portuguese grid has decreased between 2000-2021 (Statista 2022b). Further, a forecast of the declination was done for the modeling period until the carbon intensity reaches zero and 100% renewable electricity generation. The emissions were calculated from the amount of electricity purchased from the grid in the different systems. The total grid purchase per year was multiplied with the carbon intensity of the grid for that specific year. Further, the 25 years were summed up to provide the total emission of the systems.

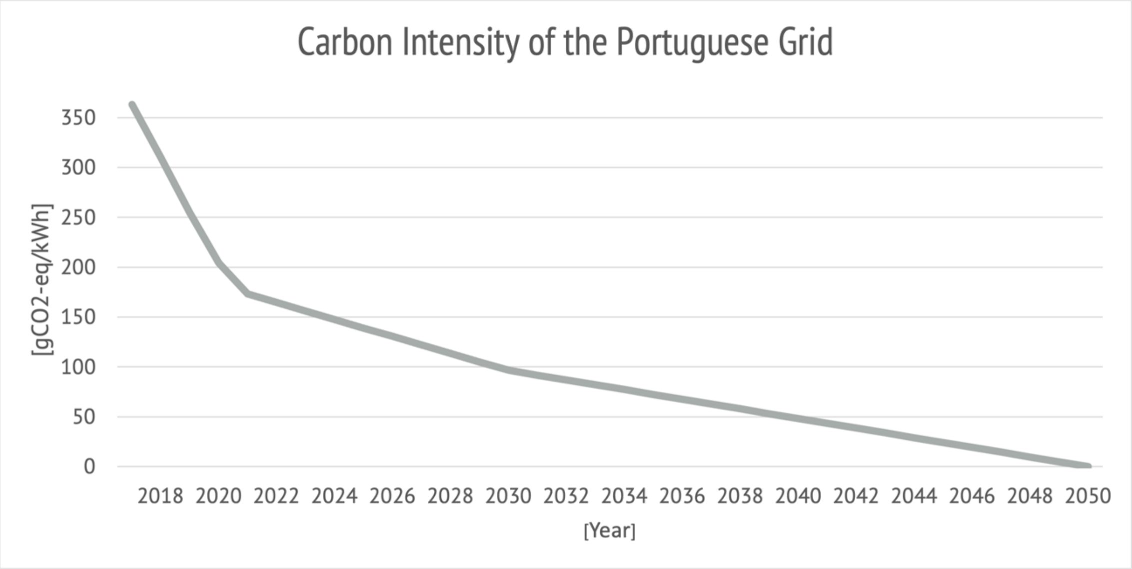


Figure 14. Carbon Intensity of the Portuguese Grid.

(Statista 2022b).

3.4. Review of Financial Support for Wave Energy

A review was executed on historical and current financial support relevant for wave energy deployment within the EU, especially focused on in Portugal. This is especially interesting to investigate as the data used for the CPO WEC in the modeling part is when it is commercial. Search engines such as GreenFILE, DIVA, Google's own search engine and Google Scholar were used to find reliable reports and articles. Mostly scientific reports and journals were used. Additionally, information from conversations with CPO was used. Words and sentences such as "marine energy technology governmental support", "wave energy governmental support", "political mechanisms Portugal" and "financial support" were used to find relevant information. The references used were compared with other similar references to secure legit and reliable information.

4. Results and Analysis

This chapter starts with an analysis of how wave and wind energy alternates in Viana do Castelo, Portugal. Following, the results from both HOMER Pro and the complementary storage model are presented and analyzed. Additionally, a sensitivity analysis of the results is done followed up with the review of financial support for wave energy. Lastly, a discussion of the results and delimitations of the study takes places.

4.1. Wave and Wind Energy Performance

To reach of 24/7 CFE the value of renewable energy technologies that peak at different times during an hour, a day and a year is becoming more significant. *Figures 15 and 16* show how the wave and wind energy technologies in Viana do Castelo alternates for two different months in 2019, here chosen to be June and February. This is presented with the same installed capacity (8 MW) of the two energy technologies. As seen during June the two alternating technologies fill an especially important role to cover the load. In the beginning of June, the wave energy output is high. However, it declines between the 1st and 15th of June. Yet, this is where the FLOW energy output increases. This is a good example on how the two technologies peak at different times.

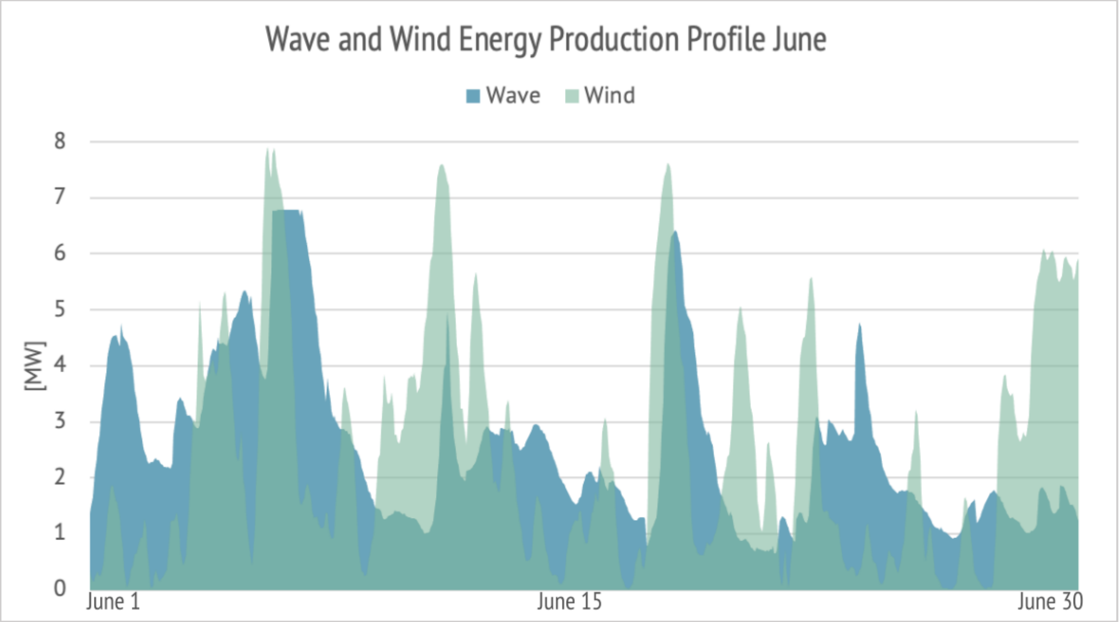


Figure 15. June Production Profile in Viana do Castelo.

The winter months show large wave energy output. In general, the waves are larger and more constant during these months. Then, the technologies no longer alternate, but rather generate during the same time. Although it depends on the load and the sizing of the plants, the total generation during these months will probably be high and surplus generation hours will be predominant for a specific load. The fluctuating total generation during different seasons will result in varying surplus or deficit for the load throughout the year. This makes sizing of battery storage a challenge as charging and discharging would not be in balance, more about this in *Section 4.3. Battery Storage Analysis*. However, fluctuating yearly generation occurs with most renewable energy sources. With more than one energy source the generation is potentially more even throughout the seasons.

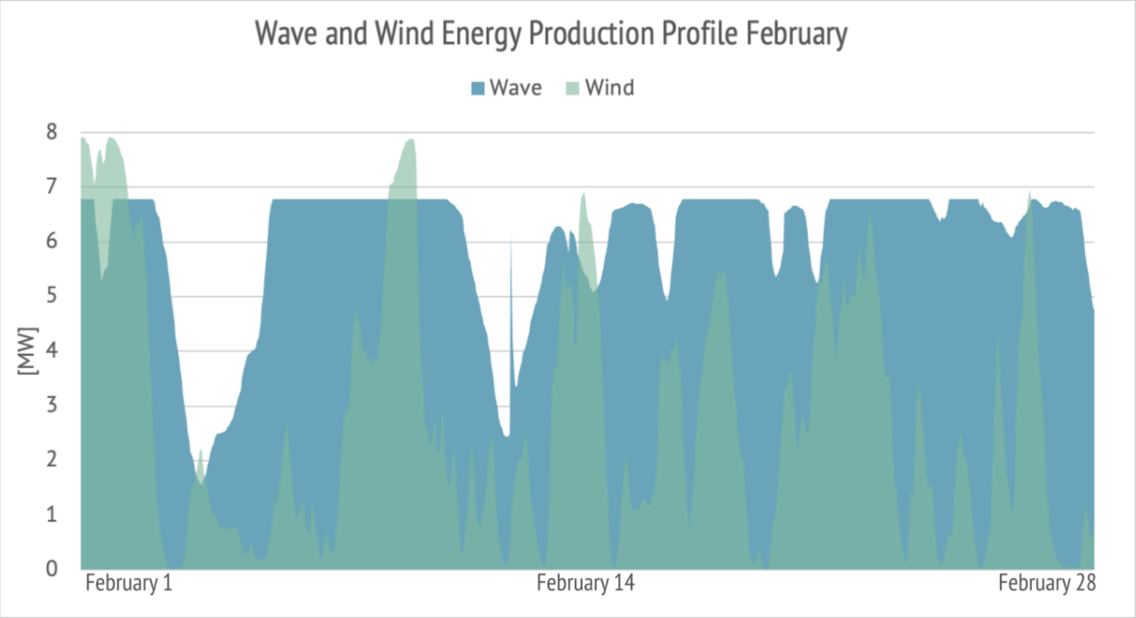


Figure 16. February Production Profile Viana do Castelo.

Figure 17 show how the seasonal production profiles for the technology's changes in 2019 in Viana do Castelo. The total energy output is summed up for each season. The wave energy output is larger than the wind energy output for the spring, summer, and winter. In this study with weather data from the same location and year, the wave energy technology from CPO performs better than the Vestas V164 8000 wind turbine in this study. The output during summer and autumn are the lowest from both technologies. Depending on the installed capacity of the energy system, these months are considerable in meeting the load.

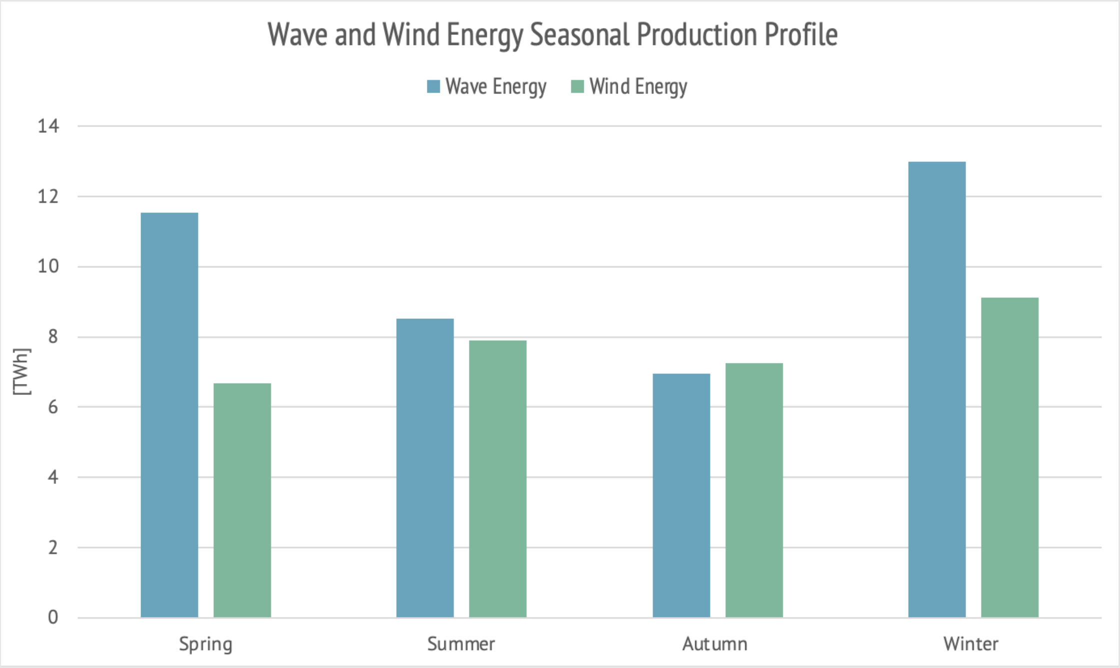


Figure 17. The Seasonal Production Profile outside Viana do Castelo.

4.2. HOMER Pro and KPI Results

In the following section an analysis of the HOMER Pro results is presented and analyzed for the systems and KPIs.

4.2.1. Generation vs Load

Figure 18 shows the RP for S4.1 (both wave and wind energy installed) provided from HOMER Pro. The yellow areas are where the power output covers the load with 100% RP. In the middle of the graph, during summer and autumn, the HRP is the lowest, except the two weeks of maintenance in July. See *Section 4.2.2.* for more results of S4.

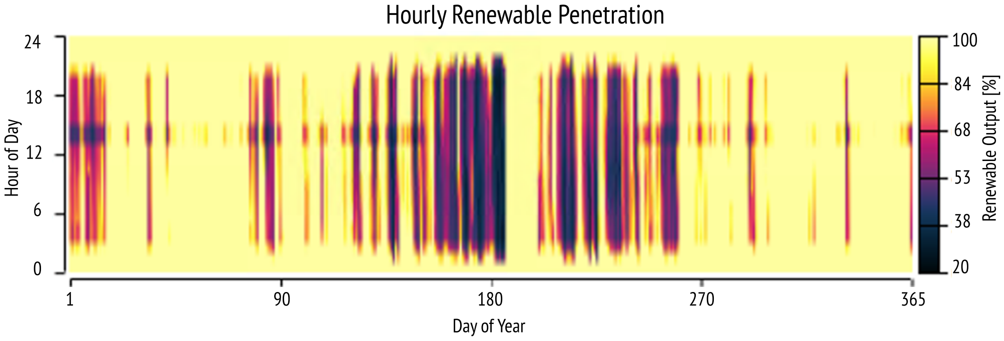


Figure 18. HRP for S4.1 from HOMER Pro.

However, the HRP throughout the year *(Figure 18)* does not show how the output meets the load in detail. For instance, when the load is low, HRP reaches 100% more easily than when the load is peaking. This means that the conditions to meet 100% HRP changes throughout the day, which is important to keep in mind. *Figure 19* shows the correlation between the load and the renewable power output for a random week of the year, here chosen to be in April. As the load cannot be explicitly shown in this report, there are no numbers on the y-axis in the figure. At the end of 13th and beginning of 14th of April is an example of when the renewable power output reaches 100% during the essential load hours. However, later the average and peak load hours are not met with renewable output. The opposite is visible on the 15th of April where the renewable power output is beyond the load and the RP is 100% throughout the whole day.

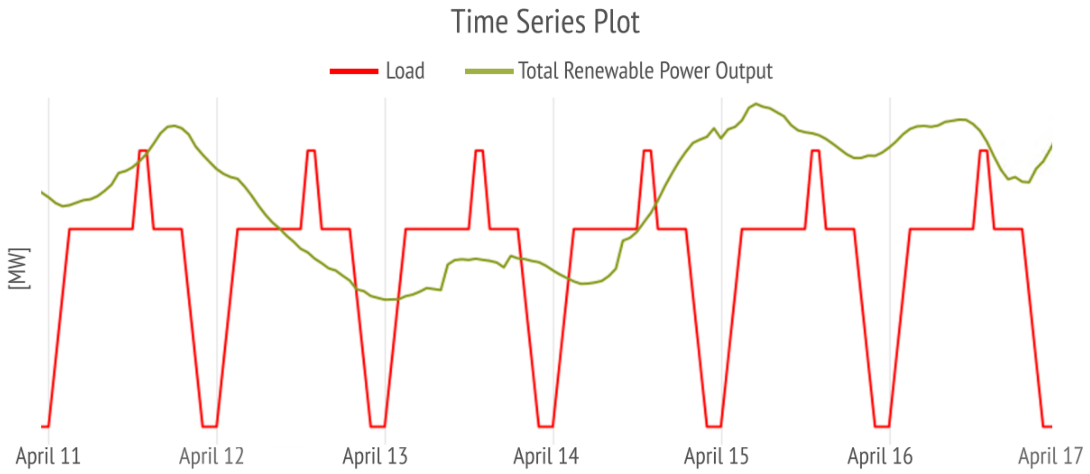


Figure 19. Time Series Plot from HOMER Pro - the RET Coverage of the Load.

A system with both wave and FLOW energy capacity could potentially supply a higher RP, thus a better 24/7 CFE performance. This due to that the two intermittent technologies can balance each other in terms of output and potentially cover a higher share of the load throughout the entire year. This was investigated by looking at two systems with equal capacities. One system with 16 MW of wave energy capacity was compared to a system with 8 MW of wave and 8 MW of FLOW. However, in this study it turns out that the theses two systems have YRPs of 50% and 45% respectively. Thus, a system with two technologies does not perform better in terms of 24/7 CFE supply. Again, this proves that that the wave energy technology from CPO performs better than the Vestas V164 8000 wind turbine, in this study.

4.2.2. System Comparison

The KPI results for the different system configurations are seen in *Table 7.* As described in *Table 1*, S2 consist of wave energy, S3 of FLOW energy and S4 of wave and FLOW energy combined. All the configurations are also connected to the grid and the Base Case with only grid resulted in and NPC of 338 million euro (MEUR). Out of all systems, the S2.1 subsystem with a WEC capacity of 32 MW resulted in the lowest NPC. Further, it has a NPV of 89 MEUR and a RF of 83.4%. S4.1 also has a positive NPV with 68 MEUR and a RF that is 86%. S4.2 is the system with the largest capacity installed and reaches the highest RF, of 98.7%. However, the NPV for this subsystem is below zero with -84 MEUR.

Although, the wave and wind production alternates well, the NPV results show that a system with only wave energy is preferred. This as the energy price for the FLOW technology used in the study is higher than for wave energy technology. Thus, S2.1 is the better option from an economic perspective. Further, a slightly oversized system is preferred to avoid grid purchase, especially for the wave energy case. However, there is a trade-off in how much the system should be oversized to cover the load as the sell-back price is lower than the electricity price. System S2.2 is an example of this where the NPV is lower than for S2.1 (84 MEUR).

S3 has only wind energy generation and the KPI performance of these systems is arguable. S3.1 has the lowest positive NPV (4MEUR) and S3.2 result in an NPV<0. Again, this is due to the higher energy price for FLOW than for wave energy used in this study. This is a selection of the results, and all number can be found in *Appendix II.*

Table 7. HOMER Pro Outputs and NPV Calculation.

System	**Wave/Wind**	**NPV**	**RF**	**YRP**
	[MW]	[MEUR]	[%]	[%]
Base Case	-	-	-	-
S2.1	32/-	89	83.4	77
S2.2	48/-	84	92.4	86
S3.1	-/8	4	22.2	20
S3.2	-/48	-65	82.4	71
S4.1	28/8	68	86	79
S4.2	48/48	-84	98.7	96

** Wave [MW], Wind [MW].*
** NPV = Net Present Value, RF = Renewable Fraction, YRP = Yearly Renewable Penetration.*

In *Table 8*, the share of the hours (in a year) reaching 100% HRP for different systems are presented. In addition, in *Appendix III* the number of hours that are under 75% and 50% for the systems can be found.

The system with 100% HRP (also with the highest RF) during most hours of the year is S4.2, with 91%. Yet, as explained before this system is not economically feasible due to a high NPC and NPV<0. To be noted is that even for this system the 24/7 CFE score struggle to reach 100% for every hour. This means that even though the system is oversized for the load with two different energy sources, 24/7 CFE for the load cannot be achieved. This is simply because during some hours of the year there is little or no wind or waves available, resulting in deficit generation no matter the capacity of the system. S3.1 only reaches the HRP of 100% during 12% of the hours per year. This as the installed capacity (8 MW) is not sufficient for the load. Lastly, the performance of S2.1 and S4.1 is similar for this metric, 64% and 65%, respectively.

Table 8. F and HRF of the System Configurations.

	System	BC	S2.1	S2.2	S3.1	S3.2	S4.1	S4.2
RF	[%]	-	83.4	92.4	22.2	82.4	86	98.7
Hours with HRP=100%	[Units]	-	5571	6616	1080	5051	5696	7955
	[%]	-	64	76	12	58	65	91

4.2.3. System Emissions

The emissions for each system were calculated throughout the project lifetime. See *Table 9* for the emissions of each system compared to the Base Case. As expected, the emissions decrease with a higher capacity of installed renewables. Out of the system configurations, S4.2 emits the least GHG emissions of 8 kton $CO_{2\text{-eq}}$. Further, S3.1 emits the most of 160 kton $CO_{2\text{-eq}}$.

Table 9. Reduction of Emissions for S2-4 Compared to Base Case.

System	RF	Total Emissions	Emission Reduction
	[%]	[kton $CO_{2\text{-eq}}$]	[%]
Base Case	-	201	0
S2.1	83.4	47	77
S2.2	92.4	29	86
S3.1	22.2	160	20
S3.2	82.4	59	71
S4.1	86.0	41	80
S4.2	98.7	8	96

4.2.4. System Configurations Without Sell-back

When analyzing the different system configurations without the possibility of selling the surplus of electricity to the grid, the optimal system capacities for the NPV changes, see *Table 10* (*Appendix II* for more numbers). This is due to the removed possibility of lowering the costs when over-generating. A capacity of 20 MW now gives the highest NPV for S2. In S4, only the wave energy capacity changes as the lowest possible wind energy capacity of 8 MW are already installed. The capacity in S3.1 remains constant for the same reason. As expected, the RF and YRP decrease with the lower installed energy capacities. To be noted is that the NPVs are now lower than when sell-back is possible.

Table 10. HOMER Pro Outputs and NPV Calculation Without Sell-back.

System	**Wave/Wind**	**NPV**	**RF**	**YRP**
	[MW]	[MEUR]	[%]	[%]
Base Case	-	-	-	-
S2.1	20/-	56	65.2	61
S3.1	-/8	0	22.2	20
S4.1	14/8	31	65.2	60

** Wave [MW], Wind [MW].*
** NPV = Net Present Value, RF = Renewable Fraction, YRP = Renewable Penetration.*

4.3. Battery Storage Analysis

In this section an analysis of Li-ion battery storage is done. This to answer if battery storage is an economically feasible option to complement wave and FLOW energy towards achieving 24/7 CFE supply of the facility in the system.

4.3.1. Incentive for Battery Storage

With the buy-all approach the lithium conversion facility often purchases more from the renewable energy generation than needed to cover the load. This surplus of energy could be stored and used for later when the RET generation is deficit. Hence, energy storage makes it possible to use more of the renewable energy generated and increase the HRP. However, the price of buying the renewable electricity generated for own use is higher than when selling the surplus electricity to the grid (PPA_{Price} > Wholesale price). Thus, selling decreases the final cost since the electricity consumer is obligated to buy all the electricity in the first place. When storing the electricity, this opportunity of a decreased cost is removed. This makes the value of installing batteries for decreasing the grid sales uncertain, as it might be more worth to sell to the grid. However, the grid purchase price is higher than the price for the RET electricity, especially from wave energy. Therefore, installing batteries for the purpose of decreasing the grid purchases is relevant to investigate from an economic perspective. Yet, the main purpose of investigating battery storage in this study is to see how it can complement wave and wind energy towards reaching 24/7 CFE of the load.

4.3.2. Battery Storage for 24/7 CFE

As mentioned, battery storage was investigated for S4, with both wave and wind energy installed and with a capacity that could cover the maximum hourly grid purchase of the system, to potentially achieve a 24/7 CFE supply. For S4.1, the maximum grid purchase for one hour was 21.8 MW. To be able to supply that in one hour with a 4-h duration battery, 88 megawatt-hour (MWh) rated energy storage is required. Hence, the energy capacity range investigated for the battery was 0-88 MWh.

As expected, the RF and the YRP increases with more installed battery storage. However, even with 88 MWh of storage capacity the increase in RF and YRP is not significant. The RF and YRP is 88.7% and 84%, respectively, which is an increase of 2.7% and 4.5% compared to using no storage in S4.1. Further, the emissions reduction with 88 MWh of battery storage decreases with 4% compared to no storage in S4.1 and 84% compared to Base Case.

For S4.1 to completely achieve 24/7 CFE, an energy storage capacity of 19.05 GWh is required. This is an unreasonably large storage capacity for a battery. Only then is the electricity load of the facility completely covered with renewable energy at every hour. However, there is still sold renewable electricity (29.15 GWh per year) with this storage capacity. This means that 19.05 GWh of battery storage is large enough to supply the facility load when the renewable energy generation is deficit. Yet, the storage cannot store the surplus generation for all hours of the year, as the battery is sometimes full. The state of charge throughout the first year with a storage capacity enabling 24/7 CFE can be seen in *Figure 20.* With start in February consecutive hours of surplus generation occurs (i.e. charging hours) and eventually the battery is fully charged. Followed with more hours of surplus generation that does not suit in the battery and still is sold to the grid. In the end of May the opposite happens. Here the number of hours with consecutive deficit generation are higher than the number of hours of surplus, so the battery discharge. At the end of the year the battery is fully charged again. This pattern shows that the number of surplus hours is more than the deficit hours. Thus, the RET generation seems too high for the load for optimal usage of battery storage. The graph indicates that a storage solution with longer duration, such as hydrogen, compressed air or thermal storage, is feasible than li-ion batteries to enable 24/7 CFE supply of the facility.

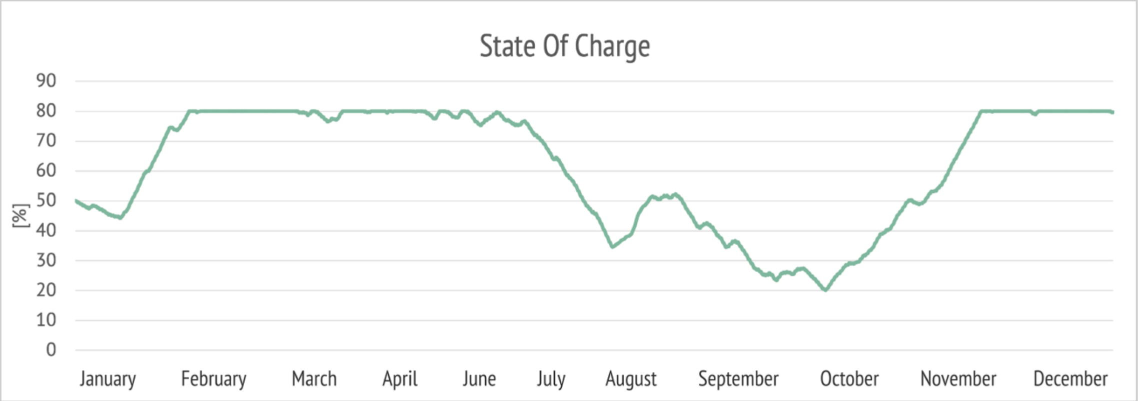


Figure 20. State of Charge - when 100% RF.

4.3.3. Economic Feasibility

Regarding the costs, it is more expensive to include Li-ion battery storage in the system than no storage. In *Figure 21*, the NPCs for the different investigated storage capacities added to S4.1 are presented. The NPC is always higher for the cases with storage than without storage, due to high battery costs. Thus, the system with the lowest NPC is when no storage is installed. Nonetheless, when not accounting for the CapEx and OpEx of the batteries any storage investment is positive. The more storage that is installed the lower is the NPC. This is because the own RET electricity use is increased with storage, lowering the total cost from grid purchases.

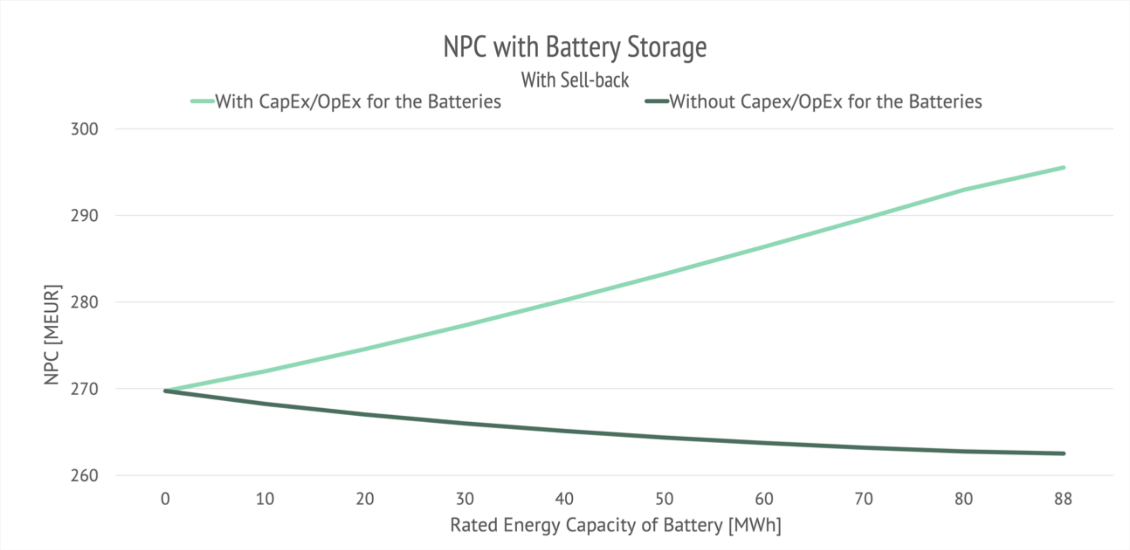


Figure 21. NPC with Storage.

In *Figure 22* the case without the possibility of selling the RET surplus to the grid is presented. As mentioned, without sell-back the storage investment is more worth because of the opportunity of decreased cost for surplus generation is removed. However, the NPC is much higher than when sell-back is still possible, since selling the surplus to the grid reduces the cost for overgeneration significantly. Thus, the possibility to sell the surplus generation seems more significant than battery storage, seen from an economic perspective.

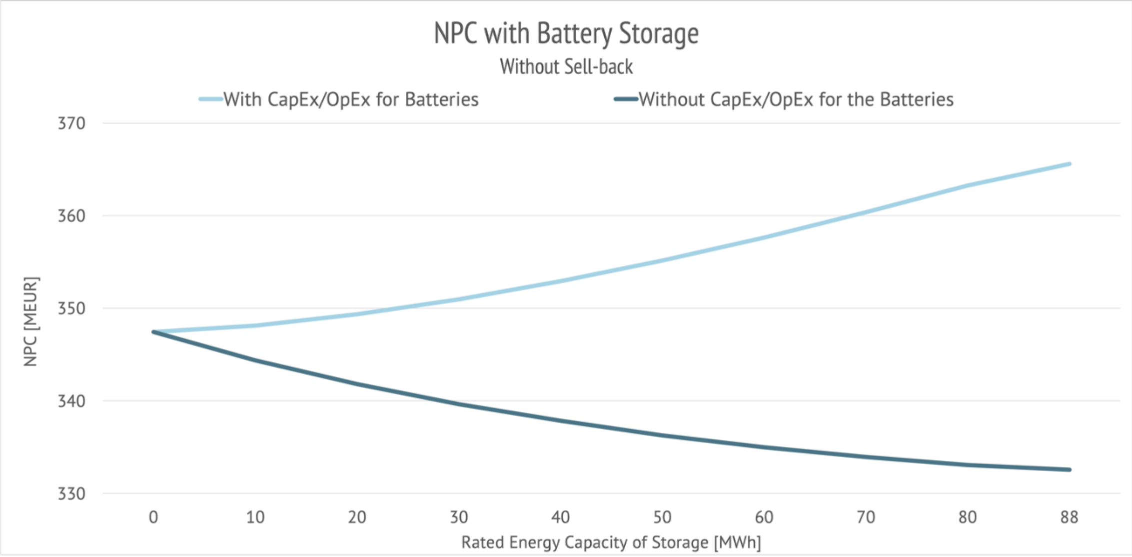


Figure 22. NPC with Battery Storage, without Sell-back.

For the battery investment to be worth the battery costs would have to be reduced. The difference in NPC between the different cases with storage and the case with no storage indicates the maximal costs that is worth to invest in batteries. *Figure 23* presents the used battery costs of the systems and the maximal costs required to have a lower NPC than without storage. Without sell-back the maximal cost is higher than when selling the surplus to the grid is possible. Thus, the economic value of battery storage is higher when sell-back is not possible. Note that for 10 MWh of rated energy capacity the max cost in the case when not selling the surplus to the grid is close to the used cost of the batteries, 3.09 and 3.78 MEUR respectively. This means that batteries are not far from being worth an investment for this storage capacity.

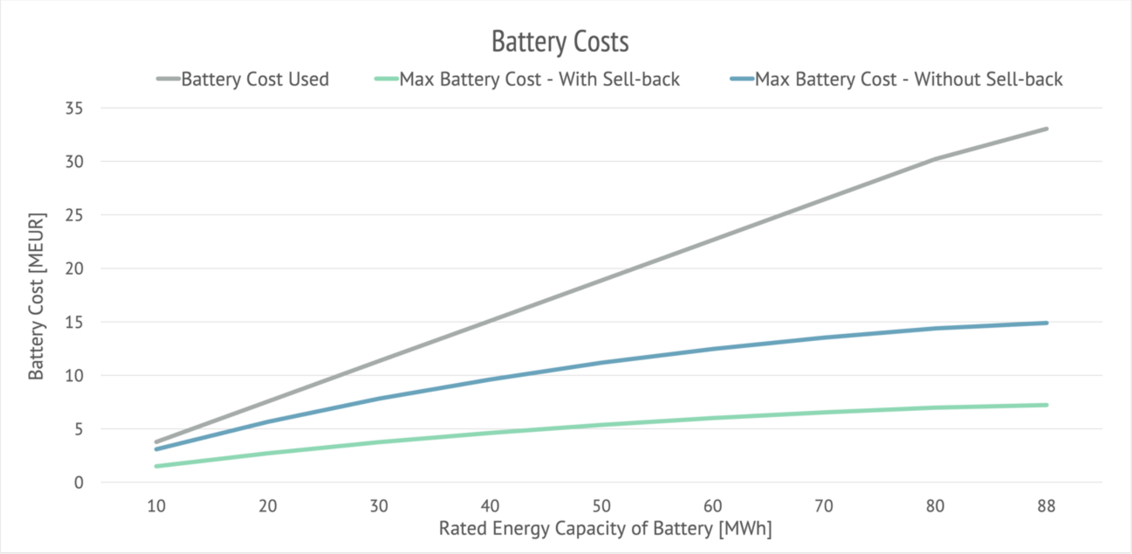


Figure 23. Battery Costs.

In fact, when applying storage to the S4 system with 14 MW of wave and 8 MW FLOW energy capacity (the optimal capacity for S4 when sell-back is not possible) batteries are worth until roughly 50 MWh of rated energy capacity, see *Figure 24.* The lowest NPC of 305 MEUR occurs with an energy storage capacity of 25 MWh for the price of 9.3 MEUR.

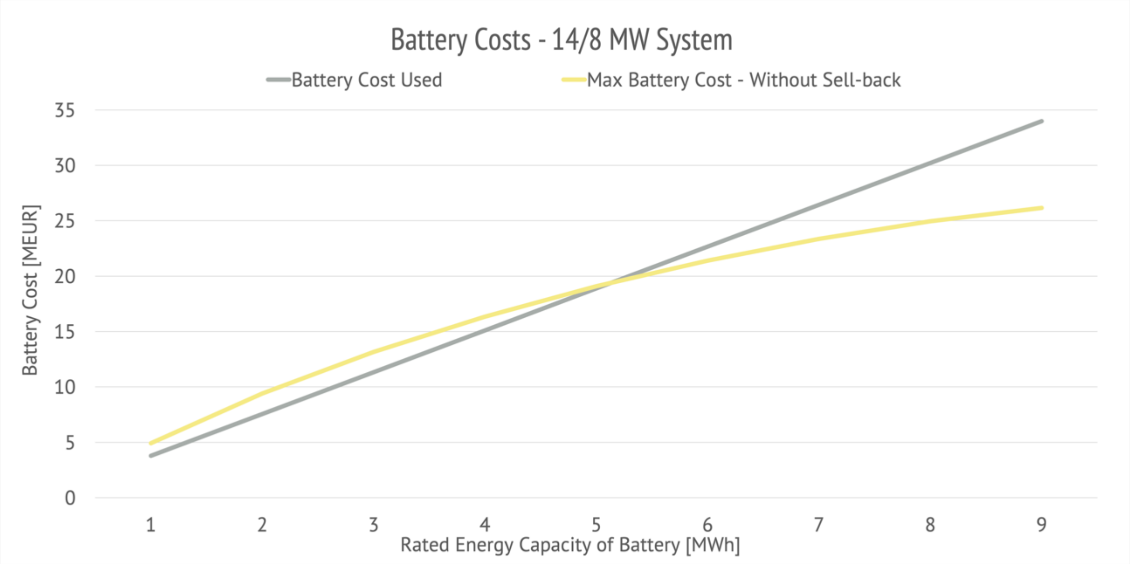


Figure 24. Battery Costs 14/8 MW System

4.4. Final Energy System Analysis

Here follows a summary of the most significant results in terms of 24/7 CFE performance of the technologies and systems investigated. Further, the NPCs for the most interesting system configurations for the electricity consumer are highlighted.

Figure 25 shows all the systems modeled in HOMER Pro with a Pareto front. Due to the low energy price of wave energy, in relation to FLOW and the Portuguese grid in this study, a system with only wave energy is preferred from an economic perspective. A higher number of WECs reduces the NPC as grid purchase is avoided. However, on the right side of S2.1 in the figure the capacity installed is too high for the load even though the surplus can be sold. The systems including 1 to 6 wind turbines are more expensive than without FLOW energy installed.

S2.1, with 32 MW of wave energy capacity, is the system with the best combination of NPC and RF. It has an NPC of 249 MEUR and a RF of 83.4% and is a good choice for supplying the load of the facility with electricity. Yet, due to energy security, a configuration with both wave and FLOW might be preferable. Considering the systems with both technologies installed, S4.1 with a total capacity of 36 MW is the system with the best combination of NPC and RF (270 MEUR and 86% respectively). However, in this study it has been showed that the two technologies do not result a better 24/7 CFE performance. If 24/7 CFE was the only KPI considered, and no financial metric, system S4.2, with a total capacity of 96 MW, would be the best option as it has a YRP of 96%.

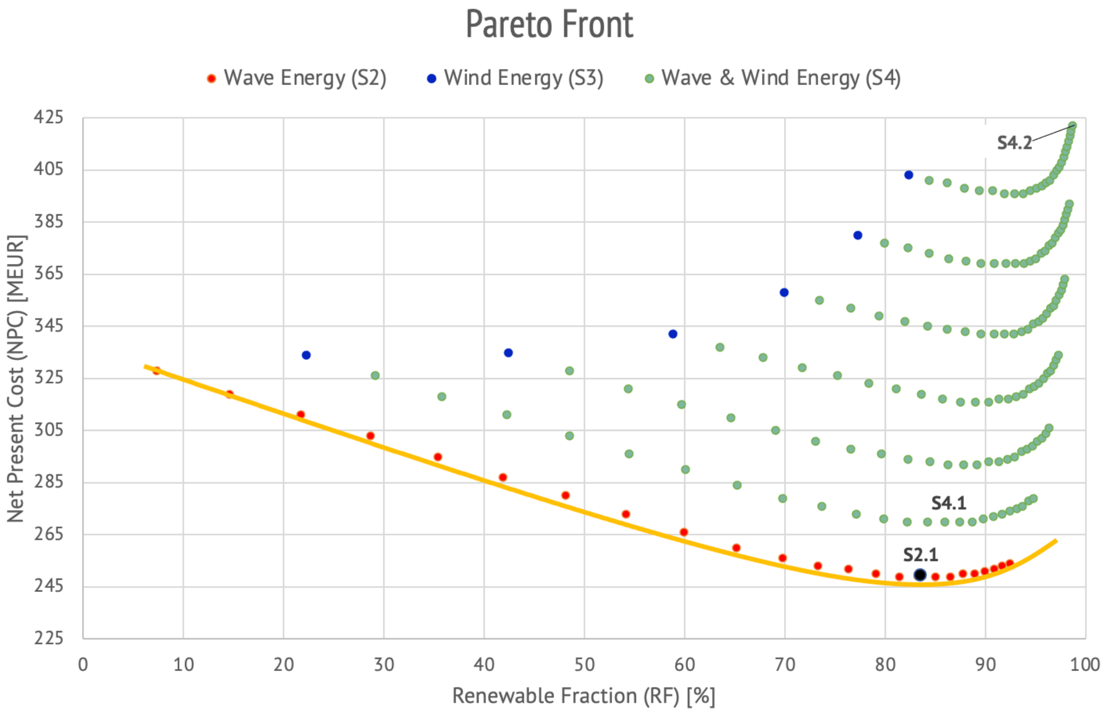


Figure 25. Pareto Front of all System Configurations in HOMER Pro.

Battery energy storage improves the 24/7 CFE performance in the energy system. However, the battery analysis in *Section 4.3.* shows that a reasonable amount of battery storage for the load/system does not improve the RF nor the YRP significantly. Economically, battery storage is not worth the investment when the RET surplus instead can be sold to the grid. However, if sell-back is not an option or if the battery costs are reduced the installation could be worth as the battery storage reduces the need of buying electricity from the grid.

To sum up, S2.1 with 32 MW of wave energy capacity is the system with the lowest cost for the electricity consumer in this study. Further, S4.2 with an oversized capacity of 96 MW is the system with the best environmental performance. Battery storage is not economically feasible if selling the surplus electricity is possible.

4.5. Sensitivity Analysis

In this section a sensitivity analysis is done for different parameters used for the energy system modeling.

4.5.1. Sensitivity Analysis – Electricity Prices

The significance of the inputs of the different electricity prices in HOMER Pro can be seen through a sensitivity analysis in *Figure 26*. As expected, the NPC increases both when the energy price for wave and wind increases. In this system wave energy has the largest installed capacity. Thus, it has a higher gradient (slope) than for the changes in wind energy price. Further, changes in the sell-back price show a decline in the NPC. When the sell-back increases it is more economically worth to sell back to the grid. A significant point of the plot is when the overgeneration of renewable energy switch from being a cost to becoming a revenue. This happens around 110% of the estimated sell-back price, then the sell-back price is higher than the energy price for the RET electricity. Thus, a significant decrease of the NPC occurs due to changes of the sell-back price.

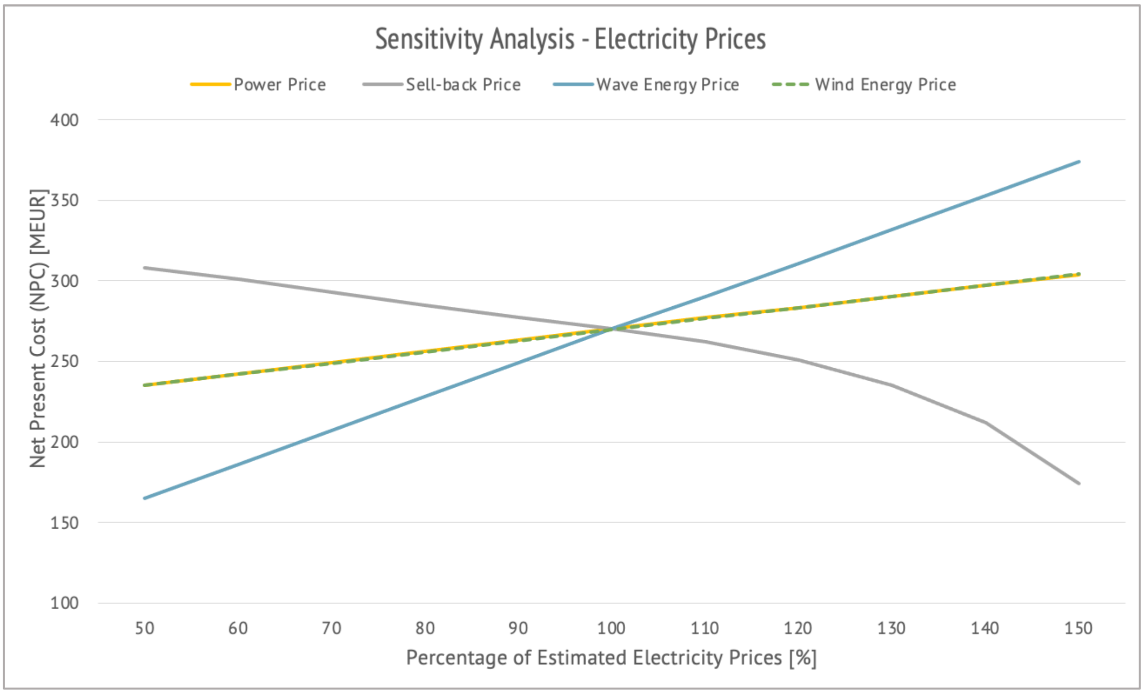


Figure 26. Sensitivity Analysis Electricity Prices in HOMER Pro.

4.5.2. Sensitivity Analysis - PPA price

Further, as explained in *Section 3.3.7. Wave and Wind Energy Price* a sensitivity analysis was executed for the energy price (or PPA price) of the wave energy plant. This to investigate how much financial support that is required for the PPA to meet the market price and be competitive. Further, *Section 4.6. Support of Wave Energy Deployment* goes into which support that is available for wave energy in Europe and especially in Portugal.

Figure 27 presents the results of the sensitivity analysis. CapEx and OpEx were changed in the energy price calculations, as different types of funding would affect them differently. Since the PPA calculation is equal to a LCOE calculation, the global LCOE for solar PV, forecasted to be 0.026 EUR/kWh in 2026 (see *Section 2.7.3.* for global LCOE of solar PV), is used for comparison. When reducing CapEx and OpEx the energy price (LCOE) decreases. The CapEx reduced with 80% (20% of its actual value) for the wave energy plant gives an LCOE of 0.025 EUR/kWh. Meaning that with a grant covering 80% of the CapEx of the wave plant of this project solar PV prices could be met. When instead reducing the OpEx to 0, the PPA price reaches 0.045 EUR/kWh. This sensitivity analysis reduced the yearly costs and did not consider the yearly revenues from selling the electricity generated. If that would have been done, the LCOE could be reduced additionally due to a negative OpEx (i.e. revenues).

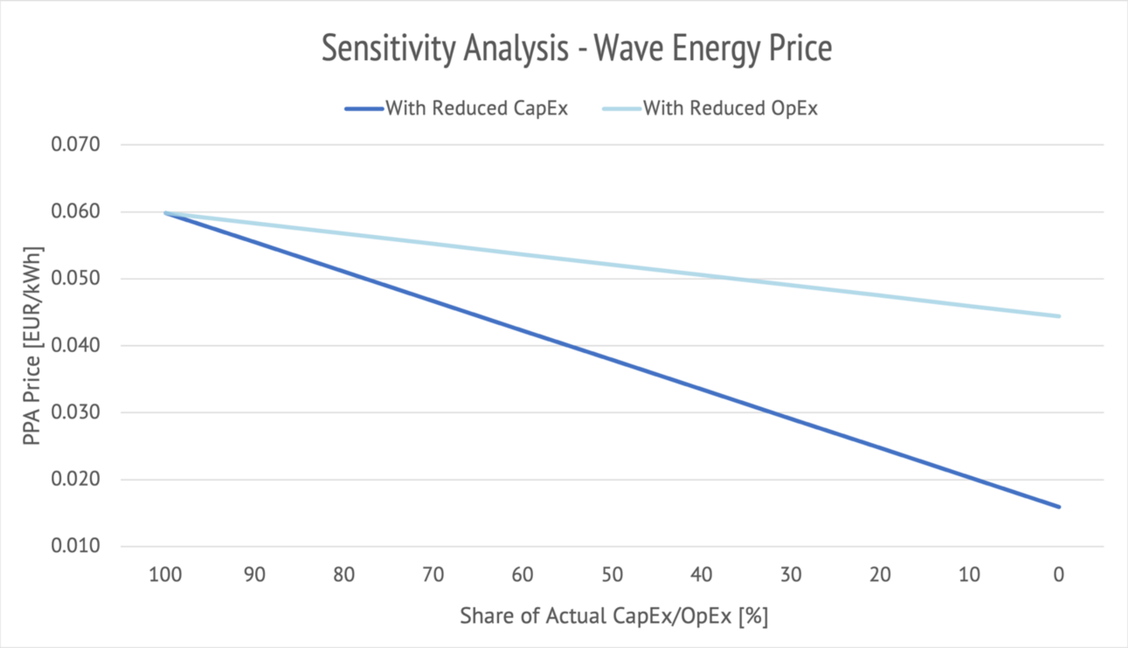


Figure 27. Impact of Funding and Subsidies on Wave PPA Price.

4.6. Support of Wave Energy Deployment

In this section the review of financial support for wave energy is presented. Support of renewable energy comes in many different forms. In this section available financial support in the EU and in Portugal for renewable energy technologies, and especially ocean energy technologies, are reviewed.

4.6.1. Significance of Financial Support

To phase out fossil-fuels and increase the pace of RET development and implementation, governmental funding is needed. Specially to attract private investment in technologies that have not yet reached a commercial stage (Tarver 2021) (GSI n.d.). Ocean Energy Europe (n.d.b.) states that marine renewable energy needs more finance for the technologies to reach a commercial stage. In their policies, an emphasized topic is how critical the demonstration phase is for the development of new technologies and that several marine technologies currently have reached this stage. The demonstration phase includes installation of pilot farms and is a challenging stage where innovative technologies commonly require more investments than in the stage of prototypes (OEE n.d.a).

4.6.1. Renewable Energy Support in EU

A support scheme for renewable energy implementation that has shown to be successful, is Feed-in Tariffs (FiT). FiT has contributed significantly increasing the share of renewables in countries within the EU, including Portugal (IRENA 2019b). FiT is introduced for promotion of new renewable projects with non-economically feasible technologies. The contract of FiT is long-term (15-20 years) and ensure access to the grid. The contractors are paid so that they are covering the capital costs for the implementation needed for the generation. In theory, all energy generating projects can be awarded with FiT. However, the non-commercial generators are the ones that take most advantage of it (Kenton 2021). Over time, the price of the service or product that is supported will decrease with the stage of commercialization. The idea of implementing a financial support on a service or product is for it to eventually become commercial and competitive to other similar ones (Tarver 2021) (GSI n.d.). The FiT mechanism has played a significant role in the transition towards more renewables. Yet, more countries have started to rely on new market-driven strategies for the support of RET installation (Kenton 2021).

Renewable energy tenders and auctions are emerging. A renewable energy auction is a bidding process where the product of interest is either energy (MWh) or power capacity (MW). The auction volume is what the auctioneer aims for and further wants to contract. The auctioneer is an entity that is responsible for starting the auction and ranking the bids that are received during the auction. Such bids are often offered through renewable power purchase agreements by bidders, also called the project developers. When the auctioneer has chosen a bid, the project developer will further be responsible for completing the project and the off taker will be the one that purchases the generated electricity from the project (IRENA 2019b). Auctions can be used to support the development of a certain technology by limiting the selection of technologies. Technology natural auctions are however better when it comes to promotion of competition as aiming for the most cost-effective technologies (IRENA & CEM 2015). However, IRENA states (2019b) that some policies will be required in co-ordination with the renewable energy auctions to make them effective. The EU have developed a renewable energy financing mechanism so that the member countries co-operate in supporting new renewable projects to rapid the renewable energy transition. This to become the first climate neutral continent and follow what is stated in the European green deal. The financial support in the scheme is allocated through competitive tenders for grants for any willing RET project host. The grants functions either as investment or operation support and are paid only to the projects with the most competitive bid price (EC n.d.b.).

Further, there are several projects and funding programs available that financially supports innovative technologies such as wave energy technology. Horizon Europe is the main funding program for research and innovation within the EU and has a total budget of 95.5 billion euro (BEUR). The European Innovation Council (EIC) is stablished under this program with a budget of 10.1 BEUR for projects in the innovations in the early stage. The EIC Forum was established in late 2021 and is connecting national authorities and ministries and help innovations of regional and national level to emerge. EIC has several funding opportunities and is special in the way that individual companies can get support both through investments and grants. EIC Pathfinder, EIC Transition and EIC Accelerator are such financial support schemes where mainly startups and Small and Medium Enterprises that need help to scale-up their technology are supported. These three are supporting different stages of innovation. The EIC Work Program 2022, where the financial support opportunities are presented, is including both challenge driven funding and open funding for all schemes possible to apply for. The first stage of EIC Accelerator is open at any time and an application process require a video pitch and question answered about the innovation. Further, the innovation is then evaluated by EIC. The next round (if the application meets the EIC criteria) is then booked through an open or challenge driven funding (EIC 2022).

Further, Ocean Energy Europe (OEE) (n.d.a.) have listed the following support projects on their webpage, thus they are relevant for ocean energy technologies. InnoFin Energy Demo Projects, a program through the European Investment Bank that funds renewable energy in the developing phase. This fund gives the opportunity for loan guarantees or loans between 7.5 to 75 MEUR. The Innovation Fund is another fund from the "EU Emission Trading Scheme and commercial technology demonstration" which is awarding both small- and large-scale projects. 27 projects were awarded in 2021 and the next will be in 2022. Further, The Insurance Fund is a third option that has identified a system that can help detect risks for manufacturers and developers. Insurance and Guarantee Fund cover a significant part of the technological risk of pre-commercial projects. New funds are being designed in addition to these (OEE n.d.a.). Additionally, the REPowerEU Plan aims for accelerating the energy transition within the EU. This is an important scheme, with a budget almost double The Innovation Fund, with 3 BEUR. The OEE states that this increase of funding can be a significant factor in which the EU reach the target of installed wave energy by 2025 (Garanovic 2022).

4.6.2. Marine Energy Technology Projects

Moving on to projects targeting ocean energy technologies. For the EU to reach 230-440 MW and 40 MW of installed offshore wind and wave energy by 2050, several support programs and projects have been developed. For instance, EU-SCORES is a 45 MEUR marine-energy-project led by the Dutch Marine Energy Center, with the aim to deliver the first bankable hybrid marine energy plant by 2025. With the start in 2021, two demonstration plants will be deployed by the project partners Ocean of Energy of the Belgian coast and CPO. The project wants to show the benefits of adding marine energy technologies into the energy mix in Europe (REW 2021). EVOLVE is another project, started by a team of partners in the ocean energy technology field. It is a 1 MEUR project, funded by the OCEANERA-Net Cofund initiative, that aims to find the overall market value of ocean energy implementation in Europe (Garanovic 2021). Further, The Offshore Plan was a project led by LNEG and funded by the EU that investigated Portugal's offshore wind and wave resources, the integration of the two technologies in the Portuguese electricity grid as well as the social, economic, and technical challenges of deployment (IEA 2021).

4.6.3. Marine Energy Support in Portugal

In Portugal the main measure to subsidize large-scale renewable energy plants before 2012 was FiT. After 2012, the tariff was excluded for all new renewable projects due to a financial crisis. However, projects signing contracts before this received FiT for the rest of their contracting period. These were mostly onshore wind projects. A modified FiT was again introduced two years later following the economic recovery. This FiT was introduced to support self-consumption and small-scale projects, more specifically small production units. This scheme was only for solar PV, hydro, biogas, and biomass projects. Later in 2018, the FiT was increased by the government in 2018 up to 0.095 EUR/kWh. However, this full rate is not for all the technologies. When solar PV and hydro receive the full rate, biogas and biomass receive 90% of the rate. However, Portugal is currently awarding more renewable energy projects through auctions. In 2019, a new system for solar PV auctions was implemented and annual Solar PV auctions are now taking place (IEA 2021). Further as mentioned, the country will soon (summer of 2022) arrange the first auction for FLOW energy with 3-4 GW farms (Reuters 2022).

To support new energy technologies such as hydrogen and marine energy, the Portuguese government has a fund to finance research and projects. There are several policies with the aim to develop the energy sector of the country. For marine energy and hydrogen technology the RD&D policy “Incentives for research and projects on innovation and technological development in the field of renewable energy” is especially relevant (RES LEGAL n.d.). In addition, for wave energy in specific, a tariff (DL 225/2007) was implemented in 2007. For the first 20 MW of installed pre-commercial wave power a remuneration of 0.26 EUR/kWh is given. For commercial plants the remuneration is 0.131 EUR/kWh for the first 100 MW installed and then for the following 150 MW it is 0.101 EUR/kWh (Trennepohl 2014). At this moment, there are several projects for wave energy emerging in Portugal at this moment. The HiWave-5 project is one of them. The wave energy to Megawatt Levels (Megaroller) project is another one which aims to find a better solution for the PTO component of the WEC. A third project Portugal is participating in is the Surging Wave Energy Absorption Through Increasing Thrust and Efficiency (SEA-TITAN) which is also aiming for PTO solutions that are innovative and that will provide a step change for the wave energy technology (IEA 2021). Despite these support measures and projects Cunha-e-Sá, Lopes et. al. states that the Portuguese political mechanisms used for promoting and accelerating the development of marine renewable energy technologies should have a more consistent approach. They argue that Plano de Ação para as Energias Renováveis which include national targets for marine renewables hinders that Portugal could be an attractive location for deployment of such technologies. Further, that a vision over a long-term perspective will be needed for the regulatory uncertainty to be reduced (Cunha-e-Sá, Lopes & Saldanha 2017).

5. Discussion

In the following section, a discussion of the set-up, results and limitations of the study takes place.

5.1. PPA set-up and price calculation

The logistics behind both the on-site generation with offshore technologies and the real-case distance between the plants and the facility were not considered in this study. The "on-site" RET plants were modeled as they are in the north of Portugal in Viana do Castelo although the location of the future lithium conversion facility is now known to be Setúbal, in the south of Lisbon. Further, on-site generation with offshore energy technologies is difficult to arrange if the electricity consumer is not located offshore or close to shore. In addition, the optimal set-up for the objective of 24/7 CFE supply for the facility can be discussed. A real-time on-demand energy contract arrangement would be preferred over a power contract to supply the facility with electricity exactly when needed. However, due to the complexity of such a system and limitations with the chosen modeling tool, this was not done in this study.

The actual possibility for a physical PPA arrangement can also be discussed. The constraint for a PPPA is that the plant and the consumer are on the same electricity market. However, it can be questioned how the distance between Viana do Castelo and Setúbal would impact the logistics of having an intermediary electricity distributor, required in a PPPA set-up. It might be that a VPPA is the preferable option from a logistical perspective. A relevant investigation would be to locate the offshore plant/plants outside Setúbal to enable on-site (close-to-site) generation. Especially, as locations close to Lisbon in Portugal will be the economically preferable for wave energy once the technology is commercial according to the literature.

The energy prices for the PPAs of the RET plants were calculated in a simplified way. They did not consider all the costs that would normally influence a PPA price. The CapEx, OpEx, decommissioning costs and WACC used did not consider factors such as inflation, annual tax payments. Also, the grid connection charges which according to literature stand for a large part in an on-site BTM system were not accounted for. Including these values would have had an impact the PPA prices. Further, the PPA price was set to be fixed, mainly due to the set-up in HOMER Pro where only one price could be used for the resources. For example, different energy prices throughout the day could have been implemented, following the off-peak, shoulder, and on-peak prices on the wholesale market.

Regarding the technical performance of the plants and its impact on the price setting, degradation of the equipment was not accounted for. Including that would have resulted in a lower total electricity supply over the project lifetime, increasing the energy price calculated and total system costs. Further, in a PPPA arrangement grid fees and losses would have played a significant role both for the technical/environmental performance and the system costs. However, as the study was set-up with on-site generation these factors were neglected.

5.2. Uncertainty of Data

The wholesale energy prices as well as the retail energy prices used in this study were average values from 2019. This year was chosen due to a more stable global energy market in this year compared to recent years. Using data from another year could have impacted the results significantly. Further, future energy price fluctuations were not considered in the modeling part, which is a source of error in the study. The same goes for the CapEx, OpEx used for the wave, FLOW and storage devices. Although, the values used were predicted for 2026, they are uncertain. Many factors can impact the future prices in both directions. However, looking at other renewables energy technologies, such as solar PV and bottom-fixed offshore wind, the prices have decreased unexpectedly fast. Given that both the wave and FLOW technologies are successfully proven, the cost-declination can be as targeted/predicted or even faster for them as well.

Further, the yearly RET generation was calculated with the same weather data throughout the 25 years of operation. This does not reflect the real scenario where both wind and waves vary from year to year. Although, there are seasonal similarities, deviating weather conditions can occur and impact the generation of the plants. However, this can be both a negative and positive for the generation, resulting in a higher or lower amount of sold electricity at the end. Ideally weather data representing an average over many years should be used.

5.3. Energy System Technologies

In this section a discussion of the modeled energy system technologies takes place. In addition, alternative technology options are mentioned.

5.3.1. Wind and Wave Costs and Performance

The energy price for wind energy used in this study is higher than for wave energy, resulting in higher NPCs for the systems including wind energy. As mentioned, all costs of the non-commercial technologies are uncertain predicted values. Hence, the costs of the systems are considerable. The significant aspect of this study is how the systems meet the approach of 24/7 CFE. However, to set equal costs for the RETs would be interesting in the model to then investigate the optimal systems in terms of costs. Furthermore, the NPC, seen as the final price for the electricity consumer Aurora in this study, only accounts for the electricity prices of the systems (PPA price for the RET electricity, the grid electricity price, the wholesale price when selling the surplus and the costs for the battery solution). In a real application, additional factors would have an impact on the price paid for electricity by the lithium conversion facility. As mentioned, the grid charges were neglected in this study. Carbon credits were not considered either, which would have reduced the price of the consumer, depending on the emissions emitted by the system.

In terms of power output, the CPO WEC performs better than the Vestas V164 8000 wind turbine in this study which depends both on the technical performance of the devices and on the weather data. Moreover, in HOMER Pro, only integers of number of the devices were selected. However, for the wind technology it is questionable that a lower installed capacity (not a whole device) was preferred from an economic perspective. A smaller turbine could have suited the system better. Nevertheless, HOMER Pro is an economic model and optimizes after the lowest NPC. As this study is focusing on environmental aspects as well, the NPC has not been the only factor for the investigated systems.

5.3.2 Battery Storage Model

The battery storage model considered a discharge/charge range. However, additional technical metrics could be added to better reflect the performance of a real battery storage application. For instance, no losses were considered, neither in the inverter nor the batteries. Another potential improvement of the battery model and analysis is the hourly duration of the storage. It was set to four hours according to the industrial/commercials peak-lopping system which costs were used. Nonetheless, it could have been investigated further to see what suited the system better. Moreover, one can argue that there are additional measures to lower the electricity bill with on-site BTM storage. The battery could be charged during off-peak hours and discharged during peak-hours, and thereby avoid high grid prices. However, as the purpose of the storage was to achieve 24/7 CFE supply this was not implemented in the model as the source would then be unknow for parts of the electricity in the battery.

5.3.3. Alternative Energy Technologies

As seen when analyzing the production profile for wave and FLOW energy, the summer and autumn months are showing a low energy output from both technologies. To reach a higher renewable output during these months, and a more balanced generation throughout the year, alternative energy technologies could have been investigated. Including solar PV in the system could be a way to ensure more stable generation, especially during the summer and autumn. This is again emphasizing how significant a mix of several technologies that peak at different times will be for an energy system to reach 24/7 CFE. As mentioned, the LCOE of solar PV is lower than the LCOE for the non-commercial technologies used in this study. Thus, solar PV would lower the overall system costs. Another option to lower the system costs could be using bottom-fixed or onshore wind energy technology. However, it is uncertain if the power output of these technologies would be lower than for FLOW and decrease the 24/7 CFE performance. Further, as mentioned, the battery storage results indicates that a storage solution with longer duration, such as hydrogen, compressed air, or thermal storage, could be more feasible than batteries to enable 24/7 CFE supply of the facility.

5.4. System Emissions and 24/7 CFE

The emissions of the renewable technologies are assumed to be emissions free for the modeling in this study. Much of the renewable technologies can be assumed to be emission free as no fossil fuels are required for their operation. Yet, this is without considering the whole lifecycle of the technologies. Transports when installing and replacing the technologies could be one factor that is contributing to emissions. Therefore, the total emissions over the modeling period would be higher if such factors were included. Additionally, as the grid in HOMER Pro is only seen as non-renewable, the metrices used to calculate the 24/7 CFE KPI (RF, YRP and HRP) can be discussed. These metrices would be higher as the Portuguese national grid already consist of a large share of renewables. Yet, as seen *Section 2.6.1,* the renewable share in the Portuguese national grid is also varying throughout a year. In this study, the accurate renewable share of the grid was neglected for the FR, YRP and HRP. However, the emissions calculations do consider this and reflects a more accurate environmental impact of the systems.

In this study the main objective was to reach 24/7 CFE supply of the lithium conversion facility. However, one can argue that 100% RF is just as important as 100% YRP from an environmental perspective. That the consumer of the RET electricity is not significant as soon as the renewable share increases in total. However, emitting less is a significant incentive for companies as it is a source of income through carbon credits. Nonetheless, along with increasing requirements and social expectations on sustainability, the importance of action and investment in measures such as renewable energy and the trending concept of 24/7 CFE supply exceeds the financial incentive for stakeholders.

5.5. Financial Support and Stage of Commercialization

Financial support exists within the sector of marine energy technologies. Support both through grant, subsidies and investments are available for innovative and non-commercial technologies. However, it can be discussed how easy it is to receive such support and how large the number of stakeholders that apply for the same schemes are. The process of applying is often through several stages with applications and interviews and is time consuming.

Further, FiT play a significant role in the renewable energy. However, more countries have started to rely on new market-driven strategies for the support of RET installation. As mentioned, Portugal has adapted FiT for renewables. Yet, the political support mechanisms have been affected by the financial crisis in the country. Therefore, it can be discussed that the economic stability in a country is a significant factor in which the financial support is adapted to a large range of renewable technologies. Portugal has as other countries announced that they will have a renewable auction for FLOW. The auction will as mentioned take place this summer (2022) and be for farms between 3 and 4 GW. This is interesting as FLOW energy is not yet fully commercial. The technology has however been proven in several full-scale applications in the water. The WindFloat Atlantic plant in Portugal is one example. Hence, the emerge of auctions for wave energy technology is promising as soon as the technology is proven, even before it reaches a commercial stage. Especially as the REPowerEU Plan is emphasizing the urgency of energy security in the EU and an increase of financial support for renewable energy technologies is to be seen. As mentioned, the OEE sees this a significant factor for wave energy, and that it could contribute to EU reaching their wave energy targets by 2025.

6. Conclusion and Future Work

This chapter consists of a conclusion answering the aim and objectives of the study and covers interesting and relevant future work.

6.1. Conclusion

The aim of this study was to investigate the value of commercial wave energy technology in an energy system. With reference to the three research questions of the study the conclusions are as follows:

1. The wave energy technology, more specifically the CPO WEC, shows to have a high power output in this study. Although a combination of wave and floating offshore wind energy better ensure energy security with generation profiles that peak at different times, the modeling shows that a system with wave energy alone has a higher 24/7 CFE performance than a system with both wave and FLOW energy capacity. Hence, the wave energy technology in Viana do Castelo in 2019 performs better than the FLOW. Additionally, compared to the Portuguese national grid, wave energy at the stage of commercialization, is less expensive and is preferred from an environmental perspective. A system with 32 MW installed wave energy capacity is the system with the best combination of the NPC and total emissions over 25 years with 249 MEUR and 47 kton $CO_{2\text{-eq}}$, respectively.

2. Regarding Li-ion battery storage in the system it is not worth an investment if the surplus of the renewable generation can be sold to the grid. Moreover, a reasonable size for the load does not contribute with a significantly improved 24/7 renewable electricity supply of the facility. To achieve 24/7 CFE supply energy storage with a longer duration is needed.

3. The wave energy price is higher than for other commercial renewable technologies such as solar PV. The LCOE of wave energy is 0.0598 EUR/kWh in this study. For wave energy to reach market price in 2026 and compete with solar PV LCOE of 0.026 EUR/kWh, financial support covering the CapEx costs with 80% is required. This could be achieved as the interest in marine energy technology, and especially wave energy, is increasing in countries like Portugal. The review of finical support for wave energy shows that governments and other stakeholders are supporting the development with financial measures. Hence, wave energy has the potential to be competitive as soon as the technology is proven.

6.2. Future Work

For the energy system to achieve 24/7 CFE supply of the facility, an on-demand energy contract arrangement would be interesting to investigate. Additionally, other technologies, such as solar PV and longer duration energy storage, should be included in the energy system. Furthermore, a system set-up where the offshore technologies are not modeled as on-site plants would reflect a more realistic case. That would require a model where the grid can be included in a larger extent, considering factors from transmission and distribution, such as costs and losses.

References

Akrofi, M.M. 2021. *An analysis of energy diversification and transition trends in Africa.* Accessed: https://link.springer.com/content/pdf/10.1007/s42108-020-00101-5.pdf [02/05/22].

Albert, L. 2020. *Wave And Wind Are The New Hybrid Renewable Energy Source.* Accessed: https://seabased.com/news-insights/wave-and-wind-are-the-new-hybrid-renewable-energy-source [03/05/22].

BEIS, Department for Business, Energy and Industrial Strategy. a2018. *Storage cost and technical assumptions for BEIS.* Accessed: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/910261/storage-costs-technical-assumptions-2018.pdf [06/05/22].

Bento, A.R., Martinho, P., Silva, D. & Soares, C.G. 2015. *High resolution local wave energy modelling in the Iberian Peninsula.* Accessed: https://reader.elsevier.com/reader/sd/pii/S0360544215011433?token=ED6CF6A6FFE250C7E0FD06870C567F5C5FE81C654AC811D8E1080DA57E8A2D415AFF5E72A56C65F0FB29080D9BAB9567&originRegion=eu-west-1&originCreation=20220510075926 [10/05/22].

Bento, A.R., Castro-Santo, L., Salvação, N., Silva, D. & Soares, C.G. 2018. *Economic Feasibility of Wave Energy Farms in Portugal.* Accessed: https://www.mdpi.com/1996-1073/11/11/3149/htm [10/05/22].

Bould, D., De Andres, A., Jeffrey, H. Maillet, J., Möller, P. & Todalshaug, J. H. 2016. *Techno-Economic Related Metrics for a Wave Energy Converters Feasibility Assessment.* Accessed: https://www.mdpi.com/2071-1050/8/11/1109/htm [26/05/22].

Blaabjerg, F., Faisal, M., Hannan, M.A., Hussain, A., Ker, P.J. & Mansor, M.B. 2018. *Review of Energy Storage System Technologies in Microgrid Applications: Issues and Challenges.* Accessed: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8368103 [03/05/22].

Callaba, I., Conde, I., Ferragut, F., Guédez, R., Hassar, Z., Laumert, B., Perez-Segarra, C., Spelling & J., Topel, M. 2016. *A Methodology for Determining Optimum Solar Tower Plant Configurations and Operating Strategies to Maximize Profits Based on Hourly Electricity Market Prices and Tariffs.* Accessed: https://asmedigitalcollection-asme-org.focus.lib.kth.se/solarenergyengineering/article/138/2/021006/379586/A-Methodology-for-Determining-Optimum-Solar-Tower [22/06/22].

Carriveau, R., Harper. S., Miller. L. & Singh. S. 2017. *Evaluating the link between LCOE and PPA elements and structure for wind energy*. Accessed: https://isiarticles.com/bundles/Article/pre/pdf/145467.pdf [23/05/22]

Chen, C., Hu, G. & Yang, Z. 2021. *Signalling the cost of intermittency: What is the value of curtailed renewable power?* Accessed: https://reader.elsevier.com/reader/sd/pii/S0959652621012178?token=338FEC84ADD0E0CF8A325F291D069E2D366C3250B86FC8C6A7ABCD79898B869E8D4B9FCE52C116318E5F0163F7C9CCB9&originRegion=eu-west-1&originCreation=20220502110132 [02/05/22].

Chestney, N. 2022. *Explainer: Why Europe faces climbing energy bills.* Accessed: https://www.reuters.com/business/energy/why-europe-faces-climbing-energy-bills-2022-02-03/ [09/05/22].

Chozau, J.F. & Têtu, A. 2021. *A Proposed Guidance for the Economic Assessment of Wave Energy Converters at Early Development Stages.* Accessed: https://www.mdpi.com/1996-1073/14/15/4699/htm [06/05/22].

Copernicus. n.d. *Atlantic -Iberian Biscay Irish- Ocean Wave Reanalysis.* Accessed: https://resources.marine.copernicus.eu/product-detail/IBI_MULTIYEAR_WAV_005_006/INFORMATION [09/05/22].

CPO, CorPower Ocean. n.d.a. Explainer: *HiWave-5.* Accessed: https://www.corpowerocean.com/projects/hiwave-5/ [09/05/22].

CPO, CorPower Ocean. n.d.b. *Wave Energy Converter.* Accessed: https://www.corpowerocean.com/technology/ [26/05/22].

Cunha-e-Sá, M. A., Lopes, A. F, Saldanha, F. 2017. *Marine Renewable Energy in Portugal*. Accessed: https://www.novasbe.unl.pt/Portals/0/KnowledgeCenters/Environmental%20Economics/documents/GulbenkianPolicyBrief_Energias_ENweb%283%29.pdf [29/04/22].

Das. P. & Khaki. B. 2019. *Sizing and Placement of Battery Energy Storage Systems and Wind Turbines by Minimizing Costs and System Losses.* Accessed: https://arxiv.org/pdf/1903.12029.pdf [09/05/22].

Deng, Z., Wang, B. & Zhang, B. 2022. *Simulation of a novel wind–wave hybrid power generation system with hydraulic transmission.* Accessed: https://www-sciencedirect-com.focus.lib.kth.se/science/article/pii/S0360544221020818 [09/05/22].

DNB, Den Norske Bank. 2022. *Currency Converter.* Accessed: https://www.dnb.no/en/business/markets/foreign-exchange/calculator/currencyconverter.html [03/05/22].

DNV. n.d. *FLOW.* Accessed: https://www.dnv.com/focus-areas/floating-offshore-wind/index.html [18/05/22].

Duffy. P., Heimiller. D., Laurienti. M., Musial. W., Optis. M., Shields. M., Spenser., R. 2021. *The Cost and Feasibility of FLOW Energy in the O'ahu Region. NREL.* Accessed: https://www.nrel.gov/docs/fy22osti/80808.pdf [23/05/22].

ECB, European Central Bank. 2022. *Pound sterling (GBP).* Accessed: https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-gbp.en.html [09/05/22].

EDP, Energias de Portugal. n.d. *FLOW-power generating platform.* Accessed: https://www.edp.com/en/innovation/windfloat [04/05/22].

EEA, European Environment Agency. 2022. *Atmospheric greenhouse gas concentrations*. Accessed: https://www.eea.europa.eu/ims/atmospheric-greenhouse-gas-concentrations [25/02/2022]

EIC, European Innovation Council. 2022. *European Innovation Council (EIC) Work Programme 2022.* Accessed: https://eic.ec.europa.eu/about-european-innovation-council_en [25/02/2022]

EnergyMag. n.d. *Availability Factor.* Accessed: *https://energymag.net/technologies/availability-factor/* [25/03/2022]

ESA, Energy Storage Association. 2018. *A beginner's Guide to Energy Storage.* Accessed: http://energystorage.org/system/files/resources/%20slides_complete v2.pdf [18/05/22].

Esteban, M.D. 2017. *Classification of Wave Energy Converters.* Accessed: https://juniperpublishers.com/rapsci/pdf/RAPSCI.MS.ID.555593.pdf [09/05/22].

EC, European Commission. n.d.a. *Strategic Energy Technology Plan.* Accessed: https://energy.ec.europa.eu/topics/research-and-technology/strategic-energy-technology-plan_en [03/05/22].

EC European Commission. n.d.b. *EU renewable energy financing mechanism.* Accessed: https://energy.ec.europa.eu/topics/renewable-energy/financing/eu-renewable-energy-financing-mechanism_en [26/05/22].

Eurostat. 2022. *Electricity prices for non-household consumers - bi-annual data (from 2007 onwards).* Accessed: https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_205/default/line?lang=en [01/06/22].

Faisal, M., Hannan, M. A., Ker, P. J., Hossain Lipu, M. S., & Uddin, M. N. 2020. *Real time implementation of fuzzy based charging-discharging controller for lithium-ion battery in Microgrid applications.* Accessed: https://doi.org/10.1109/ias44978.2020.9334749 [03/05/22].

Galp & Northvolt. 2021. *Galp and Northvolt establish joint venture 'Aurora' to develop a lithium conversion facility.* Accessed: https://www.galp.com/corp/Portals/0/Comunicados_Media/2021/Dezembro2021/20211214_Galp_and_Northvolt_establish_joint_venture_Aurora_to_develop_a_lithium_conversion_facility.pdf [10/05/22].

Garanovic, A. 2021. *EVOLVE to showcase economic value of ocean energy in Europe.* Accessed: https://www.offshore-energy.biz/evolve-to-showcase-economic-value-of-ocean-energy-in-europe/ [04/05/22].

Garanovic, A. 2022. *Ocean Energy Europe: REPowerEU as new innovation stepping stone for renewables.* Accessed: https://www.offshore-energy.biz/ocean-energy-europe-repowereu-as-new-innovation-stepping-stone-for-renewables/?utm_source=marineenergy&utm_medium=email&utm_campaign=newsletter_2022-05-20 [30/05/22].

Gunn, K. & Stock-Williams, C. 2012. *Quantifying the global wave power resource.* Accessed: https://www.sciencedirect.com/science/article/abs/pii/S0960148112001310 [03/05/22].

GSI, Global Subsidies Initiative. n.d. *RENEWABLE ENERGY SUBSIDIES & FOSSIL FUEL PHASE-OUT.* Accessed: https://www.iisd.org/gsi/what-we-do/focus-areas/renewable-energy-subsidies-fossil-fuel-phase-out [02/05/22].

HOMER Energy. n.d. *Optimize the value of your hybrid power system—from utility-scale and distributed generation to standalone microgrids.* Accessed: https://www.homerenergy.com/ [05/05/22].

IEA, International Energy Agency. 2021. *Portugal 2021 Energy Policy Review.* Accessed: https://iea.blob.core.windows.net/assets/a58d6151-f75f-4cd7-891e-6b06540ce01f/Portugal2021EnergyPolicyReview.pdf [01/03/22].

IEA, International Energy Agency. n.d. *Ocean Power.* Accessed: https://www.iea.org/reports/ocean-power [03/05/22].

IPCC, Intergovernmental Panel on Climate Change. 2021. *Climate Change 2021. The Physical Science Basis.* Accessed: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf [02/05/22].

IRENA, International Renewable Energy Agency. 2019a. *Innovation landscape brief: Utility-scale batteries.* Abu Dhabi. Accessed: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Utility-scale-batteries_2019.pdf [18/05/22].

IRENA, International Renewable Energy Agency. 2019b. *Renewable energy auctions: Status and trends beyond price*. Abu Dhabi. Accessed: https://www.irena.org/publications/2019/Dec/Renewable-energy-auctions-Status-and-trends-beyond-price [02/05/2022].

IRENA, International Renewable Energy Agency. 2020a. *Innovation outlook: Ocean energy technologies.* Abu Dhabi. Accessed: https://www.irena.org/publications/2020/Dec/Innovation-Outlook-Ocean-Energy-Technologies [02/05/2022].

IRENA, International Renewable Energy Agency. 2020b. *Global LCOE and Auction values.* Accessed: https://www.irena.org/Statistics/View-Data-by-Topic/Costs/Global-LCOE-and-Auction-values [06/05/22].

IRENA, International Renewable Energy Agency & CEM, Clean Energy Ministerial. 2015. *Renewable Energy Auctions. A Guide to Design*. Accessed: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/Jun/IRENA_Renewable_Energy_Auctions_A_Guide_to_Design_2015.pdf [16/06/22].

Jain. S. 2021, *Exploring structures of power purchase agreements towards supplying 24x7 variable renewable electricity.* Accessed: https://www.sciencedirect.com/science/article/pii/S0360544221028589 [23/05/22]

Keiner, D., Salcedo-Puerto, O., Immonen, E., van Sark, W., Nizam, Y., Shadiya, F., Duval, J., Delahaye, T., Gulagi, A. and Breyer, C., 2022. *Powering an island energy system by offshore floating technologies towards 100% renewables: A case for the Maldives.* Accessed:https://www.sciencedirect.com/science/article/pii/S0306261921016056 [18/05/22].

Kenton, W. 2021. *What Is a Feed-In Tariff (FIT)?* Accessed: https://www.investopedia.com/terms/f/feed-in-tariff.asp [28/04/22].

Kulovic, N. 2022. *EU sets out plan to tackle double whammy of dependence on Russian fossil fuels and climate crisis*. Accessed: https://www.offshore-energy.biz/eu-sets-out-plan-to-tackle-double-whammy-of-dependence-on-russian-fossil-fuels-and-climate-crisis/ [30/05/22].

McTiernan. K.L. & Thiagarajan Sharman. K. 2020. *Review of Hybrid Offshore Wind and Wave Energy Systems.* Accessed: https://iopscience.iop.org/article/10.1088/1742-6596/1452/1/012016/pdf [09/05/22].

Mendicino. L., Menniti. D., Pinnarelli. A. & Sorrentino.N. 2019. *Corporate power purchase agreement: Formulation of the related levelized cost of energy and its application to a real life case study.* Accessed: https://doi.org/10.1016/j.apenergy.2019.113577 [23/05/22]

Northvolt. 2022. *Galp and Northvolt select Setúbal to build advanced lithium conversion unit.* Accessed: https://northvolt.com/articles/aurora-setubal/ [03/05/22].

Nurunnabi, Md. & Roy, N.K. 2015. *Grid Connected Hybrid Power System Design Using HOMER.* Accessed: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7506786 [10/05/22].

OEE, Ocean Energy Europe. n.d.a. *Wave energy.* Accessed: https://www.oceanenergy-europe.eu/ocean-energy/wave-energy/ [03/03/22].

OEE, Ocean Energy Europe. n.d.b. *Financing ocean energy farms.* Accessed: https://www.oceanenergy-europe.eu/policy-topics/finance/ [02/05/22].

OMIE. n.d. *Day-ahead minimum, average and minimum price.* Accessed: https://www.omie.es/en/market-results/interannual/daily-market/daily-prices?scope=interannual&system=2 [09/05/22].

Onea, F. & Rusu, E. 2018. *A review of the technologies for wave energy extraction.* Accessed: https://doi.org/10.1093/ce/zky003 [03/05/22].

Pereira, E.T.S. 2018. *Lithium in Portugal. From an opportunity to a (hidden) threat?* Accessed: https://repositorio-aberto.up.pt/bitstream/10216/116279/2/294385.pdf [04/05/22].

Petracca, E., Faraggiana, E., Ghigo, A., Sirigu, M., Bracco, G., Mattiazzo, G. 2022. *Design and Techno-Economic Analysis of a Novel Hybrid Offshore Wind and Wave Energy System.* Accessed: https://doi.org/10.3390/ en15082739 [09/05/22].

Pfenninger, S. & Staffell, I. 2016. *Using bias-corrected reanalysis to simulate current and future wind power output*. Accessed: https://www.sciencedirect.com/science/article/pii/S0360544216311811 [10/05/22].

Principle Power. n.d. *WindFloat Atlantic.* Accessed: https://www.principlepower.com/projects/windfloat-atlantic [10/05/22].

Renewables.ninja. n.d. Accessed: https://www.renewables.ninja/ [10/05/22]

RES LEGAL. n.d. *Portugal: Overall Summary.* Accessed: http://www.res-legal.eu/search-by-country/portugal/ [02/05/22].

REN. n.d.a. *Monthly Balance.* Accessed: https://datahub.ren.pt/en/electricity/monthly-balance/ [04/05/22].

REN. n.d.b. *Daily Balance.* Accessed: https://datahub.ren.pt/en/electricity/daily-balance/ [05/05/22].

Reuters. 2022. *Portugal to auction 3-4 GW of FLOW farms in summer.* Accessed: https://www.reuters.com/business/energy/portugal-auction-3-4-gw-floating-offshore-wind-farms-summer-2022-03-16/ [26/05/22].

REW, Renewable Estate Work. 2021. *EU-SCORES Project aims to deliver 'world-first' bankable hybrid offshore marine energy parks.* Accessed: https://www.rwe.com/en/press/rwe-renewables/2021-09-01-eu-scores-project-aims-to-deliver-world-first-bankable-hybrid-offshore-marine-energy-parks [04/05/22].

Roberts, D. 2021. *An introduction to energy's hottest new trend: 24/7 carbon-free electricity.* Accessed: https://www.volts.wtf/p/an-introduction-to-energys-hottest?utm_source=url&s=r [02/05/22].

SEAI, Sustainable Energy Authority of Ireland. n.d. *Ocean Energy Technologies.* Accessed: https://www.seai.ie/technologies/ocean-energy/ocean-energy-technologies/ [04/03/22].

SEIA, Solar Energy Industries Association. 2018. *Solar Power Purchase Agreements. What is a solar power purchase agreement? Accessed: https://www.seia.org/research-resources/solar-power-purchase-agreements [23/05/22]*

Statista. 2022a. *Portugal: Inflation rate from 1987 to 2027*. Accessed: https://www.statista.com/statistics/372347/inflation-rate-in-portugal/ [17/06/22].

Statista. 2022b. *Carbon intensity of the power sector in Portugal from 2000 to 2021.* Accessed: https://www.statista.com/statistics/1290463/carbon-intensity-power-sector-portugal/ [11/05/22].

Tang, C. & Zhang, F. 2019. *Classification, principle and pricing manner of renewable power purchase agreement.* Accessed: https://www.sciencedirect.com/science/article/pii/S0301421520302135 [09/05/22].

Tarver, E. 2021. *How Do Government Subsidies Help an Industry?* Accessed: https://www.investopedia.com/ask/answers/060215/how-do-government-subsidies-help-industry.asp [02/05/22].

Trennepohl, Natasha. 2014. *Electricity – Promotion in Portugal. RES LEGAL. Accessed: https://www.aler-renovaveis.org/contents/lerpublication/EC_2014_JUL_Electricity_Promotion_Portugal.pdf* [22/05/22].

UN, United Nations. 2021. *The 24/7 Carbon Free Energy Compact.* Accessed: https://www.un.org/sites/un2.un.org/files/24-7cfe_compact_-_v2_updated.pdf [02/05/22].

UNDP, United Nations Development. n.d. *What are the Sustainable Development Goals?* Accessed: https://www.undp.org/sustainable-development-goals [02/05/22].

U.S. Department of Energy. 2021. *Offshore Wind Market Report: 2021 Edition.* Accessed: https://www.energy.gov/sites/default/files/2021-08/Offshore%20Wind%20Market%20Report%202021%20Edition_Final.pdf [06/05/22].

U.S. Department of Energy. 2022. *Demand Response in Industrial Facilities: Peak Electric Demand.* Accessed: https://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/Demand%20Response%20in%20Industrial%20Facilities_Final.pdf [10/05/22].

Xie, A. 2020. *Virtual or Physical, the PPA Is Prime. Accessed:* https://www.cleanenergyfinanceforum.com/2020/04/16/virtual-or-physical-the-ppa-is-prime [23/05/22]

Appendix I – Yearly Load Curve

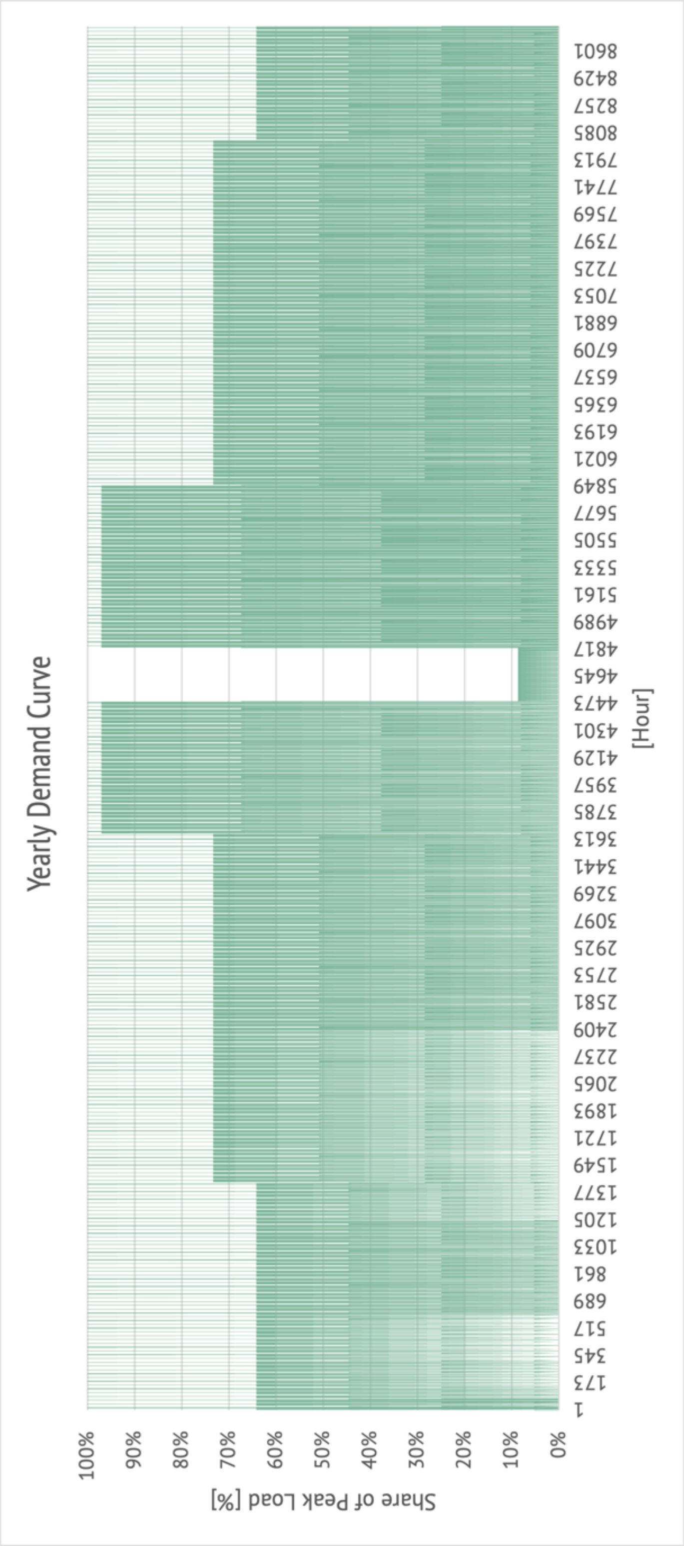


Figure 28. Yearly load curve

Appendix II - HOMER Pro Outputs and NPV Calculation

Table 11. HOMER Pro Outputs and NPV Calculation (With Sell-back).

System	WEC/WT	NPC	NPV	RF	Lowest HRP	YRP
	[MW]	[MEUR]	[MEUR]	[%]	[%]	[%]
Base Case	-	338	-	-	-	-
S2.1	32/-	249	89	83.4	9.0	77
S2.2	48/-	254	84	92.4	13	86
S3.1	-/8	334	4	22.2	0.05	20
S3.2	-/48	403	-65	82.4	0.29	71
S4.1	28/8	270	68	86	10	79
S4.2	48/48	422	-84	98.7	21	96

** WEC = Wave Energy Converter [MW], WT = Wind Turbine [MW].*

** NPC = Net Present Cost, NPV = Net Present Value, RF = Renewable Fraction, RP = Renewable Penetration.*

Table 12. HOMER Pro Outputs and NPV Calculation (Without Sell-back).

System	Wave/Wind	NPC	NPV	RF	Lowest HRP	YRP
	[MW]	[MEUR]	[MEUR]	[%]	[%]	[%]
Base Case	-	338	-	-	-	-
S2.1	20/-	282	56	65.2	5.37	61
S2.2	48/-	407	-69	92.4	13.0	86
S3.1	-/8	338	0	22.2	0.05	20
S3.2	-/48	514	-176	82.4	0.29	71
S4.1	14/8	307	31	65.2	5.64	60
S4.2	48/48	787	-449	98.7	21.0	96

** Wave [MW], Wind [MW].*

** NPC = Net Present Cost, NPV = Net Present Value, RF = Renewable Fraction, RP = Renewable Penetration.*

Appendix III - Renewable Coverage of Systems

Table 13. Renewable Coverage of Systems.

System	**RF**	**Hours of RP=100%**		**Hours RP <75%**		**Hours RP <50%**	
	[%]		**[%]**		**[%]**		**[%]**
Base Case	-	-	-	-	-	-	-
S2.1	83.4	5571	64	2451	28	1564	50
S2.2	92.4	6616	76	1564	18	812	9
S3.1	22.2	1080	12	7477	85	7143	82
S3.2	82.4	5051	58	3037	35	2226	25
S4.1	86	5696	65	2206	25	1238	14
S4.2	98.7	7955	91	439	5	144	2
SB1	82.7	5696	65	2206	25	1238	14
SB2	86.1	6870	78	1643	19	1091	12

TRITA – ITM-EX 2022:187

www.kth.se